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To Masticate or Not:

Useful Tips for Treating Forest, Woodland, and Shrubland Vegetation

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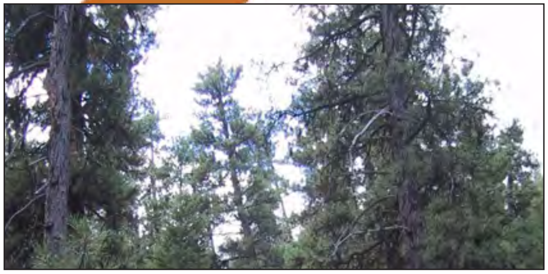

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Abstract

Forest managers use mastication to grind or shed vegetation to remove competition, prepare a site for natural or artificial regeneration, or release sapling-sized trees; or they use mastication to convert ladder fuels to surface fuels and enhance decomposition of biomass. However, determining the best mastication configuration within the context of management objectives and site limitations is challenging. This report synthesizes our current knowledge on mastication as a forest management tool. We found that excavators, skid steers, and tractors can all be carrier machines and different types of vertical and horizontal cutting heads exist that can be front-end mounted or boom mounted, each with its own advantages and disadvantages. We provide a summary on the ecological effects from mastication. We found that there were several studies on plant and soil impacts, but limited information on impacts to wildlife habitat. Although costs of mastication widely vary depending on machine size, the physical setting, size and configuration of pre-treatment biomass, and operator skill, mastication does have market and non-market benefits. Depending on the management objective, if mastication is an option, then a thorough site evaluation should consider slope, nonnative species invasions, vulnerability of soils to erode or compact, and treatment costs.

Keywords: fuel treatments, silvicultural methods, vegetation management, forest mulching, site preparation, precommercial thinning

Cover: Choosing a mastication method can often be a confusing. Managers may be taken down several different pathways to make a decision depending on their desired outcomes and financial limitations. Some of the most common pathways to masticate material include (from far left and clockwise): (1) a vertical drum on a skid steer (photograph by Mike Battaglia USFS); (2) a horizontal cutting head (photograph by Mike Battaglia USFS; (3) vertical head masticator (photograph by Mel Peterson, Director of Marketing and Training, Diamond Mowers Inc.); (4) horizontal drum cutting head (photograph by Dana Mitchel USFS); (5) chipper (photograph courtesy of Morbark LLC); and (6) dry mixed conifer forests (photograph by Jonathan Sandquist, USFS). Cover design by Pam Sikkink and Audrey Peterson, RMRS Missoula Fire Sciences Laboratory.

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Introduction

Mastication grinds, shreds, or chops noncommercial sized trees or shrubs into small chunks or pieces. The method does not reduce biomass; rather, the operator creates these small pieces and places them in contact with the soil surface to decompose (McDaniel 2013) (fig. 1). Silviculturists use mastication to eliminate vegetation competition (understory vegetation, saplings, and pole-sized trees), to prepare a site for natural or artificial regeneration, or to weed or clean sites in noncommercial thins (Jain et al. 2012). Fuel managers use mastication to convert ladder fuels to surface fuels, to enhance decomposition of dead biomass, to make prescribed fire easier and more controllable, or to slow the rate of fire spread during wildfires to assist suppression efforts (McDaniel 2013; Rummer 2010).

Several scientists have investigated the ecological effects from mastication in forest, woodland, and shrubland ecosystems throughout the western United States, Canada, and Spain (table 1, Appendix A). Vegetation types where these studies occurred included dry and moist mixed conifer, loblolly pine (*Pinus taeda* L.), longleaf pine (*Pinus palustris* Mill.), slash pine (*Pinus elliottii* Engelm.), lodgepole pine (*Pinus contorta* Douglas ex Loudon), spruce (*Picea* species), ponderosa pine (*Pinus ponderosa* Lawson & C. Lawson), pinyon-juniper (*Pinus edulis*-*Juniperus* species), oak (*Quercus* species), California chaparral woodlands, and gorse (*Ulex* species) shrublands. In these studies, investigators sometimes mention the machine used to masticate the biomass, but rarely do they provide details that guide implementation. Instead, the studies have quantified fuel loadings and distribution (e.g., Battaglia et al. 2010), soil chemical and physical properties (e.g., Busse et al. 2005), wildlife effects (e.g., Burnett et al. 2014), understory vegetation response (e.g., Fernandez et al. 2015), potential fire behavior (e.g., Kreye et al. 2014), and fuel bed characteristics (e.g., Keane et al. 2018) (table 1).

Figure 1—Mastication machine treating surface fuels and providing a fire break surrounding buildings (photograph by Dana Mitchell, USDA Forest Service, Southern Research Station).

Table 1—Mastication studies that noted the machine type throughout the United States, Canada, and Spain between 2005 and 2016.

Vegetation type[a]	Material masticated			
	life form	Size (inch)[b]	Machine[c]	Literature source
Study Location: California				
Mixed conifer	Trees, shrubs	Unknown	Machine-mounted HS	Bradley et al. 2006
Chaparral	Shrubs	Unknown	Various	Brennan and Keeley 2015
Mixed conifer	Trees, shrubs	Unknown	Not specified	Burnett et al. 2014
Mixed conifer	Trees	Unknown	Excavator w/ HS fixed teeth	Hatchett et al. 2006
Mixed conifer	Slash	Unknown	Chipper	Johnson et al. 2014
Mixed conifer	Trees	<9	Not specified	Kobziar et al. 2009
PP	Conifers, hardwood	<1	Excavator boom-mounted VS	Reiner et al. 2009
Mixed conifer	Trees, hardwoods	1 to 10	Excavator-mounted HS	Stephens and Moghaddas 2005
Shrub	Slash	Unknown	Excavator-mounted HS	Vitorelo 2011
Study Location: California and Colorado				
P-J, PP	Not described	Unknown	VS knife	Hood and Wu 2006
Study Location: California and Oregon				
Mixed hardwood	Hardwoods, shrubs	Unknown	Excavator w/ VS, w/ HS, machine w/ VS knife	Kane et al. 2009
Study Location: Colorado				
P-J, PP, LP	Not described	Unknown	HS hammers, VS knife	Battaglia et al. 2010
P-J	Trees, Shrubs	Variable	Machine mounted w/ swinging knives	Gottfried and Overby 2011
PP	Trees	≤6	Chipper	Wolk and Rocca 2009
Study Location: Florida				
Longleaf pine, slash pine	Shrubs, saw palmetto, trees	<8	Excavator w/ HS	Kreye 2012
Study Location: Georgia				
Loblolly pine, hardwoods	Trees	hardwoods; pines <8	Mulcher	Brockway et al. 2009
Study Location: South Carolina				
Loblolly pine	Hardwoods, shrubs	Down fuels	Chipper	Glitzenstein et al. 2016
Loblolly pine	Beetle-killed trees	Unknown	Excavator w/ HS	Stottlemyer et al. 2015
Study Location: Texas				
Oak, juniper	All vegetation	<6	HS hammer	Reemts and Cimprich 2014
Study Location: Utah				
P-J	Trees	Unknown	HS	McIver et al. 2010
P-J	Trees	Unknown	Machine w/ HS (brush cutter)	Moss et al. 2012
P-J	Unknown	Unknown	HS fixed teeth	Roundy et al. 2014
Study Location: Alberta, Canada				
LP, spruce	Understory trees, shrubs	Unknown	HS fixed teeth	Schiks et al. 2015
Study Location: Santander, Spain				
Gorse shrubland	All vegetation	Unknown	Excavator w/ HS fixed teeth	Fernandez and Vega 2016

[a] PP = ponderosa pine (*Pinus ponderosa*), P-J = pinyon pine (*Pinus edulis*)/juniper (*Juniperus* sp.), LP = lodgepole pine (*Pinus contorta*), longleaf pine (*Pinus palustris*), slash pine (*Pinus elliottii*), saw palmetto (*Serenoa repens*), loblolly pine (*Pinus taeda*), white fir (*Abies concolor*), oak (*Quercus* sp), spruce (*Picea* sp.), gorse (*Ulex* sp.).

[b] Size is at d.b.h. (diameter at breast height).

[c] VS = vertical shaft; HS = horizontal shaft.

Experienced foresters and fire managers recognize that treatment execution influences the desired outcome. For example, fire practitioners can apply prescribed fire in an infinite number of ways, which can create a diversity of postfire outcomes. When fire practitioners design a fire plan, they identify the time of day to ignite, the range of weather conditions they want when they will be able to burn, the ignition pattern they will use, and sometimes even specific people to implement the prescribed fire. When a fire practitioner combines these factors, they know that their burn prescription will influence the fire behavior, which subsequently creates a desired postfire outcome (Jain et al. 2012). Silviculturists combine treatment types, such as applying mechanical methods and prescribed fire, to create an outcome that favors a desired vegetation response. For instance, Jain et al. (2008) combined hand slashing followed by grapple piling followed by pile burning that created a mosaic of soil substrates and favored regeneration of multiple species. Similarly, executing mastication by altering the piece size, machine type, and cutting head—and even selecting the operator—can alter an outcome; however, limited information exists for managers concerning mastication implementation.

The variety of mastication configurations available today provides an opportunity to match the best equipment available with efficiency and safety to meet desired management objectives. The studies we found identified several references on machine configurations that can guide managers (Bennett and Fitzgerald 2008; Bolding et al. 2006; Halbrook et al. 2006; Rummer 2010; Vitorelo et al. 2009; Windell and Bradshaw 2000). For example, there are specific carrier machines, such as tractors or excavators, that carry the cutting head or other attachments; and cutting-head configurations that are better suited to specific physical settings (Jain et al. 2012). Some machines, such as carrier machines with rubber tracks, can minimize soil compaction (Schafer 2013; Windell and Bradshaw 2000). Alternatively, operators can limit the number of passes over any given area to limit compaction when they use a boom-mounted cutting head (Rummer 2010). Boom-mounted cutting heads can reach trees from above, typically working downhill on slopes, and avoid the necessity for the machine to drive to each tree because of their reaching capabilities. Alternatively, small carrier machines with front-end mounted cutting heads work well in the wildland-urban interface because these machine configurations treat younger stands and shrubs around buildings (Coulter et al. 2002). This report provides information to land managers on the application and implementation of mastication as a fuels-treatment and a silvicultural method, and is organized using the following objectives.

- Objective 1: Synthesize the current literature to describe the characteristics and costs associated with mastication machines and cutting heads used to treat forest, woodland, or shrubland biomass.
- Objective 2: Summarize the current literature that documents the ecological effects from mastication on (a) vegetation, (b) soils, (c) insects, mammals, and birds, and (d) surface fuels <3 inches in diameter.
- Objective 3: Conduct a meta-analysis on selected studies that quantify fine-fuel amounts (woody material ≤3 inches in diameter) after mastication across a large geographic area to determine if post-mastication fine-fuel loads for different vegetation types vary.

- Objective 4: Provide three decision trees and implementation criteria to aid managers in determining the type of treatment best suited to the project area and management objectives.

Methods

We used the scientific and technical literature to address objectives 1 and 2. To fulfill the first objective, we focused on informational sources that discussed different machines, cutting heads, and other related equipment. The industry is constantly changing, making it difficult to cite any one publication, manufacturer or source; however, we did find a website with a very large database of equipment related to mastication called the *Forestry Mulcher Guide*[1] (Catalytic Response, LLC 2017). We found this to be a good internet source that summarizes machine attributes by manufacturer. This source provided detailed specifications across a wide range of machine sizes and types. We explicitly cite the *Forestry Mulcher Guide* as the source of information on the ranges in horsepower, widths, lengths, heights, and other carrier and cutting-head specifications.

To fulfill the second objective, we obtained information on ecological effects from studies conducted in mixed-conifer forests, woodlands, and shrublands across the United States, Canada, and Europe (table 1). The keywords that guided this literature search were mastication, mulching, slash busting, noncommercial fuel treatments, and hazardous fuel reduction methods. We also investigated several final reports that summarized the ecological effects from mastication conducted for the Joint Fire Science Program (https://www.firescience.gov/). Appendix A summarizes the literature (reference, location, and general results) we used in the synthesis.

The third objective focused on the amount of fine woody fuels ≤3 inches in diameter, classified as 1-hour (0 to 0.25 inch), 10-hour (0.25 to 1.0 inch), and 100-hour (1.0 to 3.0 inches) produced by masticators. We hypothesized that mastication always results in the same distribution and amount of fine fuels regardless of vegetation type. We obtained data from selected papers that studied multiple sites or forest types and reported detailed data on fine fuels. Battaglia et al. (2010) and Kane et al. (2009) contained these type of data. We also added another data source from Keane et al. (2018). These data, in addition to fine-fuel amounts across different sites, also provided data on the variation in particle surface area of masticated pieces created by different cutting heads. Appendix B provides detailed descriptions of the field and laboratory methods from Keane et al. (2018).

To meet the fourth objective, we developed three decision trees. The first decision tree identified the critical site characteristic that influences whether to use mechanical treatments or prescribed fire at a site. The second decision tree provides parameters that guide treatment options, including mastication, prescribed fire, or other mechanical treatments. The third decision tree focused only on factors associated with mastication. It includes information to help decide the general size and type of machine and cutting

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[1] Because providing a specific equipment guide for mastication machines for purchase or evaluation was not the objective of this synthesis, we used information from this site to provide the reader with a range and diversity of machines that are currently available. As of August 28, 2017, this website and domain no longer exist. However, the author was able to access data listed in tables 2, 3, and 4 through the Wayback Machine (https://web.archive.org/web/20161111035457/http://www.forestrymulcherguide.com), and the lead author has the equipment specifications on file taken from this site. Data used on the regression are on file with the author.

head and discusses the particular types of mastication equipment. We organized the discussion surrounding the three decision trees around questions that managers might ask when they want to identify the best method or machine to use.

Statistical Analysis

We used regression analysis to determine diameter-to-cutting head horsepower and diameter-to-weight relationships using the regression procedure in SAS software (Myers 1990; SAS Institute 2013). We used a subset of machine specifications from manufacturers listed on the *Forestry Mulcher Guide* (Catalyst Response, LLC. 2017). In this analysis, we applied a log transformation of diameter to address residual error normality and variance homogeneity. We conducted two statistical analyses to address objective 3. First, we used a meta-analysis to determine variation in fine fuels across vegetation types. The meta-analysis method combines weighted results from various comparable studies such as an omnibus test of treatment effects analogous to standard Analysis of Variance (ANOVA) methods. For the meta-analysis, we used data from two published studies (Battaglia et al. 2010; Kane et al. 2009) and data from the Keane et al. (2018) study to determine the variation in fine fuels across sites. We used the R metaphor package (Viechtbauer 2010) to test the null hypothesis that all 3-study effects are simultaneously zero. We also used the multcomp package in R to evaluate post-hoc pairwise comparisons of the three studies (Hothorn et al. 2008). The Benjamini-Hochberg method controlled the false discovery rate for the pairwise comparisons (Benjamini and Hochberg 1995).

For the second analysis, we evaluated differences between cutting heads and chipping on surface area of masticated pieces. We used the nonparametric Mann Whitney (Wilcoxon) tests in R to explore relationships between surface area means and two cutting groups on the moist mixed-conifer study sites (Keane et al. 2018; Appendix B). We also used a Kruskal-Wallis nonparametric test to explore the relationships between the cutting heads or chipping on fine-fuel amounts in the dry mixed conifer study sites. We used Q-Q plots and Levine and Bartlett tests to evaluate for normality and homogeneity, also using R (R Core Team 2015).

Literature Synthesis

Characteristics of Carrier Machines and Cutting Heads

Mastication requires a carrier machine, a cutting head, and a cutting-head attachment. Attaching the cutting head to the carrier machine can occur in one of two ways: either directly to the machine with a front-end attachment or to a swinging boom. Equipment configurations that combine these three pieces offer land managers several options to match the equipment to the site and management objectives. We provide a short summary that illustrates the range of options.

Carrier Machines

Carrier machines can be excavators (fig. 2a), skid steers (fig. 2b), tractors (skidders) (fig. 2c) with hydraulic systems, or tractors with power take-off systems (PTO); and each machine type varies in the amount of horsepower (hp) they have, and their

Figure 2—A variety of carrier machines including excavators, skid steers, tractors with hydraulic attachments, and tractors with power-takeoff attachments can have attached mulching heads (photograph 2A provided by Nikia Hernandez, USDA Forest Service, Kootenai National Forest; photograph 2B provided by Mel Peterson, Director of Marketing and Training, Diamond Mowers; photograph 2C provided by Dana Mitchell, USDA Forest Service, Southern Research Station).

length, clearance, and whether they are on tracks (fig. 2a) or wheels (fig. 2c). The *Forestry Mulcher Guide* contained over 50 different carrier machines with tracks that range from 100 to over 700 horsepower (Catalytic Response, LLC 2017) (table 2). The dimensions of the carrier vehicles with tracks range from at least 170 to over 400 inches long and 96 to 135 inches high. Ground clearance also varies from 13 to 26 inches. Depending on the size of the machine, small machines can weigh as little as 13,500 lbs. and the largest machines can weigh up to 62,800 lbs. The *Forestry Mulcher Guide* (Catalytic Response, LLC 2017) also summarized 30 carrier machines that have wheels and operate at 160 to 500 hp. These carrier machines range from 247 to 358 inches long and 112 to 130 inches high. Widths range from 80 to 126 inches, ground clearance ranges from 19 to 21 inches, and they weigh between 16,100 to 38,000 lbs.

