

# Long-term changes in masticated woody fuelbeds in northern California and southern Oregon, USA

Warren P. Reed<sup>A,B,C,F</sup>, J. Morgan Varner<sup>D</sup>, Eric E. Knapp<sup>E</sup> and Jesse K. Kreye<sup>B</sup>

<sup>A</sup>Department of Forest Resources and Environmental Conservation, Virginia Polytechnic Institute and State University, Blacksburg, VA 24061, USA.

<sup>B</sup>Department of Ecosystem Science and Management, The Pennsylvania State University, University Park, PA 16802, USA.

<sup>C</sup>Intercollege Graduate Degree Program in Ecology, The Pennsylvania State University, University Park, PA 16802, USA.

<sup>D</sup>Tall Timbers Research Station, 13093 Henry Beadel Drive, Tallahassee, FL 32312, USA.

<sup>E</sup>USDA Forest Service Pacific Southwest Research Station, Redding, CA 96002, USA.

<sup>F</sup>Corresponding author. Email: [wpr5005@psu.edu](mailto:wpr5005@psu.edu)

**Abstract.** Mechanical mastication is a fuels treatment that shreds midstorey trees and shrubs into a compacted woody fuel layer to abate fire hazards in fire-prone ecosystems. Increased surface fuel loading from mastication may, however, lead to undesirable fire intensity, long-duration flaming or smouldering, and undesirable residual tree mortality. Two major questions facing fuels managers are: how long do masticated fuels persist, and how does the composition of masticated fuelbeds change over time? To evaluate these changes, we measured 25 masticated sites with a range of vegetation, species masticated and time since treatment (1–16 years) in the western US. Seven of the 25 sites were sampled nearly a decade earlier, providing a unique opportunity to document fuelbed changes. Woody fuel loading ranged from 12.1 to 91.9 Mg ha<sup>-1</sup> across sites and was negatively related to time since treatment. At remeasured sites, woody fuel loads declined by 20%, with the greatest losses in 1- and 10-h woody fuels (69 and 33% reductions in mass respectively). Reductions were due to declines in number of particles and reduced specific gravity. Mastication treatments that generate greater proportions of smaller-diameter fuels may result in faster decomposition and potentially be more effective at mitigating fire hazard.

**Additional keywords:** decomposition, fire hazard reduction, fuel loading, fuels treatments, timelag, woody fuels.

Received 28 September 2019, accepted 15 May 2020, published online 5 June 2020

## Introduction

Past land-use practices, including fire exclusion, coupled with increased regional warming have increased the size, frequency and duration of wildfires across the western US (Scholl and Taylor 2010; Abatzoglou and Williams 2016), highlighting the need for effective fuels management and restoration of fire-adapted ecosystems. An increasing human population living within the wildland–urban interface (WUI) further complicates fire management, posing threats to property and human safety (Radeloff *et al.* 2005), altering ignition patterns and fuel connectivity (Syphard *et al.* 2007), and restricting the use of prescribed fire where otherwise opportune as a management tool (Quinn-Davidson and Varner 2012). In many fire-prone sites, fuels treatments are used to reduce surface fire intensity, lift and separate canopy fuels, and improve resilience of retained overstorey trees (Agee and Skinner 2005).

In the US and places where the live fuels to be treated can be non-merchantable, mechanical mastication is a widely used alternative. With mastication, shrub and midstorey tree canopy fuels are typically targeted to reduce ladder fuels, decrease the

probability of crown ignition and enhance fire suppression efforts (Kreye *et al.* 2014a). Through shredding, chipping, flailing, or cutting (Keane *et al.* 2018), standing live woody and dead vegetation is converted into a layer of dead material on the forest floor (Fig. 1) The resulting surface fuelbeds are often dense and compacted accumulations of fractured woody fuels (Kane *et al.* 2009; Sikkink *et al.* 2017; Keane *et al.* 2018). Treatments can be implemented following forest thinning, and are sometimes used to enable prescribed burning where otherwise difficult (Knapp *et al.* 2011). Although mastication has been widely used in western North American shrublands and forests, the spatial extent of projects is often small owing to high treatment costs (often greater than US\$3459 ha<sup>-1</sup>) and topography that limits the use of mechanical equipment (Vitorelo *et al.* 2009; Jain *et al.* 2018).