Dedicated mastication machines (i.e., those that only perform mastication) or machines that can conduct multiple tasks with different attachments including masticating head attachments have advantages and disadvantages depending on the site and project objectives (Schafer 2013). Both dedicated mastication machines and machines capable of running multiple attachments, such as large excavators and harvesters, may be effective in large units and when treating large diameter trees (>8 inches in diameter). Small machines, such as skid steers with small cutting-head attachments, may be more effective around homes.

Table 2—Size variations in carrier machines. The *Forestry Mulcher Guide* (Catalytic Response, LLC. 2017) identified 79 different carrier machines that have tracks and 30 carrier machines that have wheels. Units are presented in inches (in), pounds (lb) and horsepower (hp).

Specification	Minimum	Median	Mean	Maximum	Number of observations
	- - - - - - - - - -*Tracked carrier vehicles with cutting head attached*- - - - - - - -				
Power (hp)	99	290	326	765	77
Length (in)	166	242	251	410	55
Height (in)	96	113	114	135	56
Width (in)	59	98	95	132	73
Ground clearance (in)	13	18	18	26	43
Weight (lb)	13,500	26,500	30,597	62,800	57
	- - - - - - - -*Wheeled carrier vehicles with cutting head attached*- - - - - - - - -				
Power (hp)	160	245	279	500	29
Length (in)	247	294	292	358	9
Height (in)	112	120	121	130	7
Width (in)	80	106	105	126	30
Ground clearance (in)	19	20	20	21	4
Weight (lb)	16,100	26,600	26,861	38,000	11

Whether machines are wheeled or tracked, machine width directly affects project success, because a machine's wheelbase length or track width determines the minimum residual tree spacing allowed, particularly the places where the equipment operates. This is simply because of the requirement for the equipment to be able to pass between two given trees while working in the stand. For example, in a study on the University of Idaho Experimental Forest, a CAT 320B excavator with a Denis brushing head conducted treatments. This machine has a track width of approximately 9.3 ft (112 inches). Assuming approximately 2 feet of clearance on either side, the residual spacing for a stand treated with this machine might be approximately 14 feet between stems, or 220 trees per acre, to avoid causing damage. However, if there are more than 220 stems acre^{-1}, a machine of this size would most likely cause damage to the residual stand from the boom hitting the trees, the machine sliding into trees while maneuvering through the stand, or the cab bumping branches. In these situations, the smaller machine the better. Trails with spacing of 50 feet or more between trail centers allow operators to maneuver equipment. With a boom, they can also reach a considerable distance to remove trees or other biomass. Variable tree spacing also adds some options to the treatment because the operator can maneuver the machine on a wider trail system or around tree groups and minimize residual tree damage.

Manager Question

> *Are there any figures that show ground pressure? I've heard soil compaction (as contributing to detrimental soil disturbance) is a concern with mastication, so showing ground pressure ranges might be helpful in facilitating a conversation between managers and soil scientists.*

Based on the literature, soil texture, soil moisture, how many times a machine drives over the same area, and whether the machine drives on top of slash influence soil compaction. Machine size and the presence of a rubber or steel track or tires can displace or compact the soil. For example, Han et al. (2006) identified a three-way interaction among the number of machine passes, soil moisture, and slash loading on harvested sites that used a cut-to-length logging system. Combining all of these factors makes it difficult to identify one clear relationship or graph. Mastication studies did not identify any negative soil effects from mastication (see section on Soil Impacts in this paper) provided the machine drove on slash. However, we suggest that forest managers evaluate compaction potential on their sites using available tools like the *Soil Disturbance Field Guide* (Napper et al. 2009) and adjust the implementation protocol to alleviate potential soil susceptibilities, such as limiting the number of passes, conducting the treatments when soils are dry, and having the machine walk over the slash.

Cutting Heads and Cutting-Head Attachments

Either vertical or horizontal shaft cutting heads masticate biomass. Vertical shaft cutting heads include a disk with fixed teeth (fig. 3a) or one or more swinging blades (fig. 3b) attached to the disk (table 3). These cutting heads work well for masticating shrubs and saplings. When boom mounted, the narrow vertical shaft cutting head enables the operator to reach around trees. This type of cutting head can masticate trees less than 8 inches in diameter, produces ragged stumps, and either shreds the biomass or creates chunks. In contrast, the horizontal shaft consists of a rotor (drum) with fixed teeth, swinging hammers, or fixed knives (fig. 4). The wider horizontal shaft cutting heads can treat larger diameter trees. Horizontal heads tend to create small pieces and chips, and they tend to leave clean-cut stumps.

The *Forestry Mulcher Guide* (Catalytic Response, LLC 2017) noted 74 different manufacturers that produce masticating heads (over 400 modes). There are over 256 models for excavators, 117 models for skid steers, 65 models for tractors with hydraulic systems, and 296 models for tractors with PTO systems. The guide also identified cutting heads that have fixed teeth (189 models) or have swinging hammers or swinging knifes (245 models). The cutting-head models range in size and power depending on the carrier machine (table 4) (Catalytic Response, LLC 2017). Cutting heads made for excavators can have working widths that range from 20 inches to 91 inches and weigh from 320 to 6,800 lbs. Skid steers tend to have cutting heads that range from working widths of 36 to 83 inches and weigh from 660 to 3,400 lbs. Tractors with hydraulic systems can have cutting heads with working widths between 58 to 101 inches and weigh from 1,800 to 10,800 lbs. Tractors with PTO have the greatest number of different cutting-head models. They range in size from 39 to 118 inches working width and weigh 948 to 11,757 lbs. Each cutting head has its own carrier machine requirements; but typically the larger the cutting head, the greater the need for a large engine and more hydraulic power from the carrier machine, although some cutting heads have their own

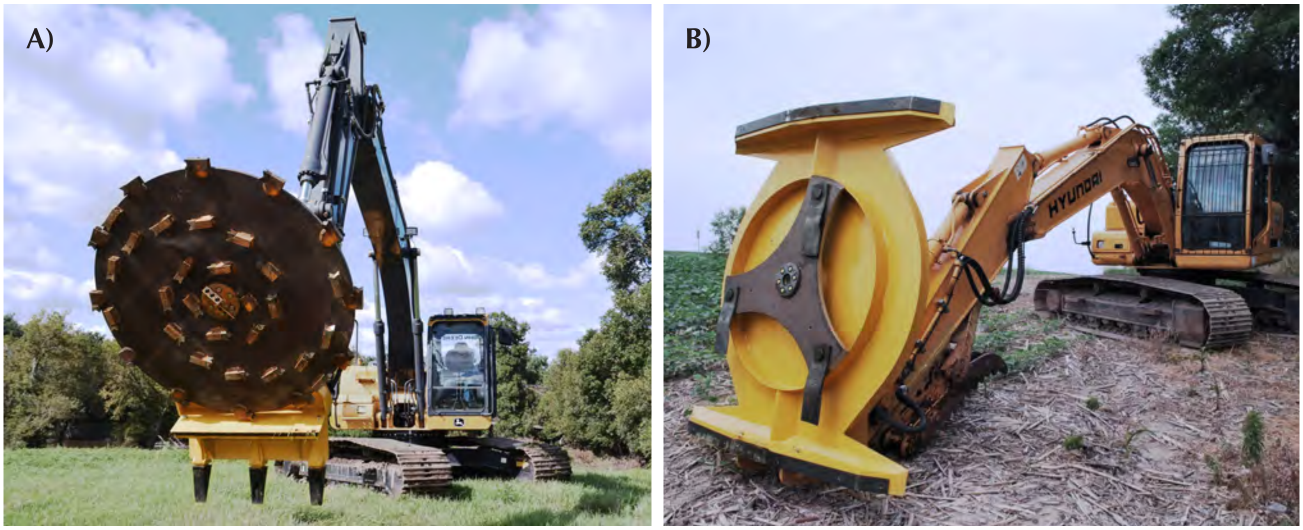

Figure 3—Vertical shaft cutting heads can either have fixed teeth (a), such as the Diamond Rotary Mower; or swinging knives (b), such as the Diamond Forestry Mulcher. These vertical shaft cutting heads come in a variety of sizes (photographs provided by Mel Peterson, Director of Marketing and Training, Diamond Mowers).

Table 3—Characteristics of the vertical and horizontal-shaft brush-cutting heads (from Coulter et al. 2002; Forest and Rangelands 2015; McKenzie and Makel 1991; Rummer 2009; Vitorelo et al. 2009; Windell and Bradshaw 2000,).

Vertical-shaft	Horizontal-shaft
- - - - - - - - - - - - - - - - - - -Head and cutting attachments- - - - - - - - - - - - - - - - - - -	
Cutting devices are attached to a disk or robust mowers	Cutting devices attached to a horizontal shaft or drum
Fixed teeth or blade (mower type)	Fixed teeth, swinging hammers, or ax/knife blade
Boom or front end mounted	Boom or front end mounted
- - - - - - - - - - - - - - - - - - - -Vegetation best suited to treat- - - - - - - - - - - - - - - - - - -	
Slash and shrubs Trees 6 to 8 inch diameter when boom mounted	Slash, shrubs when front end mounted Trees up to 30 inches diameter when boom mounted
- - - - - - - - - - - - - - - - - -Piece size and posttreatment condition- - - - - - - - - - - - - - - -	
Creates large pieces (chunks or shredded) Leaves ragged stumps	Creates small pieces Leaves clean cut stumps
- -Carrier machines- -	
Excavator, skid steer, tractors (hydraulic and power take-off)	Excavator, skid steer, tractors (hydraulic and power take-off)
- -Microtopography- -	
Broken or dissected topography with a diversity of slope angles and aspects	Continuous and similar slope angle and aspect

power source. Single purpose masticators (i.e., machines only used to masticate) are, in general, more powerful than carrier machines that have attachments (Schafer 2013).

Cutting-head attachments can also vary in configuration. Both types of cutting heads can be mounted on the front-end of a carrier machine, boom mounted, or pulled. When attached to excavators, operators can extend the boom-mounted cutting heads to hard-to-reach locations. Extended arms on long-reach excavators can range from around 40 feet to over 100 feet (http://www.purchasing.com/construction-equipment/excavators/types-and-attachments/). Front-end mounts attach directly to the machine but have limited reach.

Figure 4—Horizontal shaft cutting heads can have knives or teeth designed to work in different settings, such as on rocky soils (photographs provided by Fecon Inc.).

Table 4—Size variations for masticator heads. The *Forestry Mulcher Guide* (Catalytic Response, LLC. 2017) summarized masticator head sizes for each type of carrier machine. The units are inches (*in*), centimeters (*cm*), pounds (*lb*), kilograms (*Kg*), gallons per minute (*gpm*), liters per minute (*lpm*), and horsepower (*hp*), kilowatts (*kW*).

Description	**Minimum**	**Median**	**Mean**	**Maximum**	**Number of models**
- - - - - - - - - - - - - - - - - - - -*Masticator heads for excavators*- - - - - - - - - - - - - - - - - - - -					
Total width (in) (cm)	33 (84)	62 (157)	64 (162)	102 (258)	147
Working width (in) (cm)	20 (50)	49 (124)	50 (128)	91 (230)	254
Weight (lb) (kg)	320 (145)	2,080 (945)	2,198 (997)	6,803 (3085)	238
Min hydraulic flow (gpm)	4 (16)	30 (114)	30 (115)	74 (280)	201
Max hydraulic flow (gpm) (lpm)	5 (20)	40 (151)	45 (169)	210 (795)	153
- - - - - - - - - - - - - - - - - - - -*Masticator heads for skid steers*- - - - - - - - - - - - - - - - - - - -					
Overall width (in)	45 (115)	73 (185)	73 (186)	102 (258)	108
Working width (in) (cm)	36 (91)	60 (152)	61 (153)	83 (211)	115
Weight (lb) (kg)	660 (300)	2,382 (1,079)	2,171 (984)	3,400 (1,540)	108
Min hydraulic flow (gpm) (lpm)	12 (45)	26 (100)	26 (97)	40 (150)	101
Max hydraulic flow (gpm) (lpm)	18 (67)	37 (140)	38 (143)	65 (246)	92
- - - - - - - - - - - -*Masticator heads for tractors with hydraulic system*- - - - - - - - - - - - - -					
Overall width (in) (cm)	69 (175)	105 (265)	101 (258)	121 (307)	60
Working width (in) (cm)	58 (147)	89 (2,25)	85 (215)	101 (256)	65
Weight (lb) (Kg)	1,800 (820)	5,400 (2,449)	5,596 (2,538)	10,800 (4,900)	63
Min hydraulic flow (gpm) (lpm)	27 (102)	75 (285)	76 (291)	150 (600)	58
Max hydraulic flow (gpm) (lpm)	45 (170)	120 (454)	122 (463)	210 (795)	56
- - - - - - - -*Masticator heads for tractors with power take-off system (PTO)*- - - - - - - - -					
Overall Width (in) (cm)	51 (129)	93 (236)	92 (233)	138 (350)	270
Working Width (in) (cm)	39 (100)	79 (200)	77 (197)	118 (300)	296
Weight (lb) (Kg)	948 (430)	3,682 (1,670)	4,363 (1,979)	11,757 (5,333)	290
Min PTO power (hp) (kW)	55 (41)	105 (78)	141 (104)	295 (218)	32
Max PTO power (hp) (kW)	90 (67)	17 (127)	221 (161)	450 (336)	32

Operator and Economic Factors

Operator Experience Level

Several anecdotal statements from the literature identify the value of operator experience to complete mastication treatments effectively. Coulter et al. (2002), Kryzanowski (2007), and Windell and Bradshaw (2000) noted that operator skill can highly influence mastication outcomes and the efficiency of operating the machine. Mastication is a violent activity that shatters, grinds, or shreds wood, so an inexperienced operator can damage a machine within a few weeks or it may be necessary to replace the cutting head more often than repair or replacement costs associated with an experienced operator (Kryzanowski 2007). Boom-mounted machines have less operator visibility and thus may require a more skilled operator to reposition the carrier machine and maneuver the cutting head to the target tree efficiently (Windell and Bradshaw 2000).

An inexperienced operator may also need a spotter to help guide machine movement, which adds another crewmember and makes the spotter vulnerable to objects spraying from the machine (Bolding et al. 2006). An experienced operator knows how to maneuver the machine to avoid creating berms or making excessive turns so the overall site impact from tree damage to soil impacts may be less (Vitorelo 2009). The more experienced the operator, the more cost efficient the project will be, regardless of the configuration of the machine.

Economic Advantages and Disadvantages

For foresters accustomed to using classical forest economics to balance costs of timber harvesting operations with anticipated revenues, mastication treatments appear as an expensive option. We identified two reasons why mastication is expensive. First, mastication does not produce merchantable forest products (e.g., saw logs, ton wood) that generate immediate revenue like some treatments (e.g., commercial thinning). Second, the stands that benefit most from mastication treatments treat biomass that has low commercial value. Mastication treats individual trees and removing each additional stem per acre translates into additional dollars spent, so lack of revenue combined with high costs lacks appeal from an economic standpoint.

Operator experience:

The more complex the project, the greater the need for an experienced operator. Factors requiring highly skilled operators include broken slopes, a high density of residual trees (>100 trees acre^{-1}), and whether or not the project requires masticating biomass around houses or maneuvering the machine on steep slopes (35 percent to 50 percent slopes).

- An experienced operator can create smaller or larger piece sizes by adjusting the time spent masticating a particular piece.
- Skilled operators can efficiently move the machine and cutting head and minimize the number of passes over a particular area, thus reducing project costs.

Suggestion: A site evaluation can help determine the operator skill needed to conduct the project successfully and efficiently.

Mastication costs range from $300 to $400 per acre up to $1,500 or more (Coulter et al. 2002; Halbrook et al. 2006; Vitorelo et al. 2009). Lyon et al. (in review) reported that costs were $3.88 and $4.45 per individual tree when masticated to create chunky and fine chips, respectively. At 200 trees per acre masticated, that corresponds to $776 per acre for the treatment, or 2.5 to 3 times the cost of a hand-thinning crew cutting in a similar stand with a lop-and-scatter treatment, if limbs and tops were left to degrade. However, if chipping or hand piling and burning followed the hand thinning, then costs could start to become more comparable (Halbrook et al. 2006; Jain et al. 2008).