Reliance on mastication to mitigate fire hazard has generated substantial interest in characterising these novel fuelbeds, their dynamics, and the fire behaviour and effects that may result if burned (Kane *et al.* 2009; Kreye *et al.* 2014a; Coop *et al.* 2017; Sikkink *et al.* 2017; Keane *et al.* 2018; Black *et al.* 2019).



**Fig. 1.** Photograph of a mechanically masticated fuels treatment at the VAN site in the Six Rivers National Forest, California, taken 2 years after mastication.

A study in Colorado found that surface fuel loading ranged from 3.2 to 8.5 times higher following mastication compared with adjacent untreated stands (Battaglia *et al.* 2010). Others have noted that following mastication, fire behaviour in these novel fuels has been highly variable and difficult to predict with standard fuel models (Bradley *et al.* 2006; Knapp *et al.* 2011; Kreye *et al.* 2014a). High surface fire intensity and significant residual flaming and smouldering can result following stand-alone mastication treatments. Long-duration (several hours) lethal soil heating has been observed in experimentally burned mesocosms of masticated fuels, particularly when soils are dry (Busse *et al.* 2005, 2010). This can exacerbate the potential for residual tree mortality when sites are burned. Changes in fire behaviour and effects are attributed to increased amounts of surface fuels and their compacted arrangement, creating questions and challenges for forest and fuels managers such as issues related to smoke production and resulting ecological responses (Keane *et al.* 2018).

Knowing how fast masticated material decomposes and how fuel characteristics change over time is key to evaluating the benefits and challenges. The long-term efficacy of masticated fuels treatments remains poorly understood (Kreye *et al.* 2014a). Laboratory studies assessing the influence of fuel bed age on fire behaviour in masticated fuels are rare and results vary from no effect (Sikkink *et al.* 2017) to a dampening effect as fuels age (Kreye *et al.* 2016). To assess physical changes in masticated fuels over time, we measured characteristics of downed woody fuels in 25 masticated sites across northern California and southern Oregon, USA, varying in time since treatment (range 1 to 16 years) and vegetation type. Of the 25 sites, seven were previously measured (detailed in Kane *et al.* 2009). Remeasurements provide specific descriptions of within-site changes in fuelbed composition and loading over a period of 8 to 9 years. To date, no study on masticated fuels treatments that we are aware of spans this range of times since treatment, and none has included remeasurement data from individual sites. The specific hypotheses tested in this study

were: (i) fuel loading will decrease as time since mastication increases; (ii) smaller-sized woody particles will make up a lower percentage of total load as time since mastication increases; (iii) fuelbed depth will decrease as time since mastication increases; and (iv) specific gravity of fuel particles will decrease as time since mastication increases. These results are relevant for predicting the effects of mastication on fire behaviour as well as the longevity or persistence of masticated surface fuel loading in the study region.

## Methods

### Study sites

In the summer of 2014, 25 sites in northern California and southern Oregon previously treated with mechanical fuel mastication were sampled. Sites in the Sierra Nevada, Southern Cascades, North Coast Ranges and Klamath Mountains were selected from treatment maps provided by regional forest managers, with the chronosequence of time since treatment ranging from 1 to 16 years (Fig. 2). Average annual precipitation across the 25 study sites ranged from 648 to 1752 mm while mean annual temperature averaged 11.2°C and varied from 6.4 to 16.8°C (PRISM Climate Group 2004). The elevation of the sites spanned 237 to 2083 m above sea level. Treatments at the sites were implemented using rotary blade or rotary drum masticator heads mounted on various machinery. Information regarding the equipment used to treat the sites was compiled from local fuels managers for most sites (Table 1). The vegetation was highly variable with communities of montane chaparral, oak woodland, pine-dominated and mixed-conifer forest. Species that comprised the residual vegetation were noted at the time of sampling to give a rough description of the forest ecosystem type and the type of vegetation targeted in the mastication treatment was categorised from photos of adjacent untreated areas (Table 2). Seven of the 25 sites were previously sampled 8 or 9 years before the present study by Kane *et al.* (2009) and remeasured to compare changes in fuel loading, depth, size class composition



**Fig. 2.** Locations of masticated study sites in northern California and southern Oregon, USA.

and fuel particle specific gravity without the usual challenges associated with chronosequence studies.