Even though mastication initially appears cost prohibitive, mastication can provide economic benefits into the future. For example, Bagdon et al. (2016) describe several examples of long-term economic benefits through reduced future costs resulting from a variety of methods to treat fuels. These include both market and non-market benefits. Market benefits from fuel reduction treatments include harvested saw logs (Bagdon et al. 2016; Selig et al. 2010) and positive impacts to local economy (Bagdon et al. 2016; Hjerpe and Kim 2008). Fuel treatment implementation also creates jobs locally for administrators, foresters, equipment operators, and hand crews. The Four Forest Restoration Initiative (4FRI) restoration project required an estimated 491 full-time equivalent (FTE) positions in the public and private sector (Bagdon et al. 2016; Combrink et al. 2012). Moreover, the manager designed fuel treatments to reduce fire suppression costs in the future. For example, Buckley et al. (2014) and Bagdon et al. (2016) found that the offset of fuel treatments ranged from $158 to $422 per acre when compared to fire suppression costs.

In a forest management context, long-term advantages can be gained from masticating to prepare a site for planting or natural regeneration, removing unwanted advanced regeneration, or conducting pre-commercial thinning. Pre-commercial thinning in dense conditions lead to a favorable growth response from a timber perspective. Hand thinning stands that contained 600 to 800 stems per acre of 3- to 4-inch diameter trees typically cost $125 to $250 per acre in the Inland Northwest United States based on communication with regional contractors (J. Odell, Alpha Services, LLC, Coeur d’Alene, Idaho, personal communication, August 2016). However, these treatments also tended to generate bulky fine fuels that persisted for several years after treatment. They required additional costs for in-woods chipping or hand piling and burning (Jain et al. 2008) to decrease fire hazard in the short-term. In addition to removing ladder fuels, this dense layer of masticated fuels also acts as mulch that cools the soil and suppresses subsequent shrub growth and natural regeneration. Alternately, masticated biomass can also increase fire hazard; but the piles may not last as long as hand-felled slash because this material is in contact with the soil surface and decomposing. Mastication has the great benefit of compacting fuels in small or large pieces that are close to the forest floor to promote decomposition.

Given the wide range of costs associated with mastication, there are several attributes that affect mastication costs. These include:

- Tree diameter. Mastication costs increase as tree diameter increases (Vitorelo et al. 2009). Whether mounted with vertical (disk) or horizontal (drum) type head attachments, excavator-based mastication equipment will always require more horsepower to treat larger stems and greater boom length to reach taller trees that occur in more mature stands. When the machine size or cutting head and target trees are incompatible, productivity decreases leading to higher costs.

- Fuel load. The more biomass that needs treatment, the more expensive the project becomes. However, mastication is a mechanical method making this technique a better alternative than hand slashing, piling, and burning (Halbrook et al. 2006; Jain et al. 2008).
- Site conditions. Costs are commensurate with site conditions, with uniform topography providing easier maneuverability than sites with broken topography or sites with steep slopes (e.g., 40 percent) (Halbrook et al. 2006; Rummer 2008).
- Particle size requirements. Costs vary by the target piece size desired for the mastication treatment. The more time spent to treat the biomass (i.e., the number of passes that a machine needs to make to reach target size), the more costs increase (Coulter et al. 2002; Halbrook et al. 2006).

Factors Affecting Mastication Costs

Increased or decreased costs may result from:

- The number of stems that are treated; more stems are more expensive.
- The physical setting, such as whether the topography is broken or uniform. Broken topography may be more expensive than uniform topography.
- Large machines may cost more than small machines.
- The less time the operator spends masticating one piece, the more efficient and less expensive the project.

Decreased costs may result from:

- Mastication can treat numerous stems (>100 stems/acre) with considerably lower labor costs than hand slashing, piling, and burning.
- Mastication can accomplish work in one entry. Other treatments can require multiple entries, such as slashing (1 entry), piling (2 entries), and burning (3 entries). Prescribed fire requires a specific burning window, which may or may not occur in a given time period.
- Mastication does not remove non-merchantable biomass and avoids removal costs.

Manager Question

It is clear that mastication removes competing vegetation, but can it be used for site preparation?

Yes, Jain et al. (2008) used mastication for treating advanced regeneration and as a site preparation. As a site preparation tool, mastication diminished competing vegetation, which aided in finding planting spots. When managers want excessive advanced regeneration removed, mastication becomes a viable option.

Ecosystem Response

Vegetation

We identified over 22 studies that related vegetation (forbs, grasses, shrubs) response to mastication, and results varied across forest types, regions, and time since treatment (Appendix B). Nine of the studies noted vegetative benefits associated with mastication. Brockway et al. (2009) noted that mastication in eastern pine and hardwoods in Georgia led to an increase in woody and herbaceous plants in the first 2 to 3 years after treatment. In pinyon-juniper woodlands, mastication contributed toward maintaining a shrub-dominated system, and mastication tended to have increased cover and species richness when compared to other treatments over the 8 years of measurements after treatment (Bybee et al. 2016; Shakespear 2014; Young et al. 2013a). Owen et al. (2009) also found that masticated plots 2.5 years after treatment had more plant cover and richness than untreated plots. However, Coop et al. (2017) noted an expansion of herb and shrub cover 11 years after treatment and an increase in nonnative plant species. In dry mixed-conifer forests, Burnett et al. (2014) and Collins et al. (2007) noted that mastication reduced shrub and herbaceous cover 2 to 6 years after treatment. In contrast, Fornwalt et al. (2017) found that masticated sites had higher understory plant richness and cover and had little effect on shrubs when they compared their results to a control (no treatment) 6 to 9 years after treatment.

In contrast to positive vegetative response, several studies found negative vegetative effects after mastication. After chaparral (*Calystegia* sp.) ecosystems were masticated, they tended to have an expansion of nonnative grasses and a reduction in native forbs 3 to 7 years after treatment (Perchemlides et al. 2008; Potts et al. 2010; Potts and Stephens 2009). In pinyon-juniper woodlands, Havrilla et al. (2017) and Coop et al. (2017) found an increase in nonnative grasses several years after treatment. In gorse shrublands in Spain, Fernandez et al. (2013a,b, 2015), and Fernandez and Vega (2016) found that species richness on masticated sites was less than burned areas.

Some studies related vegetation cover and richness to forest floor depth. Fornwalt et al. (2017) and Wolk and Rocca (2009) showed a significant negative relation between understory plant cover and richness and forest floor depth after mastication. Wolk and Rocca (2009) noted that as woodchip and natural litter depth increased on ponderosa pine sites in Colorado, plant cover and species richness decreased. They found that when forest floor depth was greater than 4 inches (10 cm), species richness and plant cover diminished to zero. Fornwalt et al. (2017) noted similar results on masticated studies also conducted in Colorado in pinyon-juniper, dry mixed-conifer, and lodgepole pine forests. In their study, they found that total plant richness and total plant cover diminished to zero when forest floor depth also exceeded 4 inches (10 cm). In both these studies, species richness and total plant cover appeared to plateau when the forest floor depth was between 0 and 2 inches (5 cm) deep.

Tree mortality and regeneration also varied across ecosystems on masticated sites. In mixed-conifer forests, there was minimal tree mortality from mastication (Collins et al. 2014; Kreye and Kobziar 2015). Moghaddas et al. (2008) noted variation in seedling density of tree species as a function of soil substrate created from mastication, prescribed fire, and mastication followed by prescribed fire. They showed that black oak (*Quercus kelloggii*) and sugar pine (*Pinus lambertiana*) seeding density was less in all treatments when compared to the control. However, they found that ponderosa pine and Douglas-fir (*Pseudotsuga menziesii*) seedling density increased in masticated sites followed by prescribed fire and on sites that only had prescribed fire. Hamma (2011) identified no significant differences between mastication and prescribed fire for stand-level carbon.

Manager Question:

> *Did these studies look at depth of mastication slash? Are there any guidelines from research that could be helpful for managers to know related to masticated material depth that may inhibit or change site characteristics? I know there has been research on chipping but I was not sure if there was research related for mastication as a tool to remove densely stocked areas where there could be heavier mastication residue/particles left. If depth of mastication residue could become an issue, it would be great to know depth ranges so we could put specifications in contracts to help mitigate any potential issues.*

We found two studies that explicitly related total plant cover and species richness to forest floor depth (including masticated biomass) (Fornwalt et al. 2017; Wolk and Rocca 2009). Vegetation establishment diminished to zero when forest floor depth exceeded 4 inches (10 cm); when forest floor depths were approximately 2 inches (5 cm) or less, species richness increased. In current research at the University of Idaho, Becker and Keefe (in prep.) are using pretreatment stand conditions based on LiDAR and silvicultural prescriptions, particularly the trees/acre to be removed during mastication, to characterize expected fuel bed depths after treatment over several thousand stands on a portion of the Nez Perce-Clearwater National Forests.

Many factors influence unwanted plant species invasion (Hughes et al. 2007; Radosevich et al. 2007). The environment, species traits, growing space, release of resources, and how often a site is treated can increase the potential for invasive plants (Radosevich et al. 2007). Radosevich et al. (2007) and Coop et al. (2017) identified several attributes to consider in treatment planning that will minimize invasive plants:

- Identify the potential nonnative species that surround the treatment area.
- Identify the environment that favors regeneration for the specific species of concern, such as the type of soil substrate (mineral, organic, blackened). For example, some species (e.g., *Ceanothus velutinus*) regenerate on burned surfaces easier than soils with a deep organic surface layer (Morgan and Neuenschwander 1988).
- Identify the species shade-tolerances because the amount of, or lack of, residual overstory may influence establishment (Coop et al. 2017).
- Clean equipment before entering a site to diminish the chance of introducing outside seed from nonnative species.
- Avoid scarifying the forest floor.
- Consider increasing forest floor depth to 4 inches or greater to avoid plant establishment.

Vegetation response after mastication varies depending on:

- Time since treatment. Most monitoring occurred 2 to 9 years after treatment, but the response varied depending on the vegetation type.
- Vulnerability to nonnative plant establishment increases in grasslands or some types of shrublands and woodlands.
- Mastication resulted in minimal or no residual tree mortality.
- Prescribed fire after mastication may lead to better seedling regeneration, depending on the vegetation type.

Soil Impacts

We identified 17 studies that evaluated the effect of mastication on soil compaction, erosion, and nutrition (Appendix A). Two studies in mixed-conifer forests in California noted that mastication did not increase runoff using rainfall simulators when compared to bare mineral soil using a rainfall rate of 2.9 inches hr-1 (73 mm hr-1) (Hatchett et al. 2006), or when residue covered >25 percent of the study area (Harrison et al. 2016). Soil compaction was also insignificant when machines drove over masticated residue (Moghaddas and Stephens 2008). Cline et al. (2010) noted that masticated residue in pinyon-juniper sites had higher infiltration rates and lower sediment yield than bare mineral soil using a rainfall simulator. Ross et al. (2012) also found that soil aggregate stability in pinyon-juniper ecosystems was lower in thin pile-and-burn treatments and masticated sites when compared to areas with no treatment.

Soil moisture and temperature did vary in masticated sites when compared to other treatments. Gottfried and Overby (2011) noted in pinyon-juniper woodlands that materials in masticated sites served as a mulch and the residue prevented the infiltration of rainwater leading to a decrease in soil moisture. However, other studies conducted on pinyon-juniper sites showed masticated sites had higher soil moistures than untreated sites (Owen et al. 2009; Rhoades et al. 2012; Young et al. 2013b) and Rhoades et al. (2012) found similar results on ponderosa pine forests. These studies also showed that the residue mitigated temperature extremes when compared to temperatures measured on untreated sites. Microbial activity did not differ among mastication and other treatments on chaparral in California or southern pines in South Carolina (Southworth et al. 2011; Stottlemyer et al. 2013). Most studies did not identify a decrease in C and N; and some studies identified an increase in plant available nitrogen on masticated sites when compared to controls (Moghaddas and Stephens 2007; Rhoades et al. 2012).

Mastication Effects on Soils:

- There were no negative effects to erosion or compaction if the operator drives the carrier machine over masticated residue (Cline et al. 2010; Hatchett et al. 2006; Harrison et al. 2016, Appendix A).
- Soil nutrition was not adversely affected by mastication (Moghaddas and Stephens 2007; Rhoades et al. 2012).
- Masticated materials insulated the soil, created uniform temperatures, and diminished temperature extremes (Owen et al. 2009; Rhoades et al. 2012).
- Soil moisture was higher on masticated sites on lodgepole and dry mixed-conifer when compared to the controls (Rhoades et al. 2012).
- On pinyon-juniper sites, mastication did prevent rainwater from infiltrating into the soil, which decreased soil moisture (Gottfried and Overby 2011); however, Rhoades et al. (2012) did not find any decrease in soil moisture on their pinyon-juniper sites.
- Mastication did not diminish microbial activity (Southworth et al. 2011; Stottlemyer et al. 2013).

Suggestion: Although mastication did not adversely affect the soils in these studies, good management practices (such as executing mastication on dry soils, driving on slash, deciding whether the machine needs to drive to each tree; or if a boom-mounted cutting head is desired) are preferred. All of these factors will help diminish soil scarification or compaction.

Insects, Mammals, and Birds

Five studies focused on insect or wildlife habitat (Appendix A). In mixed-conifer forests in California, Apigian et al. (2006) observed that prescribed fire and mastication treatments resulted in overall beetle community composition change, but the communities remained diverse and abundant. They further stated that there were minimal differences in beetle communities among the treatments but the conditions the treatments created, and therefore management objectives, should dictate the preferred treatment method. In similar forest ecosystems, Amacher et al. (2008) examined control, fire only, mastication only, and mastication plus fire treatments and found that deer mouse (*Peromyscus maniculatus*) populations diminished on masticated only and control sites but increased in the fire only and mastication plus fire treatments. California ground squirrel (*Spermophilus beecheyi*), brush mouse (*Permyscus boylii*), and long-eared chipmunk (*Tamias quadrimaculatus*) abundance increased between pre- and posttreatment period, but their abundance did not vary among the treatments. The authors concluded that the increased abundance of these mammals related to sampling years that had higher precipitation, a major cone crop event, and a reduction in predator occurrence prior to implementing the treatments. In California mixed-conifer forests, Burnett et al. (2014) found that bird community abundance varied on the residual forest structure and not necessarily on the type of treatment. They reported that changes in avian guilds related to canopy cover, shifts in ground-cover species and their abundance, and snag abundance. They found that these changes did not relate to the actual treatment, but to conditions created from the treatment. In oak woodlands and chaparral ecosystems, some bird species were favored after mastication, particularly if their habitat needs contained open areas (Seavy et al. 2008). In Texas oak shrublands, Reemts and Cimprich (2014) did not find any differences in the probability of black-capped vireo nests on masticated sites when compared to a control. Overall recommendations included

Wildlife Effects From Mastication

- Only a few studies exist that quantify the effects of mastication on fauna.
- Posttreatment conditions influence wildlife species selection and not necessarily the treatment itself. Different treatments create different compositions and structures, which can favor some species over others.
- Treatments did influence beetle community composition but communities remained diverse and abundant.

Suggestions:

- In general, the species of concern and their habitat needs will determine if mastication will affect wildlife.
- An option to consider when planning treatment may be to diversify treatment types in a given area, which also diversifies the habitat (Apigian et al. 2006). This strategy can address multiple objectives, diversify the surface vegetation, create different soil substrates to favor a diversity of species that were spatially diverse, and produce a variety of habitat attributes (Jain et al. 2008).

(1) that mastication could replace prescribed fire with no effect on vireo nesting (Reemts and Cimprich 2014), (2) that size and shape of treated areas could benefit some bird species (Seavy et al. 2008), and (3) that diversifying treatment types in an area could increase habitat heterogeneity benefiting multiple leaf litter arthropods including rare species.

Fire Behavior in Masticated Fuelbeds

Kreye et al. (2014) produced a literature review on studies associated with masticated fuel beds and fire behavior. In summary, laboratory experiments showed that fuel load, fuel depth, and fuel moisture influenced fire behavior. However, field studies show that the fuel variability and recovering vegetation can also influence fire behavior. Heinsch et al. (2018) noted that ignition of masticated fuelbeds requires fine litter, such as litter or leaves. Once ignited, masticated fuels have short-flaming and long-smoldering combustion and long-duration heating. Smoldering fires in masticated fuelbeds can potentially flare up under high wind conditions causing embers to ignite fuels outside of the masticated treatment (Heinsch et al. 2018; Kreye et al. 2014). Bass et al. (2012) suggested that managers place buffers that separate masticated fuel treatments from surrounding areas that managers can later use as a fireline.

Fine-Fuel Characteristics Created by Mastication

Fine-fuel amounts can vary significantly among sites within specific studies (table 5). Battaglia et al. (2010) identified that 1-hour and 10-hour fuels on masticated sites were significantly greater than untreated controls from four different cover types in Colorado. On pinyon-juniper sites, when compared to untreated sites, there was a 72 percent increase in 1-hour fuels, 90 percent increase in 10-hour fuel, and 75 percent increase in 100-hour fuels. Kane et al. (2009) also showed significant differences among sites dominated by shrub and hardwood vegetation in California. Using data from Keane et al. (2018), there were no significant differences among the forest types in 1-hour and 10-hour fuels. The most productive sites (moist mixed conifer) had more fine fuels than the less productive sites (dry mixed conifer and ponderosa pine).

Table 5—Time-lag fuel loads (tons/ac) separated by size class and depths of masticated sites from studies in the United States. Within columns of a specific study, means that are followed by the same letter are not statistically different.

	1-hr		10-hr		100-hr		
Vegetation type	**Mean**	**SE[1]**	**Mean**	**SE**	**Mean**	**SE**	**Total**
	-Kane et al. 2008-						
Mixed hardwood (10 locations)	2.5^{b}	0.4	7.5^{abc}	1.3	4.1^{a}	1.0	14.4
	0.4^{de}	0.1	6.4^{bc}	6.4	5.8^{a}	0.6	12.6
	1.0^{cde}	0.2	2.7^{d}	0.5	2.1^{a}	0.6	5.8
	1.9^{bc}	0.2	13.4^{a}	1.7	3.2^{a}	0.8	18.6
	0.9^{de}	0.1	3.6^{cd}	0.7	1.4^{a}	0.5	5.9
	0.4^{de}	0.1	3.6^{cd}	1.0	3.2^{a}	0.7	7.2
	4.4^{a}	0.5	9.5^{ab}	1.5	4.0^{a}	0.8	17.8
	2.0^{bcd}	0.2	7.0^{bc}	0.9	3.7^{a}	0.9	12.7
	0.7^{de}	0.1	4.5^{cd}	0.6	0.8^{a}	0.2	5.9
	1.2^{cde}	0.4	4.5^{bcd}	0.6	3.4^{a}	0.6	10.4
	-Battaglia et al. 2010-						
Pinyon-juniper	3.5^{a}	1.0	5.4^{a}	1.1	1.9^{a}	0.3	10.7
Ponderosa pine	3.6^{a}	0.8	8.0^{a}	1.5	3.3^{a}	0.4	14.9
Lodgepole pine	7.5^{a}	2.6	8.6^{a}	1.2	2.3^{a}	0.4	18.5
Dry mixed conifer	10.3^{a}	3.9	10.9^{a}	2.5	4.8^{a}	1.8	26.0
	-Keane et al. 2017-						
Ponderosa pine	1.4^{a}	0.4	4.5^{a}	0.8	3.5^{a}	1.0	9.4
Dry mixed conifer	1.2^{a}	0.4	4.1^{a}	0.7	3.4^{a}	0.6	8.7
Moist mixed conifer	2.3^{a}	0.4	5.7^{a}	0.7	8.6^{b}	2.3	12.1

[1] SE = Standard error.

The meta-analysis from selected studies did identify some differences in fine-fuel loads based on where the sites were masticated (Battaglia et al. 2010; Kane et al. 2009; Keane et al. 2018). For 1-hour fuels, sites measured by Battaglia et al. (2010) had significantly more 1-hour fuels than the Kane et al. (2009) or Keane et al. (2018) sites (fig. 5). Particularly, masticated sites in lodgepole pine forests had a mean of 16.9 mg/ha with a 95 percent confidence interval (CI) of 5.3 and 28.5 mg/ha; mixed-conifer forests had a mean of 23 mg/ha with a CI of 5.7 to 40.2 mg/ha. Among the different studies, there was more variation in 10-hour fuels among the sites (fig. 6). For example, Kane et al. (2009) had some sites exceed 15 mg/ha. Battaglia et al. (2010) also had high amounts of 10-hour fuels (18 to 24 mg/ha). However, when comparing 10-hour fuels across the three studies, our meta-analysis did not identify any significant differences. The 100-hour fuel amounts were consistent across the sites and studies. More variation tended to occur on the more productive sites in Battaglia et al. (2010) dry mixed conifer sites and the moist mixed-conifer sites of Keane et al. (2018) (fig. 7).

Cutting heads did lead to significant differences in surface area among the 1-hour, 10-hour, and 100-hour fuel loads (fig. 8). In the dry mixed-conifer sites and pinyon-juniper woodlands, chipping created the smallest pieces in 1-hour (1 inch^2, 7 cm^2), 10-hour (3 inches^2, 19 cm^2), and 100-hour (12 inches^2, 77 cm^2) fuel classes. The vertical shaft cutting heads with fixed teeth tended to create the largest piece sizes within a given fuel time-lag including in 1-hour (3.4 inches^2, 22 cm^2), 10-hour (10 inches^2, 65 cm^2), and 100-hour (46 inches^2, 300 cm^2) fuels. Similar cutting heads consisting of swinging knives also created larger pieces in 1-hour (2.5 inches2, 16 cm^2), 10-hour (7.4 inches^2, 48 cm^2), and 100-hour (27 inches^2, 173 cm^2) fuels than machines with fixed teeth cutting heads. The surface area of each time-lag fuel created by horizontal shaft cutting heads did not exceed surface area of sites masticated with vertical shaft cutting heads. In the moist mixed-conifer forests, significant differences in surface area occurred only in the 1-hour size class. Although the means appear different, the variation in each fuel class was not significant in the 10-hour and 100-hour fuel classes.

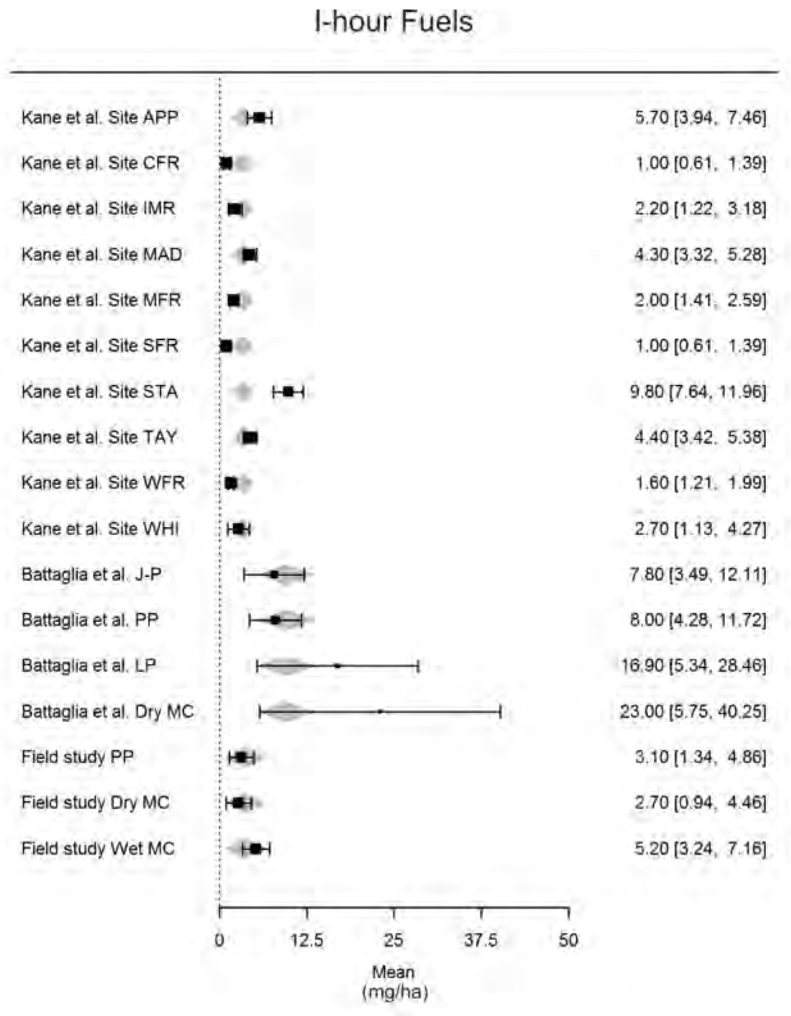

Figure 5—One-hour fuels (mg/ha) mean differences among studies and sites. The forest plot shows the mean (squares), 95th confidence interval. Numbers on the left are the values for the mean and confidence intervals. Battaglia et al. (2010) had significantly more 1-hour fuels than Kane et al. (2009) and our field study (Keane et al. 2018).

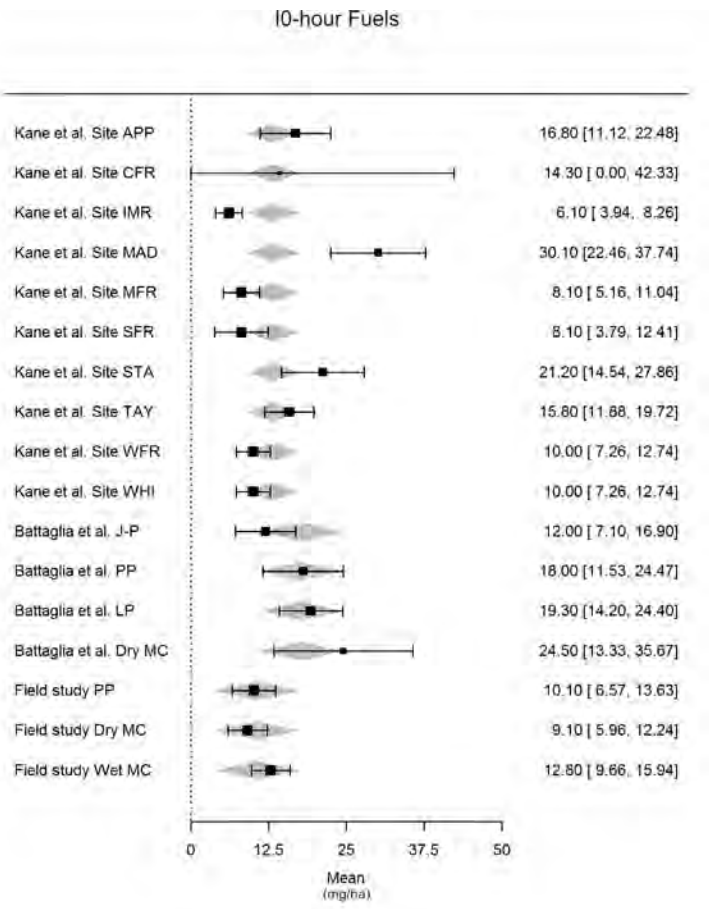

Figure 6—Ten-hour fuels (mg/ha) mean differences among studies and sites. The forest plot shows the mean (squares), 95th confidence interval (lines). Numbers on the left are the values for the mean and confidence intervals. Studies include Keane et al. (2009), Battaglia et al. (2010), and our field study (Keane et al. 2018).

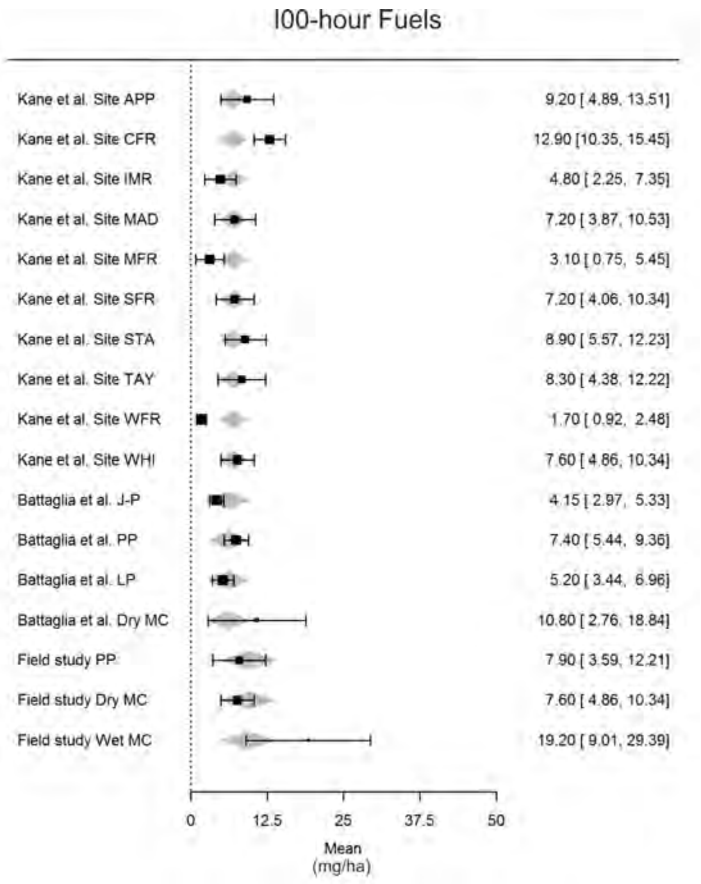

Figure 7—One-hundred hour fuels (mg/h) mean differences among studies and sites. The forest plot shows the mean (squares), 95th confidence interval (lines). Numbers on the left are the values for the mean and confidence intervals. The 100-hour fuel amounts were similar across sites and the variation in amounts were more consistent across studies and sites. Studies include Keane et al. (2009), Battaglia et al. (2010), and our field study (Keane et al. 2018).

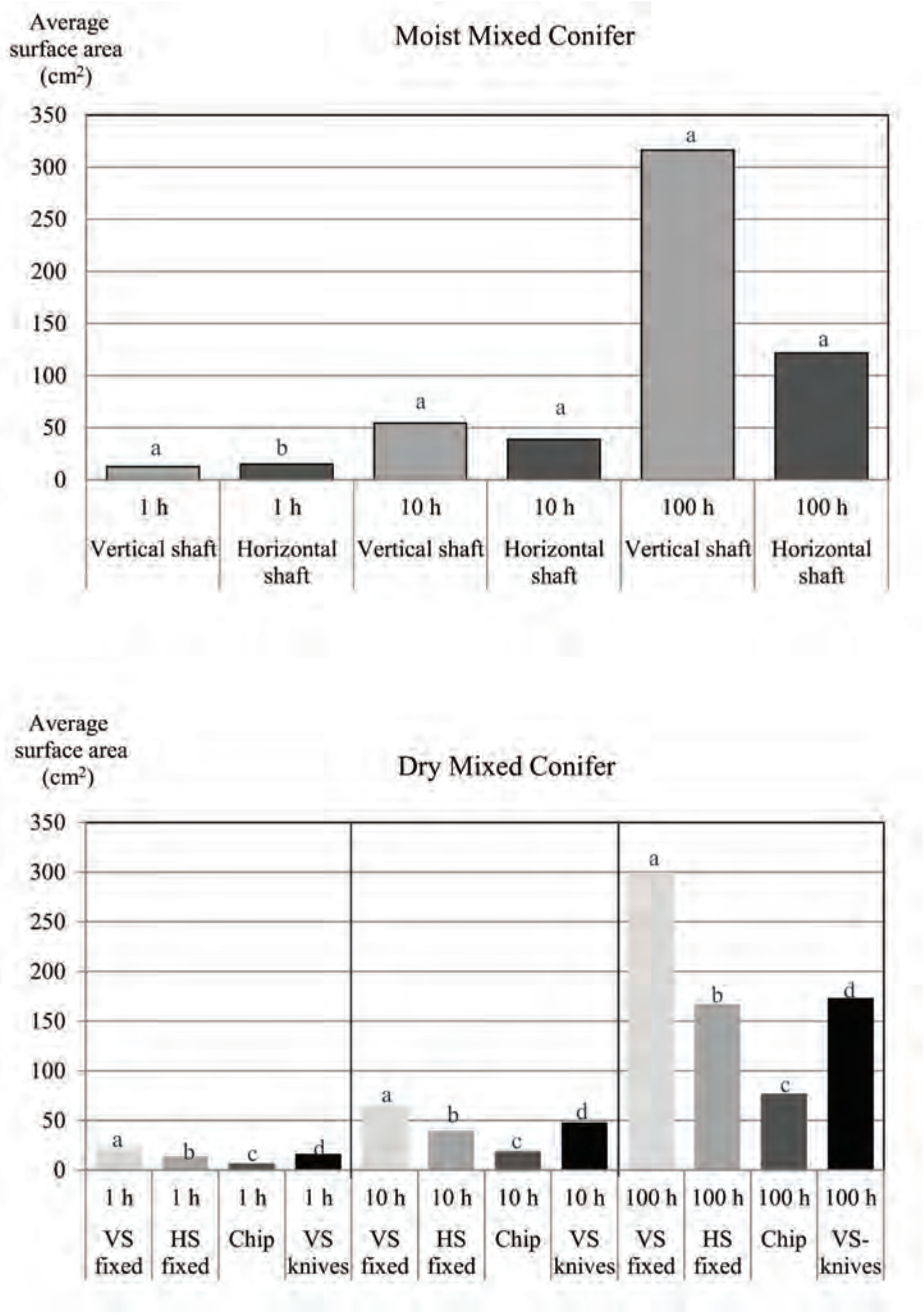

Figure 8—The cutting head designs can result in different piece sizes. Chipping creates the smallest pieces and the vertical shaft cutting head with fixed teeth or swinging knives created the largest pieces (data is from our field study (Keane et al. 2018) (Appendix A). Different letters indicate significant statistical differences among cutting heads within different piece sizes (time lag fuel).