#### Field data collection

We sampled 15 plots ( $0.5 \times 0.5$  m) every 10 m along randomly oriented primary transects up to 50 m in length within treated areas at each site following Kane *et al.* (2009). Within each plot, all surface fuels (1-h,  $<0.625$  cm; 10-h,  $0.625$  to  $2.54$  cm; 100-h,  $2.55$  to  $7.62$  cm woody, litter and duff) were collected, bagged together, and transported to the laboratory. At one site (VAN), two of the plot bags were misplaced and only 13 plots therefore were used to calculate subsequent summaries and analyses. Woody material crossing the plot boundary was cut and only the portion within the plot retained. We measured surface fuel depths (combined litter and woody owing to incorporation during treatment) and depths of duff at four locations in each plot, 10 cm from sample corners, for an average value at each plot (Fig. 3). Because of difficulty discerning when surface fuels were deposited, we sampled all surface fuels that could have been present before treatments as well as those that could have accumulated after. The 1000-h woody fuels were infrequent, so we followed the guidelines of Kane *et al.* (2009) using the planar intercept method (Brown 1974) on fifteen 20-m-long (300 m per site) transects at random azimuths oriented from the destructive sampling method plots along main transects.

In the laboratory, we sorted fuels from each plot by fuel type (litter, duff, woody) and separated woody fuels into standard timelag diameter classes (1-, 10-, 100-h). Owing to the irregular shape of masticated material, we determined timelag size classes as in Kane *et al.* (2009) where particle diameters were measured using the thinnest cross section at the midpoint (i.e. where heat and moisture transfer is expected to be the most rapid). All sorted fuels were oven-dried at  $85^{\circ}\text{C}$  until no further weight loss occurred (at least 72 h) and oven-dry mass recorded.

To evaluate particle degradation over time, we measured particle specific gravity (analogous to particle density; Sackett 1980) for each woody timelag size class, using methods described by Kane *et al.* (2009). Immediately following weighing of oven-dry woody fuels, we randomly selected three masticated pieces from each size class per plot, and weighed them as individuals ( $n =$  up to 45 per site per size class; not all plots had particles in all size classes). After weighing, we submerged the dry samples into a small water bath, using a needle, atop a bench scale. The resulting mass recorded from the bench scale equals the buoyant force acting on the submerged particle and was used to estimate the specific gravity of each particle using the following equation (ASTM 2002):

$$\text{specific gravity} = \text{oven dry weight (g)} \div \text{buoyant force (g)}$$

#### Data analyses

Total fuel loading for each surface fuel category (1-, 10-, and 100-h woody, duff and litter) was calculated and averaged across plot samples for each of the 25 sites. Regression was used to determine the relationships between both fuel loading and depth with time since mastication. Because woody decomposition typically follows a negative exponential pathway, we used a natural log-transformation on the surface fuel mass to fit the relationship between fuel load and time since treatment for each of the fuel size classes as well as for total fuel load. Hence, we examine the relationship between surface fuel load and time since treatment as the equation:

$$\ln(y) = a + b \times x$$

Therefore,

$$y = e^{(a+b \times x)}$$

where  $y$  = woody surface fuel mass ( $\text{Mg ha}^{-1}$ ) at time  $x$  (years),  $a$  = the initial surface fuel mass ( $\text{Mg ha}^{-1}$ ),  $b$  = the constant of the exponential model and  $x$  = the time since treatment (years). To further explore potential drivers of decomposition with time since treatment, models predicting total surface fuel mass by time since treatment included metrics of mean annual precipitation (mm) and mean annual temperature ( $^{\circ}\text{C}$ ) and the interaction between the two as covariates. Only significant predictors were retained to arrive at the simplest model. Results from this analysis are graphically displayed as untransformed metrics for clarity and simplicity. The model and assumptions of homoscedasticity and equal variance were evaluated using diagnostic plots in *R* statistical software (R Core team 2018). To examine particle size class dynamics in masticated surface fuels over time, we also tested the relationship between the proportion of 1-h fuels and time since treatment.