Fire Behavior

- Needles, leaves, or other 1-hour fuels are required for masticated fuels to ignite.
- Once ignited, masticated fuels smolder for long periods.
- Fine-fuel loads:
- One-hour, 10-hour, and 100-hour fuels always increase after mastication (Kreye et al. 2014).
- 1-hour fuels vary depending on vegetation types and studies.
- 10-hour fuels do not vary among the vegetation types and studies.
- A site's productivity and amount of biomass influences 100-hour fuel loads.

Suggestions:

- Not all biomass on a site need treatment or mulching into small pieces. Some trees can remain as down logs. These additional logs provide wildlife habitat and do not contribute to an increase in the fine fuels. Some trees can have tops cut (particularly with a boom-mounted masticator) and left standing for future snag recruitment.
- The operator has the ability to adjust the piece size by using a vertical shaft that creates larger pieces or by minimizing the amount of time spent chopping each piece, resulting in larger pieces left on the ground.

Resistance to Decomposition

- Resistance to decomposition can determine whether masticated fuel will decompose quickly. Species resistant to decay may pose a long-term surface fuel problem compared to species that tend to decay more rapidly.
- The wood handbook lists domestic and imported woods according to their average heartwood decay resistance (Clausen 2010). Species very resistant to decay include Pacific yew (*Taxus brevifolia*), locust (*Robinia pseudoacacia*), and red mulberry (*Morus rubra*). Species resistant to decay include the cedars (*Thuja* sp.), old-growth redwoods (*Sequoia sempervirens*; *Sequoiadendron giganteum*), junipers, oaks (*Quercus* sp.) and other hardwoods. Moderately resistant species include Douglas-fir, western larch (*Larix occidentalis*), young redwoods, black cherry (*Prunus serotina*), young bald cypress (*Taxodium distichum*), old longleaf pine, old slash pine, and old eastern white pine (*Pinus strobus*). Slightly and nonresistant to decomposition include the true firs (*Abies* sp.), aspen and other poplars (*Populus* sp.), hemlock (*Tsuga* sp.), elms (*Ulmus* sp.), maples (*Acer* sp.), sweetgum (*Liquidambar styraciflua*), spruces (*Picea* sp.), several pines, plus several other species.

Decision Trees for Machine Selection

The complexity of integrating multiple factors can be overwhelming. Partitioning these factors into a set of decision trees can help identify the right method, and subsequent equipment, to address the requirements and limitations needed on any given management project. We used a series of questions to aid in deciding what method may best fit the project and whether or not to use mastication (Hover 2012; Schafer 2013; Windell and Bradshaw 2000). When designing any fuel or silvicultural treatments, a site assessment identifies the scope of work, matches the appropriate equipment to the project goals and objectives, and identifies the level of operator experience needed to meet desired outcomes (Mitchell 2005; Nyland 2016; Windell and Bradshaw 2000).

Decision Tree 1

How Does Slope Percent Influence Treatment Options?

The slope percent will dictate treatment options (fig. 9). If slopes are greater than 40 percent, treatment options may only include prescribed fire, hand slashing and piling, or no treatment, unless managers plan to use mechanical equipment specifically designed to maneuver on steep slopes. However, if slopes are less than 40 percent, then managers can apply prescribed fire, mechanical treatment, or hand thinning. Moreover, if the biomass does not create a fire hazard or regeneration success does not require site preparation, then the site may not need a treatment.

Ground-based carrier machines work best on slopes less than or equal to 35 percent slope. However, with recent improvements to ground-based machines to work on steeper slopes, there are a few more options to treat sites with mastication depending on the carrier machine. Visser and Berkett (2015) suggest that rubber-tired skid steer and tractors should be operated on slopes less than or equal to 35 percent. Excavators,

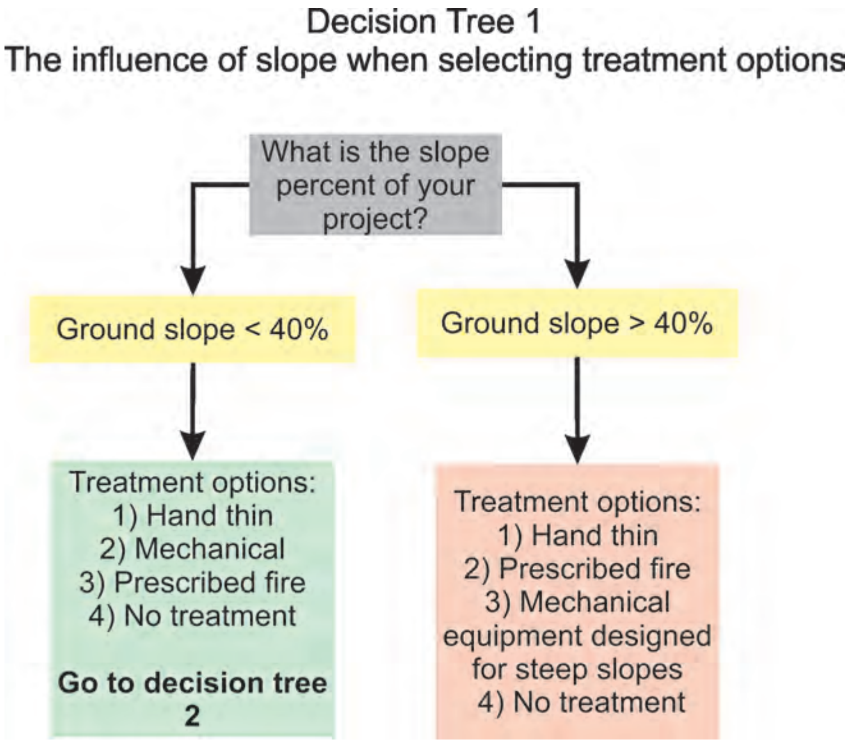

Figure 9—Decision tree 1. There are several choices that need consideration when determining if mastication is the best treatment option. The most important component is to determine if the slope angle is less than 40 percent, which would favor the use of machinery. Slopes greater than 40 percent mechanical treatment is rarely an option, unless machines are tethered so as not to tip over.

crawler tractors, or similar machines should operate at or below 40 percent, and ground equipment specifically designed for operating on steep slopes should not exceed 50 percent slope.

Decision Tree 2

Does the Site Need Post-Harvest Slashing or Does the Site Have Excessive Advanced Regeneration?

For sites less than 40 percent slope, the abundance, distribution and type of unmerchantable material will dictate if the site needs treatment (fig. 10). If the result of a commercial harvest created the biomass, or if there is excessive advanced regeneration or a shrub-dominated understory, then managers may need to apply some type of mechanical treatment followed by prescribed fire or mastication. If smoke, risk of escape, or residual species (not fire resistant) do not limit using prescribed fire, then prescribed fire becomes a viable option if managers want a blackened surface to promote certain types of regeneration or to meet other management objectives, including decreasing treatment costs. If smoke production or residual live biomass is not fire resistant, then managers can execute a mechanical treatment, such as mastication or grapple piling. Mastication becomes the best option when substantial advanced regeneration (>100 stems/acre) exists.

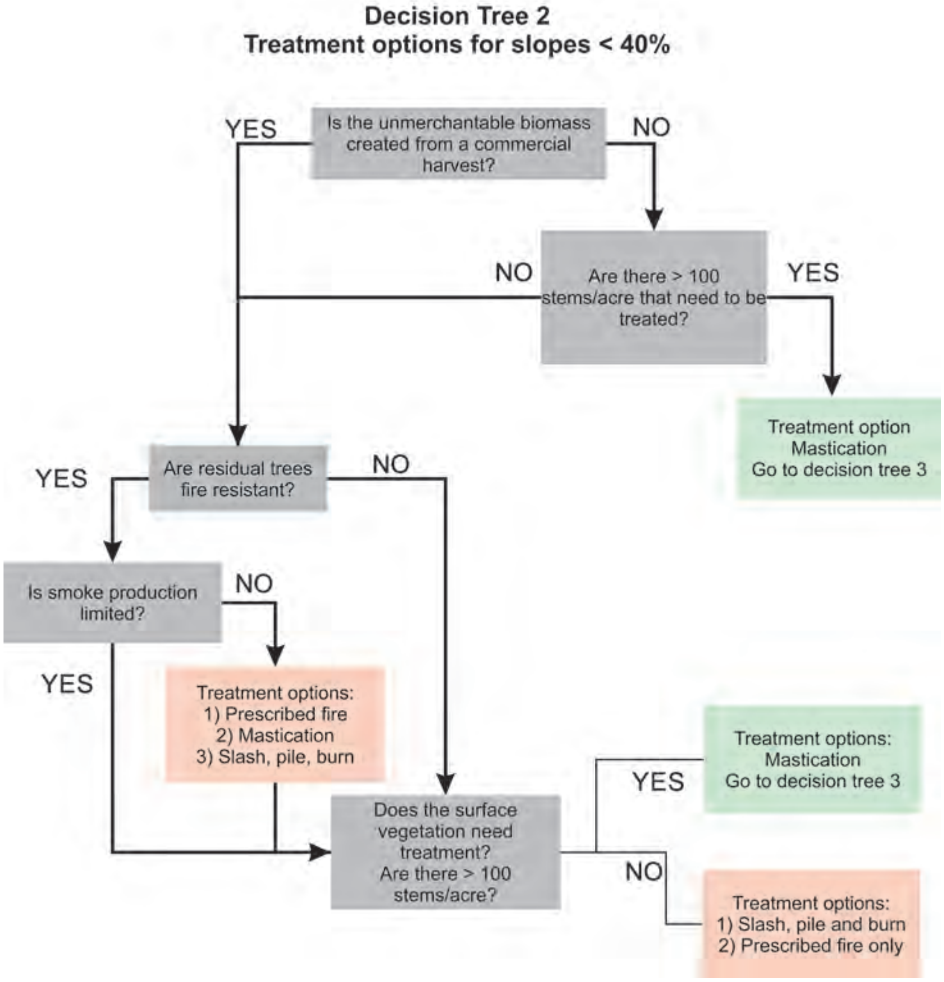

Figure 10—Decision tree 2 provides treatment site conditions that may identify treatment including no treatment option, chipping (not included), prescribed fire, or grapple pile followed by burning. If mastication is the preferred option then go to decision tree 3 to determine what machine combination may be the best option.

Mastication becomes viable when a site has no commercial value but still has numerous shrubs or hundreds to thousands of small unmerchantable trees per acre. In contrast, if only a few trees or shrubs exist, then more practical options emerge, such as hand slashing followed by either prescribed fire or grapple piling. This would remove the biomass and create a blackened surface; or with grapple pile and burning, the site would have a diversity of soil substrates that may address site preparation objectives. Chipping (not included in the decision tree) also can achieve desired objectives; however, it tends to create very small pieces and deep fuel beds (Battaglia et al. 2010). Chipping does produce other products such as biochar (Anderson et al. 2016).

Does the Time of Year When Masticators Create Slash Favor Increased Mortality From Ips Beetle (Ips sp.)?

Another important consideration when choosing among mastication methods, prescribed burning, or other treatments is the timing of the treatment window and any possible adverse effects associated with insects or disease. For example, in treatments that leave green slash, *Ips* beetle can undergo rapid population growth, which could cause subsequent residual damage to standing trees. Under these circumstances, masticating the biomass removes the bark, which diminishes *Ips* survival (Conner and Wilkinson 1983).

Decision Tree 3

If a manager decides to use mastication, then decision tree 3 provides the elements that will help match the masticator to the site and project objectives (fig. 11). We adapted a decision tree from Jain et al. (2012) that provides the flow of elements to guide the choice of masticator to use.

Is the Soil Prone to Compaction?

Soil moisture and structure, the machine type and size, whether the machine has tracks or tires, the number of passes over a given area, and whether the machine drives over slash all influence soil compaction. Dry soils lead to less compaction (Coulter et al. 2002; Han et al. 2006; Rummer 2010). Driving on slash mats can also decrease compaction (Harrod et al. 2009; Moghaddas and Stephens 2008). More efficient and mobile, wheeled carriers can create ruts, particularly on wet soils (fig. 12). Tracked machines, in general, cause less soil disturbance because the machine weight is spread over a larger area (track) and these machines can maneuver through the site without causing ruts like wheeled carriers (Sakai et al. 2008; Windell and Bradshaw 2000). Rubber tracks tend to offer the lowest pressure and are the best choice on sensitive soil conditions. However, if the ground is rocky, then steel tracks are preferred (Schafer 2013). Equipment with boom-mounted cutting heads enable the operator to reach over difficult areas or maneuver around tighter spaces; therefore, this equipment avoids driving to every tree, which also diminishes soil disturbance.

Is the Terrain Uniform or Complex, or Are There Wet Areas Present That Need Protection?

Uniform terrain favors a machine-mounted cutting head. A more complex site with broken topography favors a boom-mounted cutting head (Bolding et al. 2006). A boom-mounted cutting machine can maneuver down ridges and reach over wet areas and across

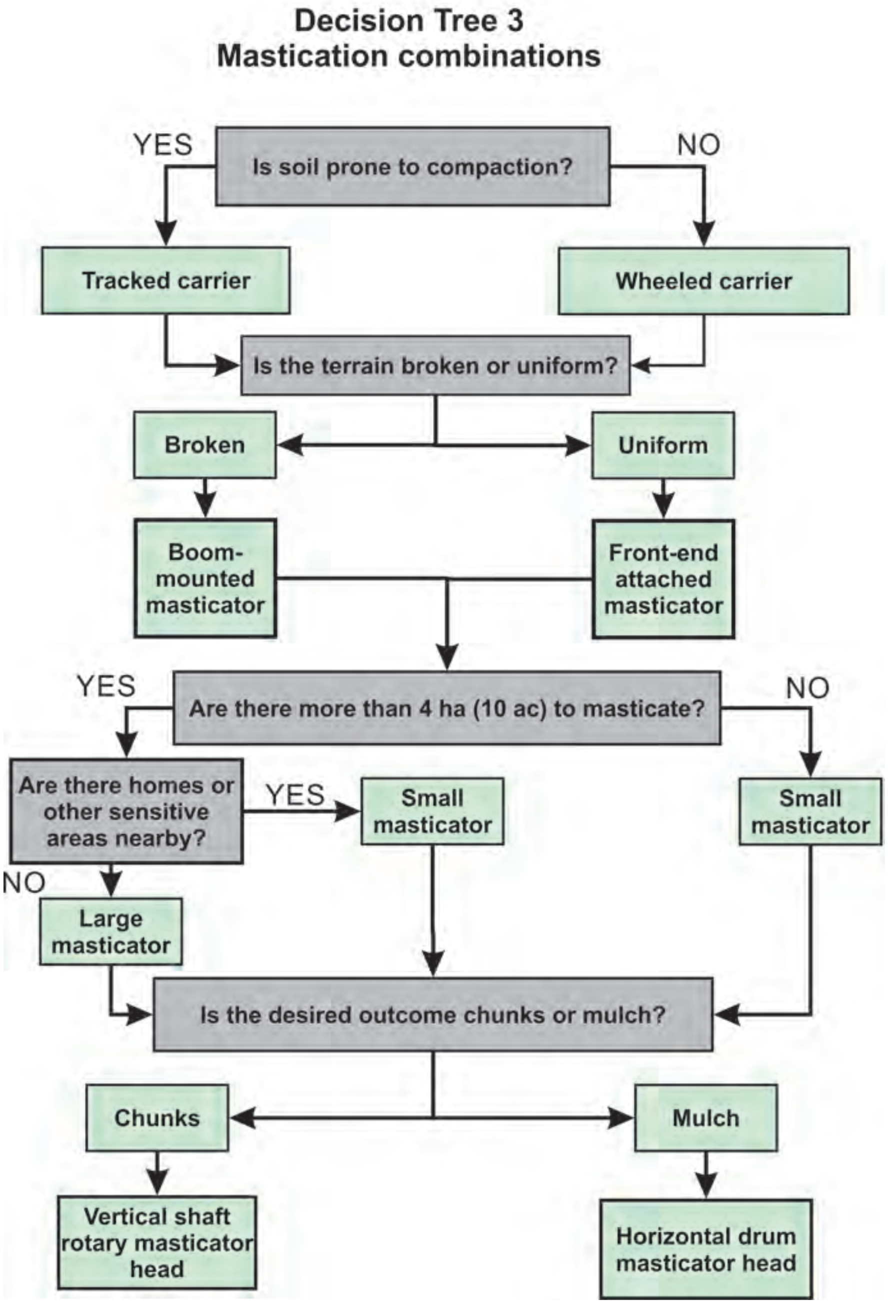

Figure 11—Decision tree 3 provides the site specific components that may aid in identifying the best machine and masticator head for the project.

draws to reach trees. A machine-mounted cutting head requires driving to each tree (Coulter et al. 2002).