**Table 1. Description of masticated study sites in northern California and southern Oregon**

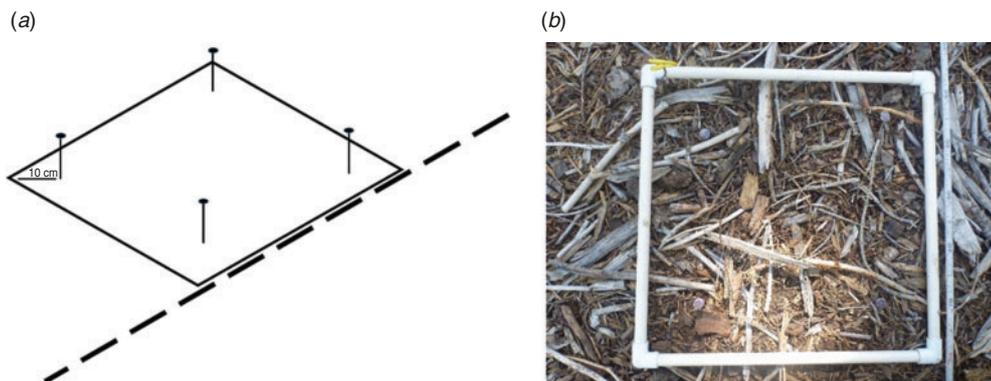
Identification numbers are arranged from north to south and correspond to points in Fig. 2. Treatment equipment identified from managers: BM, boom-mounted; FE, front-end-mounted; RB, rotary blade; RD, rotary drum

ID	Site name	Time since treatment (years)	Latitude	Longitude	Location	Elevation (m)	Average annual precipitation (mm)	Average annual temperature (°C)	Treatment equipment
1	APP	9	42°17'14.58"N	123°0'22.32"W	Applegate Valley, OR (BLM)	764	671	10.8	BM/RB slashbuster brushcutter on John Deere 690E-LC
2	APP04	10	42°17'13.32"N	122°59'3.00"W	Applegate Valley, OR (BLM)	720	648	10.9	BM/RB slashbuster brushcutter on John Deere 690E-LC
3	BLM06	8	42°16'26.64"N	122°59'6.60"W	Applegate Valley, OR (BLM)	674	663	11.1	BM/RB slashbuster brushcutter on John Deere 690E-LC
4	APP01	13	42°14'26.76"N	123°1'0.18"W	Applegate Valley, OR (BLM)	565	672	11.6	BM/RB slashbuster brushcutter on John Deere 690E-LC
5	APP98	16	42°13'12.12"N	122°56'58.74"W	Applegate Valley, OR (BLM)	816	665	10.6	BM/RB slashbuster brushcutter on John Deere 690E-LC
6	MFR	11	41°22'6.06"N	122°18'58.92"W	Shasta-Trinity National Forest (USFS)	1348	1105	10.6	FE/RD Rayco forestry mower (small) on a bulldozer
7	TAY	9	41°10'7.20"N	123°0'33.48"W	Klamath National Forest, CA (USFS)	1756	1598	8.3	BM/RD Brontosaurus head on an excavator
8	TRN	8	41°9'59.28"N	122°59'49.62"W	Klamath National Forest, CA (USFS)	1741	1598	8.1	BM/RD Brontosaurus head on excavator
9	SHL	4	40°51'7.74"N	122°24'8.94"W	Shasta-Trinity National Forest, CA (USFS)	441	1752	15.7	BM/RB Slashbuster masticator head on Komatsu PC160 track excavators
10	SHL2	10	40°46'34.02"N	122°20'22.50"W	Shasta-Trinity National Forest, CA (USFS)	411	1669	16.0	BM/RB masticator head on Komatsu PC160 track excavators
11	WHI	12	40°38'30.78"N	122°35'55.62"W	Whiskeytown National Recreation Area, CA (NPS)	382	1390	14.8	FE/RB Slashbuster on ASV Positrack
12	IMR	11	40°38'15.42"N	122°27'25.56"W	Redding, CA (BLM)	237	1312	16.8	FE/RD masticating head on ASV Positrack
13	HF07	7	40°29'30.72"N	123°7'4.14"W	Shasta-Trinity National Forest, CA (USFS)	1048	1104	10.9	FE/RD Magnum masticating head on ASV Posi-trac RC-100
14	HF09	6	40°28'26.70"N	123°9'13.08"W	Shasta-Trinity National Forest, CA (USFS)	839	1146	11.3	FE/RD Magnum masticating head on ASV Posi-trac RC-100
15	VAN	2	40°25'54.72"N	123°31'5.70"W	Six Rivers National Forest, CA (USFS)	851	1588	11.6	FE/RD Takeuchi, TL150 with FECON Bullhog shredder head
16	SFR	11	39°33'20.52"N	120°14'31.68"W	Tahoe National Forest, CA (USFS)	2040	883	6.4	FE/RD Rayco forestry mower (small) on a bulldozer
17	ERR	2	39°9'0.54"N	120°46'21.54"W	Tahoe National Forest, CA (USFS)	1280	1468	13.4	BM/RD Fecon head on an excavator
18	SPR11	3	39°7'39.72"N	120°46'44.22"W	Tahoe National Forest, CA (USFS)	1151	1468	13.6	BM/RD Fecon head on an excavator
19	EOW12	2	39°2'33.72"N	120°35'8.94"W	Tahoe National Forest, CA (USFS)	1517	1693	12.0	Information not available
20	DLB	6	38°59'5.46"N	120°6'3.24"W	Lake Tahoe Basin Management Unit, CA (USFS)	2013	936	6.6	BM/RD Fecon head on John Deere excavator
21	EMB	6	38°56'38.70"N	120°6'0.66"W	Lake Tahoe Basin Management Unit, CA (USFS)	2083	990	6.5	BM/RD Fecon head on John Deere excavator
22	SLT13	1	38°54'26.22"N	119°58'17.94"W	Lake Tahoe Basin Management Unit, CA (USFS)	1951	815	7.1	BM/RD Fecon head on John Deere excavator
23	FLL07	7	38°55'13.86"N	120°3'2.10"W	Lake Tahoe Basin Management Unit, CA (USFS)	1926	669	7.0	BM/RD Fecon head on John Deere excavator
24	STA	11	38°5'18.48"N	120°19'19.32"W	Stanislaus National Forest, CA (USFS)	860	961	14.2	BM/RD Environmental Forestry head on excavator
25	JD09	6	37°34'0.30"N	119°53'1.44"W	Sierra National Forest, CA (USFS)	1316	1057	13.2	BM/RB slashbuster head RH3748 on Volvo VE 0247 excavator