What Are the Project Size and Access? Do Homes or Other Buildings Exist in the Project Area That Will Require Machine Maneuvering?

Initial plans will need to identify the transportation costs, the ease of machine fueling, and if repair sites are located close by. Walking the machine from site to site can also decrease costs. When operating in difficult conditions or long days, these machines can experience wear and tear. Replacing broken teeth or knives makes easy road access necessary. Schafer (2013) noted that skid steers and compact track excavators typically have the advantage in tight places, such as around homes. However, a larger dedicated masticator fits well when sites are inaccessible and sufficient space for maneuvering the machine exists.

Figure 12—Examples of soil rutting (a) erosion, and compaction (b) (photographs provided by Deborah Page-Dumroese, USDA Forest Service, Rocky Mountain Research Station).

What Is the Target Size, Type, and Density of Biomass?

Vertical shaft masticating heads work best on slash and shrubs and can typically treat trees 6 to 8 inches in diameter when they are boom mounted. In contrast, horizontal-shaft masticating heads can treat larger trees (some up to 30 inches in diameter) particularly when they are mounted on a boom (table 2). However, larger trees need a more powerful and larger cutting head and a carrier machine may be required for the job. To illustrate this relationship, our analysis indicated a highly significant relationship ($P < 0.0001$) between target tree size, machine power, and cutting head weight. As trees get larger, machine power needs to increase, as does the cutting head weight ($r^2 = 0.60$) (fig. 13). For example, to masticate a 20-inch diameter tree will require about a 200 horsepower engine and a 5,800 lb. cutting head (fig. 13). A complementary machine designed to masticate a 10-inch diameter tree would have a 200 horsepower cutting head and weigh 3,000 lbs.

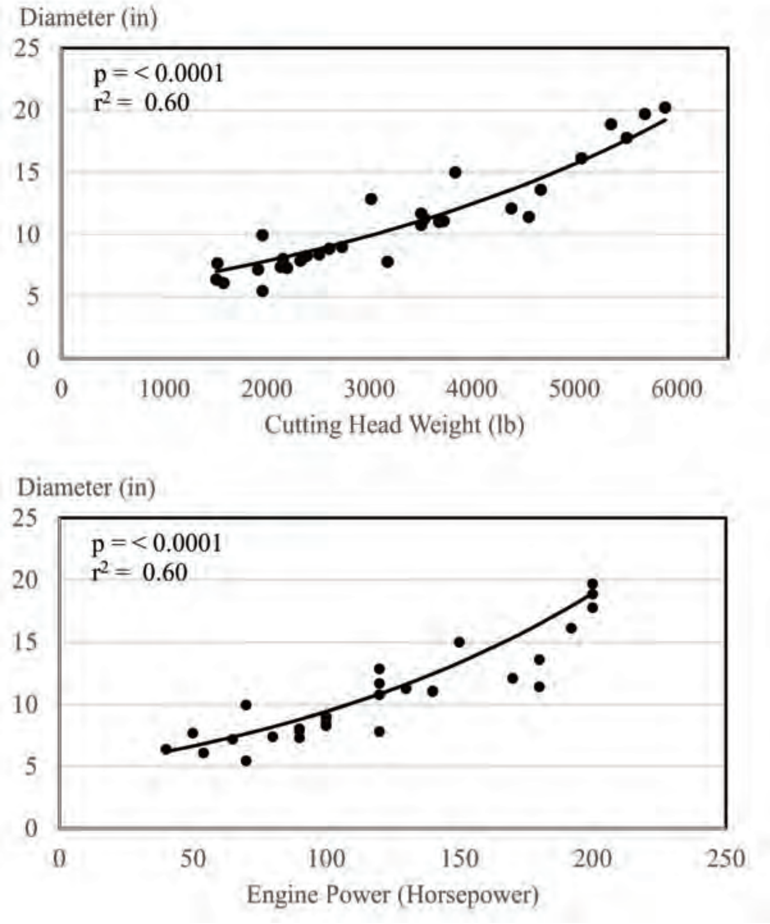

Figure 13—Relation of cutting head weight (a) and horsepower (b) to tree size. As the target tree size increases, a larger and more powerful cutting head and carrier machine is needed (data from Catalytic Response 2017, currently on file with author Theresa Jain, Rocky Mountain Research Station, Moscow, ID).

However, the head size and horsepower of the machine should be complementary to the tree size targeted for mastication and there may be additional parameters to consider when identifying the best machine for a particular job. As stem density increases, such as in stands dominated by large shrubs, a dedicated masticator is more efficient than a machine with a cutting-head attachment (Schafer 2013). Tree size and biomass density ultimately influence the cost of implementation. Cost increases as density increases; as mentioned previously, every increase in the number of stems above approximately 100 stems ac-1 results in a cost increase of 1 percent (Fight and Barbour 2005).

What Is the Desired Residual Forest Structure?

The desired conditions, such as residual stand density and its spatial distribution, can influence the type of carrier, mounting technique, and cutting head. Widely spaced trees (e.g., 22 x 22-foot spacing) favor a drive-to-tree mastication method because it takes less time (Bolding et al. 2006). However, if tight spacing between trees exists, a carrier machine with a boom-mounted cutting head has greater flexibility because this machine allows the operator to move the cutting head into places that might have narrow tree spacing. In addition, a skid steer may be preferable to an excavator in tight places if trees are small (Schafer 2013).

For pre-commercial thinning (trees < 2 in d.b.h.), skid steers with a vertical shaft masticator armored with blades (similar to large blade mowers) can maneuver easily and cut close to residual trees at a 14-ft spacing.

Manager Question

Do the authors have any knowledge of, or literature to reference, mastication of surface fuels with lots of large woody debris (such as blowdown, high loads of mortality fuel, etc.)?

Mastication typically treats standing biomass or post-harvest slash. However, there are other circumstances, such as wind events, beetle infestations, or wildfires that can create standing dead and down wood. In these situations, mastication becomes a viable option. Stottlemyer et al. (2015), working in beetle-killed stands in South Carolina, reported treatment effects on surface fuel quantities, determined if these sites required a custom fuel model, and conducted a fire behavior simulation. Their management recommendations suggested that timing of treatments is important when treating beetle-killed stands. They noted that if prescribed fire were the preferred method, burning toward the end of the beetle infestation would provide sufficient surface fuels that would carry the fire. Unlike with prescribed fire, masticated sites had no dead standing trees (the masticating machine removed all standing trees to reduce occupational hazard and improve stand accessibility) and they suggested that mastication might be a better site preparation for artificial regeneration.

What Is the Preferred Piece Size of Masticated Biomass?

Piece size influences the distribution of fine fuels defined as 1-hour (0 to 0.25 inch), 10-hour (0.25 to 1 inch), and 100-hour (1 to 3 inches) fuels. The time designation on these fuels indicates a particle size and drying time. The cutting head, how much the operator spends time masticating a particular piece, and the size of targeted biomass influence the posttreatment piece size.

Characteristics of the treated biomass will differ based on the cutting tool used. The vertical shaft cutting head creates larger piece sizes by shredding the biomass than the horizontal cutting head (table 3, fig. 4). The vertical shaft also usually creates pieces with higher surface areas, particularly in the 10-hour and 100-hour fuel classes, compared to the surface area of pieces created from horizontal shaft. If piece size is not of concern, then a horizontal drum attached to the machine may be the most efficient method to use, even if it tends to create more 1-hour and 10-hour fuels.

Depending on the operator's skill level, either a vertical shaft or a horizontal cutting head is capable of creating larger or smaller pieces. An operator also can influence the piece size that the machine creates using slow, methodical passes or multiple passes across an area. Typically, the more time the operator spends grinding, the smaller the pieces become; thus, when the operator moves quickly, the piece size increases.

Battaglia et al. (2010), Kane et al. (2009), and Keane et al. (2018) showed that the amount of 1-hour and 10-hour fuels varied across sites. This variation often results from the type and size of pretreatment biomass. For example, if the target biomass is all less than 3 inches diameter, such as some shrubs or saplings, then the reconfiguration of the biomass will tend to add more 1-hour and 10-hour fuels because all material being masticated is below the 100-hour diameter threshold. However, if the target biomass that is treated is larger, such as 5 inches or 7 inches in diameter like pole-sized trees, then 100-hour fuels may increase as well as the 1-hour and 10-hour fuels.

The productivity of the site may have contributed to fine-fuel abundance. Keane et al. (2018) noted sites that were more productive, such as those that occurred in the

Manager Comment

> *A side note with small tree mastication from issues I have run into with contracts and mastication projects. If there are a high density of small trees in the stand adjacent to the residual trees, then the mastication heads cannot get close enough to remove the small seedlings. Thus, the contractor always has to have a saw present and manually cut small seedlings adjacent to residual leave trees to prevent damage. Does any of the current research provide suggestions for types of heads/mastication equipment to help with this issue? Otherwise, managers should be aware of this potential limitation and design their project and/or contracts accordingly.*

In our literature search, we did not find any reference that specifically addressed this issue; however, in the Black Hills Experimental Forest, a small skid steer with a vertical head attachment was able to accomplish noncommercial thinning in saplings that were very close together. The smaller machine and cutting head appeared to have considerable maneuverability and was able to accomplish the task.

moist mixed conifer (DC1, PRCC1), tended to have more 100-hour fuels than sites that were less productive (Amber, BHMix, BHMow) (Appendix B). Similar trends also occurred on sites measured by Battaglia et al. (2010) where they showed the dry mixed conifer had the highest fine-fuel loads after mastication and pinyon-juniper had the lowest fuel loads after mastication. Kane et al. (2009) may have also had similar cause for increased fuels on some sites, but they did not mention differences in productivity related to the total amount of fine fuels.

What Are the Operator's Skill Requirements for the Project?

As previously mentioned, machine operator skill is a very important factor to consider in mastication implementation. A person who has more experience (hundreds of hours) on masticator equipment can move through the project efficiently and optimize the machine's assets. In our review of the literature, several anecdotal references stated that operator experience could highly influence mastication outcomes and the efficiency of operating the machine (Coulter et al. 2002; Kryzanowski 2007; Windell and Bradshaw 2000). Just as an inexperienced operator can damage a mastication cutting (Kryzanowski 2007), so can an inexperienced operator damage the residual stand by bumping, hitting residual stems, or removing bark with flying projectiles of masticated particles. An experienced operator may be able to move the cutting head to avoid homes or other values at risk. Some operators prefer to work in a downslope direction when visibility is impaired in dense stands because of improved visibility seeing the tops of stems. An inexperienced operator may need a spotter to help guide him, which adds another crewmember, and the spotter may be vulnerable from objects coming from the machine (Bolding et al. 2006). The more experienced the operator, regardless of the machine, the more cost efficient the project will be and the overall site impact from tree damage to soil impacts may be less by minimizing turns and limiting the number of passes (Vitorelo et al. 2009). Experienced operators can more carefully direct the thrown material away from areas of concern by proper machine and cutting-head placement, which increases safety.

How About Safety Considerations?

Masticators produce two types of hazardous objects (1) sawteeth or cutters and (2) foreign objects (wood) displaced by the cutting tool (Rummer and Klepac 2011). OSHA and ISO standards require protective cab glazing material to protect the operator from broken saw teeth and flying wood. Injuries to foresters and contract supervisors overseeing mastication activities can occur because they sometimes get too close to the equipment and do not have an enclosed cab to protect them. Even with specific standards, safety is a continuous process of hazard recognition, engineering analysis, and adoption of improved countermeasures and practices. However, carrier machines used in forestry operations need to meet OSHA standards that have rollover protective structures (ROPS) and falling object protective structure (FOPS).

Conclusion and Management Implications

Managers can apply a wide range of silvicultural methods that provide many options to identify the best method or a combination of methods best suited to meet project objectives. Mastication is unique, but fortunately, there is an abundance of literature to inform decisions on whether to use mastication as a treatment option. This paper attempts to synthesize this literature to provide information to decisionmakers to determine if mastication will achieve their objectives. That said, we still lack literature and research to inform several aspects of mastication. We know that masticator machines and implementation strategies will continue to evolve; this report provides information on the current knowledge. Ecologically, we know more about plant and soil response, but not all ecosystems have mastication studies; therefore, we cannot assume consistent results across all vegetation types. We have limited knowledge of the effects of mastication on wildlife and wildlife habitat. If a manager selects mastication as a treatment option, then treatment implementation becomes paramount. A thorough site evaluation should include consideration of factors such as nonnative species invasion, the vulnerability of soils to erode or compact, and treatment costs. Only after evaluating the site, objectives, and goals can a manager identify the carrier machine, cutting head, and mounting system best suited to complete the project safely and efficiently.

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Appendix A—Summary of Key Results From Mastication Studies

Introduction

Each of the four tables in Appendix A provides a summary of key results from studies that evaluated the effects of mastication on the biological, ecological, or physical response. Table A.1 summarizes understory and shrub vegetation. Table A.2 summarizes the effects of mastication on remaining trees and regeneration. Table A.3 summarizes soil erosion, compaction, and nutrition. Table A.4 summarizes the effects of mastication on insects, mammals, and birds. Each table has the literature reference, the location where the study occurred, the forest or vegetation type, the treatments that were tested, and a short summary of the results. Unique to the understory vegetation table is the listing of lifeforms (shrubs, forbs, grass) that were studied. In some cases, multiple studies occurred on the same study site; in these situations, we placed all the references relevant to the results in the same table row.

Each table has the following headings:

Study: Number of each study in a particular subject area, for tracking purposes.

Reference: Literature reference.

Location: State or country where the study occurred.

Ecosystem: Vegetation type of the study site.

Treatments: Treatments the authors evaluated.

Life-form studies: This is unique to table A.1 and lists the vegetation lifeform the authors evaluated.

Summary: This provides the primary results from the individual study.

Table A.1—Effect on understory and shrub vegetation from mastication and associated treatments.

Study	Reference	Location	Ecosystem	Treatments	Life forms studied	Summary
1	Brockway et al. 2009	Georgia	Pine, hardwoods	• Mastication • Mast. plus prescribed fire (PF) • Control	tree, shrub, forb, grass	• 2-3 yrs posttreatment, • Mastication (Mast.) led to initial increase of woody and herb. plants, • Addition of mast. and prescribed fire was needed to reduce woody regrowth and increase grasses and forbs.
2	Burnett et al. 2014	California	Mixed conifer	• Mastication • Thinning	tree, shrub, forb	• 2-6 yrs posttreatment, • Mast. and thinning treatments reduced shrub and herbaceous cover.
3	Busby and Southworth 2014	Oregon	Chaparral	• Mast. plus PF	grass	• 7 yrs posttreatment, • Seeding after Mast+PF had only a minimal effect on bunchgrass persistence, native and introduced cover, species richness over control.
4	Bybee et al. 2016; Shakespear 2014; Young et al. 2013a	Utah	Pinyon/Juniper (P-J)	• Mastication • Prescribed fire • Thinning • Control	tree, shrub, forb, grass, nonnatives	• 1-8 yrs posttreatment, • Mast. and thinning produced similar results, • Mast. maintained a shrub-dominated ecosystem, • Mast. and Mast+PF increased herbaceous plant cover, • Mast. improved growth of cheatgrass and bluebunch wheatgrass.
5	Carvajal-Acosta et al. 2015	Nevada	Pine/Fir	• Mastication • Control	forb	• 1-yr posttreatment, • No significant difference in plant community variables (richness, cover, etc.) to mast.
6	Collins et al. 2007	California	Mixed conifer	• Mastication, • Prescribed fire, • Mast. plus PF • Control	tree, shrub, forb, grass, nonnatives	• 1-yr post treatment, • Mast. reduced shrub cover relative to PF and Mast+PF, • Mast+PF had greatest species richness and number of nonnative plants, • PF and Mast+PF decreased native species.

Table A.1—*Continued.*

Study	Studies	Location	Ecosystem	Treatment	Life forms studied	Summary
7	Fernandez et al. 2013a,b, 2015; Fernandez and Vega 2016	Spain	Shrubland	• Mastication • Prescribed fire	shrub	• 1.5-4 yrs. posttreatment, • Higher species richness in PF than mast., • More shrub seedlings in burned areas than mast, • Neither mast. or PF hindered shrub recovery.
8	Fornwalt et al. 2017	Colorado	P-J, Mixed Conifer	• Mastication • Control	shrub, forb, grass, nonnatives	• 6-9 yrs posttreatment, • Mast. had higher understory plant richness and cover than control, • Mast. had little effect on shrubs.
9	Gottfried and Overby 2011	Colorado	P-J	• Mastication • Thinning (pile burning) • Control	tree, shrub, forb, grass	• 1-3 yrs posttreatment, • Mast. and thinning-pile burning produced veg. mosaics and adequate tree regeneration • Pile burns resulted in higher occurrence of nonnatives.
10	Kane et al. 2010	California	Ponderosa pine	• Mastication • Mast. plus PF • Control	shrub, forb, grass, nonnatives	• 1-4 yrs posttreatment, • Mast. had no effect on understory species richness, •Mast+PF increased both native and nonnative species richness as well as shrub seedling density in comparison to controls.
11	Kreye et al. 2014	Florida	Pine forest	Mastication	tree, shrub	• 1-yr posttreatment, • Shrub layer recovered quickly after mast.
12	Owen et al. 2009	Colorado	P-J	• Mastication • Prescribed fire (piles) • Thinning • Control	shrub, forb, grass	• 2.5 yrs post treatment, • Mast. plots had more plant cover and richness than pile burns or control, • Pile burn plots dominated by nonnatives and 6x times fewer native plants than controls.
13	Perchemlides et al. 2008	Oregon	chaparral, oaks	• Mastication • Control	tree, shrub, forb, grass	• 4-7 yrs posttreatment, • Mast. led to expansion of nonnative grasses, reduction in native perennial cover, dominance of annual forbs.
14	Phillips et al. 2013	South Carolina	Pine forest	• Mastication • Prescribed fire • Mast. plus PF • Control	nonnatives	• 7 yrs posttreatment, • Pine stands affected by pine beetle had highest nonnative species after Mast., • Pine stands not affected by pine beetle had highest nonnative species after Mast+PF.

Table A.1—*Continued.*

Study	Studies	Location	Ecosystem	Treatment	Lifeforms Studied	Summary
15	Potts and Stephens 2009; Potts et al. 2010	California	Chaparral	• Mastication • Prescribed fire	shrub, forb, grass	• 3 yrs posttreatment, • PF had higher shrub cover than mast., • Mast. had highest numbers of nonnative species, esp. nonnative grasses, • Cool season fire may be best for controlling nonnative grasses.
16	Redmond et al. 2014	Utah	P-J	• Mastication • Prescribed fire • Thinning (pile burn) • Control	shrub, forb, grass	• 2 yrs posttreatment, • With seeding, both mast. and PF increased herbaceous cover over pile-burn, • With no seeding, herb. cover only increased with PF, • All treatments increased nonnatives, esp. PF.
17	Ross et al. 2012	Utah	P-J	• Mastication • Prescribed fire • Thinning • Control	shrub, forb, grass	• 1-2 yrs posttreatment, • Both mast. and thin-scatter-burn had positive influence on understory plant cover.
18	Sikes and Muir 2009	Oregon	Chaparral	• Mastication • Thin-pile-burn • Control	tree, shrub, forb, grass, nonnatives	• 1-2 yrs posttreatment, • More shrub seedlings in both treated areas than in controls, • Thin-pile-burn increase in nonnatives, • Mastication may reduce species diversity.
19	Weekley et al. 2008	Florida	Oak scrublands	• Mastication • Prescribed fire • Mast. plus PF • Control	Shrub, forb, grass	• 1-5 yrs posttreatment, • PF and Mast+PF better than Mast. for recruitment of rare herbaceous plants because of increased bare sand & reduced litter and lichen cover.
20	Wolk and Rocca 2009	Colorado	Ponderosa pine	• Mastication • Thinning • Control	tree, shrub, forb, grass, nonnatives	• 3-5 yrs posttreatment, •Chip depth negatively- related to understory cover, • Cover of nonnatives higher in thin only as opposed to control or thin plus mast, • Species composition different in thin plus mast as opposed to control or thin only.

Table A.2—Effect on residual tree attributes and regeneration from mastication and associated treatments.

Study	Studies	Location	Ecosystem	Treatment	Summary
1	Brockway et al. 2009	Georgia	Pine, hardwoods	• Mastication • Mast. plus PF • Control	• 2-3 yrs posttreatment, • Mast. resulted in reduced stand density and increased mean DBH, • Mast. reduced tree species richness.
2	Collins et al. 2014[a]	California	Mixed conifer	• Mastication • Prescribed fire • Mast. plus PF • Control	• 7 yrs posttreatment, • For Mast, residual tree mortality was consistently lower for all species, • For PF, except Douglas-fir, residual tree mortality was higher, • Mast+PF had high residual tree mortality for white fir and sugar pine.
3	Hamma 2011	California	Mixed conifer	• Mastication • Prescribed fire • Control	• 4-11 yrs posttreatment, • No differences between mast. and PF treatments for stand-level carbon dynamics or air pollution removal.
4	Kreye and Kobziar 2015	Florida	Southern pine	• Mastication • Prescribe fire • Mast. plus PF	• 1-week post-burn, • Minimal tree mortality after PF and Mast+PF.
5	Moghaddas et al. 2008[a]	California	Mixed conifer	• Mastication • Prescribed fire • Mast. plus PF • Control	• 4 yrs posttreatment, • All treatments decreased black oak and sugar pine seedling density, • PF and Mast+PF increased Douglas-fir seedling density, • Mast+PF increased ponderosa pine seedling density.
6	Potts et al. 2010	California	Chaparral	• Mastication • Prescribed fire	• 3-yrs posttreatment, •Treatment did not affect shrub height, species richness, or composition.
7	Reemts and Cimprich 2014	Texas	Oak shrubland	• Mastication • Control	• 1-6 yrs posttreatment, • Mast. treatment produced lower shrub heights for 4 growing seasons.
8	Stephens et al. 2009[a]	California	Mixed conifer	• Mastication • Prescribed fire • Mast. plus PF • Control	• 1-2 yrs posttreatment, • Aboveground live carbon was significantly reduced with Mast. and Mast+PF, and unchanged for PF compared to control, • PF and Mast+PF had significantly greater CO2 emissions than Mast or control.
9	Stephens and Moghaddas 2005[a]	California	Mixed conifer	• Mastication • Prescribed fire • Mast. plus PF • Control	• 1-2 yrs posttreatment, • Treatments did not affect snag volumes for all the decay classes, • Snag density in decay class 1 was significantly greater in PF and Mast+PF compared to Mast and control.

[a] Used the same study site in northern California.

Appendix A.3—Effect on soil erosion, compaction, and nutrition from mastication and associated treatments.

Study area	Studies	Location	Ecosystem	Treatment	Summary
Soil Erosion and Compaction					
1	Cline et al. 2010	Utah	P-J	• Mastication • Control	• 1-yr posttreatment, • Tire tracks increased penetration resistance, • Bare plots with mast. residue had higher infiltration rates and lower sediment yields than plots without residue.
2	Harrison et al. 2016	California and Nevada	Mixed conifer	• Mastication • Prescribed fire • Control	• Mast. plots manipulated for residue density; PF plots on as-is burned areas with varying fire severity, • Mast. residue >25% coverage mitigated erosion, • Sites with >35% surface burned resulted in highest sediment yield.
3	Hatchett et al. 2006	California	Mixed conifer	• Mastication	• Mast. in fall; meas. next spring, • Mast. resulted in slight to insignificant erosion as long as a layer of masticated wood chips left on site.
4	Moghaddas and Stephens 2008	California	Mixed conifer	• Mastication • Mast. plus PF • Control	• 1-2 yrs posttreatment, • No significant soil compaction due to mast. as it was buffered by created debris bed, • Greater compaction in skid trails so any reduction in number of skid trails is advantageous to long-term soil health.
5	Ross et al. 2012	Utah	P-J	• Mastication • Prescribed fire • Thin • Control	• 1-2 yrs posttreatment, • Compared to controls, soil aggregate stability was lower in thin-pile-burn and mast. sites.
Soil moisture, temperature, and nutrition					
1	Busse et al. 2005, 2010	California	Oak-Ponderosa pine	• Mast. plus PF	• Constructed fuel beds, • Soil type did not have an effect on soil heating, • Soil moistures >20% limits lethal soil heating, • Burning fuel depths >7.5 cm in dry soils resulted in soil damage.
2	Godwin 2012	Florida	Southern pine	• Mastication • Prescribed fire • Control	• Soil CO2 efflux rates not altered by mast. or PF, • Forests regularly burned over 60 yrs had lower soil CO2 efflux rates than forests that had never been burned.
3	Gottfried and Overby 2011	Colorado	P-J	• Mastication • Thin • Control	• 1-3 yrs posttreatment, • Soil microbes were not decomposing mast. material, • Mast. decreased soil moisture and temp. extremes.

Table A.3—*Continued.*

Study area	Studies	Location	Ecosystem	Treatment	Summary
4	Johnson et al. 2014	California	Mixed conifer	• Mastication • Prescribed fire • Mast. plus PF • Control	• 1-yr posttreatment, • Mast+PF resulted in the export of soil nitrogen from the site, • Mast. added potassium to the forest floor.
5	Kobziar and Stephens 2006	California	Ponderosa and Jeffrey pine	• Mastication • Prescribed fire • Mast. plus PF • Control	• 1-2 yrs posttreatment, • Mast. resulted in reductions in soil respiration and soil moisture, • PF raised soil respiration rates, • Mast+PF lowered soil respiration rates.
6	Moghaddas and Stephens 2007	California	Mixed conifer	• Mastication • Prescribed fire • Mast. plus PF • Control	• 1-yr posttreatment, • PF and Mast+PF reduced in C and N of forest floor, • No difference in total C and N in mineral soil compared to control.
7	Owen et al. 2009	Colorado	P-J	• Mastication • Prescribed fire • Mast. plus PF • Control	• 2.5 yrs post treatment, • Pile burns degraded soil properties and mycorrhiza levels, • Mast. had lower soil temps and higher soil moistures.
8	Rhoades et al. 2012	Colorado	P-J, mixed conifers	• Mastication • Control	• 3-5 yrs posttreatment, • Mast. had lower max. summer soil temperatures and increased soil moisture, • Available nitrogen higher in mast. than in control.
9	Ross et al. 2012	Utah	P-J	• Mastication • Prescribed fire • Thin • Control	• 1-2 yrs posttreatment, • Soil aggregate stability and nitrogen fixation potential were lower in the pile and burn and mast. treatments than control.
10	Southworth et al. 2011	California	Chaparral	• Mastication • Prescribed fire • Mast. plus PF • Control	• 5 yrs posttreatment, • Ectomycorrhizal communities did not differ between treatments, • PF and Mast+PF inhibited fruiting of truffles.
11	Stottlemyer et al. 2013	South Carolina	Southern pine	• Mastication • Prescribed fire • Control	• 0-1 yr posttreatment, • Mycorrhizal inoculum did not differ among treatments, but was highly variable within treatments.
12	Young et al. 2013b	Utah	P-J	• Mastication • Control	• 2-5 yrs posttreatment, • Mast. sites had more wet degree days than untreated sites.

Table A.4—Effect on insects/animals/birds from mastication and associated treatments.

Study	Studies	Location	Ecosystem	Treatments	Summary
1	Amacher et al. 2008	California	Mixed conifer	• Mastication • Prescribed fire • Control	• 1-yr posttreatment, • PF and Mast+PF increased deer mouse populations, • Mastication decreased deer mouse populations, • Brush mice positively influenced by leaving dense, low vegetation, • Other small mammals not affected by treatments.
2	Apigian et al. 2006	California	Mixed conifer	• Mastication • Prescribed fire • Mast. plus PF • Control	• 1-yr posttreatment, • Moderate changes in species richness and abundance of leaf litter arthropods among treatments • Increased habitat heterogeneity by implementing a diversity of treatments may provide habitat for more rare species.
3	Burnett et al. 2014	California	Mixed conifer	• Mastication • Thin • Control	• 2-6 yrs posttreatment, • Bird community composition and abundance only moderately affected by mast. and thinning treatments.
4	Reemts and Cimprich 2014	Texas	Oak Shrubland	• Mastication • Control	• 1-6 yrs posttreatment, • No difference in probability of black-capped vireo nests in mast. sites vs. control, • Mast. can serve as substitute for PF in restoring shrubland structure with no detriment to vireo nesting.
5	Seavy et al. 2008	Oregon	Oak woodlands; chaparral	• Mastication • Control	• 1-5 yrs posttreatment, • Bird species associated with shrub cover more abundant on controls, • Bird species associated with open areas more abundant in treated areas, • Size and shape of treated areas benefit particular species.

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Appendix B—Methods Used for Determining Sample Sites, Collecting Fine Fuels, and Calculating Particle Density and Surface Area of Masticated Fuels for the MASTIDON Study

This appendix is an excerpt from Keane et al. (2018) that describes how the sites were chosen, data were collected, and laboratory analysis were used to obtain the fine fuel loads and the particle characteristics that we present in this report.

Site Descriptions

Keane et al. (2018) sampled 14 study sites in mixed coniferous forests of the Rocky Mountains (table B.1). The sites selected in the study required a variety of treatment ages, mastication methods, mixed-conifer stand types, and geographic areas throughout the Rocky Mountains. After contacting numerous agencies and fire managers, we found only 14 sites that met these criteria and that could be feasibly sampled, processed, and analyzed within the 2 years allotted to this study. These sites represented seven ages (i.e., years after treatment) of masticated fuel (table B.1) and two moisture regimes. Moist mixed-conifer sites were dominated by western hemlock (*Tsuga heterophylla*), western red cedar (*Thuja plicata*), western white pine (*Pinus monticola*), and western larch (*Larix occidentalis*). These sites were located on Priest River Experimental Forest (EF) and Deception Creek EF in northern Idaho. Collaboration with the University of Idaho provided fuels from an additional moist site that was dominated mainly by ponderosa pine (*Pinus ponderosa*) within a pine plantation. All other sites were dry or xeric mixed-conifer sites dominated by ponderosa pine and Douglas-fir (*Pseudotsuga menziesii*) or juniper (*Juniperus* sp.). The xeric sites ranged from central Idaho to southern New Mexico and east to the Black Hills Experimental Forest in western South Dakota.

Field Sampling Protocols

For the field sampling, a 30 x 50 m macroplot was established that bounded the measurement area within the study site. This macroplot broadly represented the general conditions of the mastication treatment. The 30 m sides of the rectangular macroplot were oriented up the slope and the 50 m sides were established perpendicular to the slope (fig. B.1). Latitude and longitude were recorded at each corner of the macroplot, and at several points on a grid established within the macroplot, using a global positioning system. Within the macroplot, 20 microplots were established to collect data and fuel samples. To establish these microplots, a random number between 6 and 24 was selected to delineate a starting point (in meters) (1) along the 10-m line and (2) the reverse starting point (30 minus the random number) along the 40-m line. Each of these random points marked the intersection of four transects running in the four cardinal directions (fig. B.1). Microplots were 1 m × 1 m and established every 5 meters (out to 20 m) in the four cardinal directions from this initial cross point. The microplots were oriented as shown in figure B.2; where, facing uphill, the bottom left corner was placed at the appropriate meter mark. We photographed the microplot from below its downhill

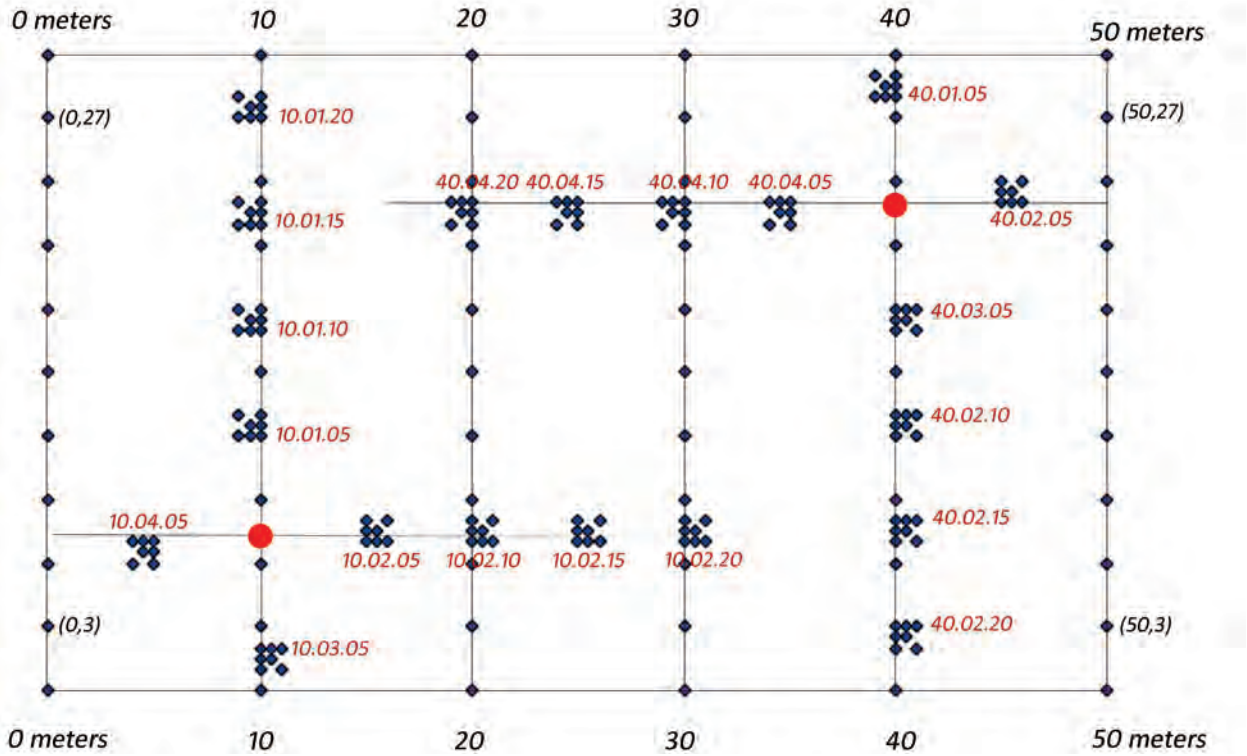

Figure B.1—Grid sampling design implemented at each site. The 50 x 30 m macroplot was oriented so that the top was uphill. Six lines were located within the macroplot at 0 m, 10 m, 20 m, 30 m, 40 m and 50 m. Two methods were used to sample within this macroplot. Sampling method 1 tested the consistency in depth of masticated material within the entire macroplot. Depths of each fuelbed layer were measured at 3 m intervals along each of the six lines starting at the zero baseline. Samples were labeled as (major line number, meter footage), that is (0, 3). These depth plots are represented within this figure by the regularly spaced small blue diamonds within the macroplot. Sampling method 2 tested the variation in depths of the masticated materials at 0.5 to 1 m intervals and provided the materials used to describe the masticated material within the macroplot. Small-scale sampling using Hood and Wu (2006) microplots is located at the closely spaced dots along lines 10 and 40 m that form the tightly arranged squares. The randomly located start point for each line of microplots is designated with a large red circle. Samples were labeled using the following protocol: major line number, direction, and meter mark with direction varying from northerly (1) to westerly (4). These samples were taken along the 10 m and 40 m major lines only.

side. Finally, we established a 0.25-m^2 (0.5-m × 0.5-m) quadrat at the lower left corner of each microplot from the downhill side to delineate where fuels would be collected.

At each microplot, depths of five masticated fuelbed layers were taken at the corners of the microplot and at the corners of the quadrat (fig. B.2). The five layers included undecomposed litter, masticated fuels, masticated-duff mixed together, duff only, and duff mixed with mineral soil. After all depth measurements were taken, all materials within the quadrat were collected down to the mineral soil, then sorted into three general fuel types (fresh litter, masticated fuels, duff) and placed in paper bags that were labeled as to site, transect, location along transect segment, date, photo number, and fuelbed category. The material could not be sorted into the same five layers as the depth measurements because it was too difficult to separate these categories in the field during the destructive sampling. As a result, we collapsed the masticated-duff, duff, and duff-soil layers into just one bag and called it duff. We sorted the duff bag in the laboratory into its proper components. We did not collect live biomass from shrubs, herbs, or logs because they were rare and beyond the scope of this study, but general vegetation was recorded at each microplot. The collections from the University of Idaho sites (UI,

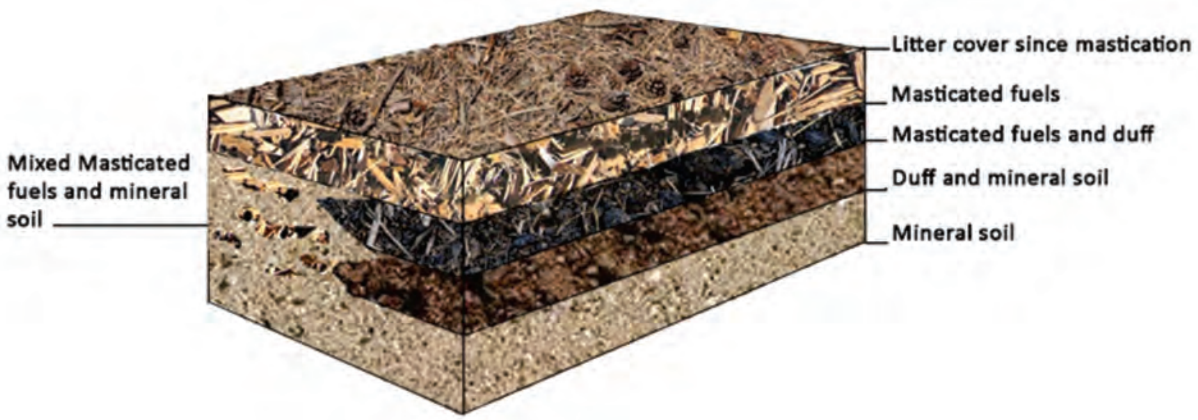

Figure B.2—A cross section of the masticated fuelbed illustrating the five fuelbed layers that were characterized in this study.

table 4 in main text) were done with slightly different methodologies and these are documented in Lyon (2015).

Laboratory Tasks

Laboratory tasks consisted of five broad types of activities. These included (1) sorting of the field particles, (2) measuring and weighing a subsample of individual particles, (3) obtaining particle densities from this subsample, (4) burning fuel to compute heat content and lignin and cellulose fractions from this subsample, and (5) running chemical tests on particle subsample for percentages of carbon and nitrogen. In this Appendix, we will only focus on activities associated with activities one, two, and three. Ten of the 20 microplot collections from each study site were randomly selected to acquire data for these three activities in the laboratory. A total of 151 microplots were analyzed in this way.

Sorting

The first step in the processing of a masticated sample to create a physical description of its components was to sort collected material into the five masticated fuelbed layers. The fresh litter did not require sorting or sizing. Masticated wood was sorted into 15 shape categories (not presented in this paper) and three size categories (1-, 10-, 100-hr fuels). Bark was sorted into large chunks (100-hr) and small pieces (1-, 10-hr). We removed all fresh litter, bark, and wood particles from the duff collected in the field, which left pieces of debris less than 6 mm (0.25 inch) for the duff category. See Keane et al. (2018) for a complete description of the shape categories that were divided and analyzed.

Physical Measurements

After sorting, the particles in each size and shape class were oven-dried at 90 ºC for 2 days, then weighed to compute total load in each shape, size, and layer class. A randomly selected subset of particles from each shape and size class was then measured for their individual dimensions and to obtain their particle dry weight (PW). A minimum of one or two particles from each shape, size, and layer class were selected; however, in some cases, there were more than 200 particles (e.g., 1-hr parallelograms). In these situations, a maximum of 10 particles was selected for each subsample. Length (mm), width (mm), and height (mm) of each woody particle was measured to the nearest 0.1 mm using a caliper connected to a computer to capture measurements. Depending on the particle shape and other dimensional measurements needed to compute volume and surface area for each particle, more data measures were added.

Particle Density of Individual Particles

Particle densities (PDs) of individual particles were determined using a two-fluid displacement process that has historically been used to determine density in soils or duff (Williamson and Wiemann 2010). The method consisted of slowly submerging particles in a large cylindrical tube containing a combination of two fluids (fig. B.3). The upper fluid was 100 percent kerosene; the lower fluid was a solution of 50 percent glycerin and 50 percent water. Both fluids were approximately 20 cm deep to allow enough room

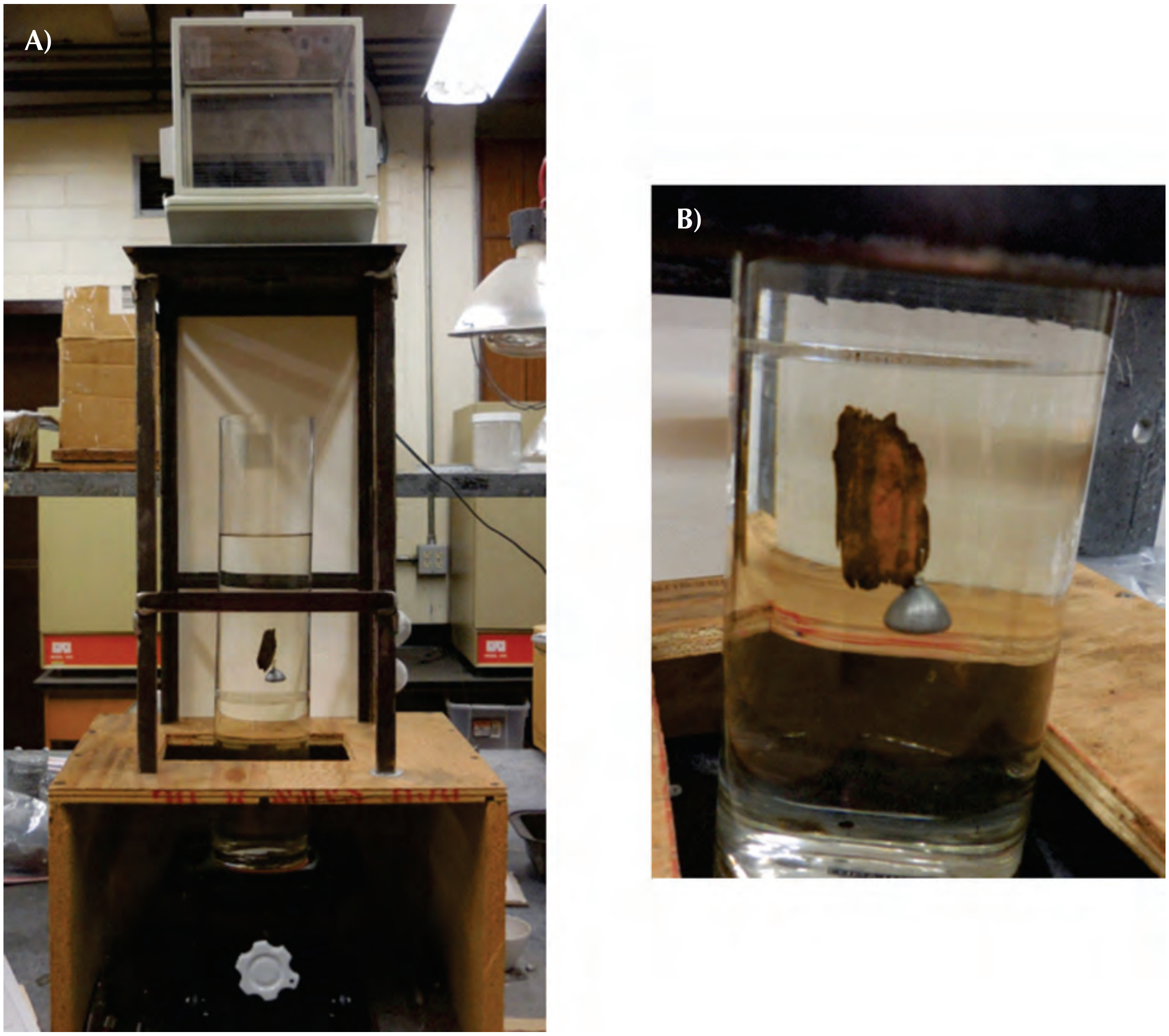

Figure B.3—Apparatus used to estimate the density and volume of masticated fuel particles. (A) Parts of apparatus include a scale (top), a fluid column with two fluids (kerosene at top and a 50:50 mixture of glycerin and water at bottom), and a lift (bottom) to raise and lower fluid column. (B) Closeup of a particle in kerosene. Particle has weight attached to assure it stays submerged in each fluid.

for submersion of large particles; the cylinder sat on a lift so that it could be raised and lowered, as needed, during the submersion process. The technician attached the particle to plastic line that had a large lead weight at the end to keep it submerged. The line with the lead weight and the particle was attached to a scale. The lead weight and line were tared by submerging them in each fluid without a particle attached and recording a weight in each fluid from the scale. Densities for each fluid were taken from the literature for inputs in the formulas that follow.

In the displacement method, the scale was first tared to zero with the particle, line, and lead weight all connected but outside of the fluids. Then the technician slowly lowered the particle into the kerosene until it was about 1 cm above the kerosene-glycerin boundary, and it remained at that depth for 3 minutes (fig. B.3). After 3 minutes, the weight on the scale was recorded. The technician than lowered the particle into the glycerin-water layer to within 1.25 cm of the boundary between the two fluids and left to equilibrate and displace glycerin. After 3 minutes, the weight of the particle in the glycerin-water layer was recorded.

The PD was computed using the following equation (Sarli et al. 2001):

$$PD = PW\ ((Pk\text{-}Pmix))/((Wk\text{-}Wmix))$$

where PD is the particle density (g/cm^{-3}); PW is the particle dry weight (g); Pk and Pmix are the densities of the kerosene and the glycerin-water mixture, respectively (g/cm^{-3}); and Wk and Wmix are the weights (g) of the particle in the kerosene and glycerin-water mixture layers, respectively.

Surface Area of Individual Particles

Surface area (SA) was calculated by solving for particle volume (PV) from the PD measurement (determined above) and then calculating a new length from generalized volume equations for each shape. The new length was put in generalized surface area equations.

First, PV was calculated as follows: $PV = PW/PD$

where PV is the particle volume (cm^3); PW is the particle dry weight (g); and PD is the particle density (g/cm^{-3}). Using PV from the particle density, a new length was calculated for the shape using the standardized shape-volume equations taken from the literature. The new length was applied to standard formulas used to compute surface area for the individual particle shapes. Although not a perfect solution, the resulting surface areas were at least semi-adjusted for the departure from a perfect shape in a manner similar to the particle densities. The method had problems, especially in the parallelograms, where a total length was measured and a mean length was calculated for the two long sides. In this case, only the mean length was adjusted in the surface area formula. Calculating new lengths in ellipses also required some assumptions, including that the longest axis was length and the shortest axis was height.

Table B.1—Field locations examined in this study. EF = Experimental forest; NF = National Forest; NP = National Park. Tree abbreviations include PP = ponderosa pine, *Pinus ponderosa*, DF = Douglas-fir, *Pseudotsuga menziesii*, WH = western hemlock, *Tsuga heterophylla*; WRC = western Redcedar, *Thuja plicata*, WP = western white pine, *Pinus monticola*, and WL = western larch, *Larix occidentalis*.

Location	Site Name	Primary tree species	Treatment Date	Mastication type
Dry mixed conifer				
Boise Basin EF, ID	Amber	PP	2004	Vertical shaft/teeth
Boise Basin EF, ID	Amber New	PP, DF	2010	Horizontal shaft/teeth
Black Hills EF, SD	BHMix	PP	2012	Vertical shaft/knives
Black Hills EF, SD	BHMow	PP	2012	Vertical shaft/knives
Manitou EF, CO	MEFChip	PP, DF	2004	Chipped
Manitou EF, CO	MEFWS	PP, DF	2005	Horizontal shaft/teeth
San Juan NF, CO	Skelton	PP, DF	2010-2011	Horizontal shaft/teeth
Santa Fe NF, NM	LG	PP	2006	Horizontal shaft/teeth
Santa Fe NF, NM	PAL	PP	2011-2012	Horizontal shaft/teeth
Valles Caldera NP, NM	VC1	PP	2007-2008	Horizontal head/teeth
Valles Caldera NP, NM	VC2	PP	2012	Horizontal head/teeth
Moist mixed conifer				
Deception Creek EF, ID	DC1	WH, WWP, WL	2004	Vertical shaft/teeth
Priest River EF, ID	PR3	WRC, WH, WWP, WL	2011	Horizontal head/teeth
Priest River EF, ID	PRCC1	WH, WRC, WWP, WL	2007	Vertical shaft/teeth
University of Idaho EF, ID	UI	PP	2014	Horizontal head/teeth

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