**Table 2. Species present of the residual vegetation from visual assessments within the masticated sites sampled in this study listed alphabetically (not in order of abundance or dominance)**

ID numbers correspond to location of mapped sites in Fig. 2

ID	Site	Residual tree and shrub species in treatment	Treated and targeted vegetation
1	APP	<i>Arbutus menziesii</i> , <i>Arctostaphylos viscida</i> , <i>Quercus garryana</i> , <i>Quercus kelloggii</i>	Understorey shrubs/midstorey trees
2	APP04	<i>A. menziesii</i> , <i>A. viscida</i> , <i>Q. garryana</i> , <i>Q. kelloggii</i>	Understorey shrubs/midstorey trees
3	BLM06	<i>A. menziesii</i> , <i>Pinus ponderosa</i> , <i>Pseudotsuga menziesii</i> , <i>Q. kelloggii</i>	Understorey shrubs/midstorey trees
4	APP01	<i>A. menziesii</i> , <i>A. viscida</i> , <i>Ceanothus cuneatus</i> , <i>P. ponderosa</i> , <i>Q. garryana</i>	Understorey shrubs
5	APP98	<i>A. menziesii</i> , <i>A. viscida</i> , <i>P. ponderosa</i> , <i>P. menzeisii</i> , <i>Q. garryana</i>	Understorey shrubs/midstorey trees
6	MFR	<i>P. ponderosa</i>	Understorey shrubs
7	TAY	<i>Abies concolor</i> , <i>Calocedrus decurrens</i> , <i>C. velutinus</i> , <i>Pinus jeffreyi</i> , <i>P. ponderosa</i>	Understorey shrubs/small conifers
8	TRN	<i>Ceanothus velutinus</i> , <i>Arctostaphylos patula</i>	Understorey shrubs
9	SHL	<i>A. viscida</i> , <i>Pinus attenuata</i> , <i>Quercus chrysolepsis</i> , <i>Q. kelloggii</i> , <i>Q. wislizeni</i>	Understorey shrubs
10	SHL2	<i>A. viscida</i> , <i>Pinus sabiniana</i> , <i>Q. chrysolepsis</i> , <i>Q. kelloggii</i>	Understorey shrubs
11	WHI	<i>P. attenuata</i> , <i>Q. kelloggii</i>	Understorey shrubs
12	IMR	<i>A. viscida</i> , <i>Heteromeles arbutifolia</i> , <i>P. attenuata</i> , <i>P. ponderosa</i>	Understorey shrubs
13	HF07	<i>Pinus lambertiana</i> , <i>P. ponderosa</i> , <i>P. menziesii</i> , <i>Q. chrysolepsis</i> , <i>Q. garryana</i>	Understorey shrubs/midstorey trees/small conifers
14	HF09	<i>P. ponderosa</i> , <i>Q. garryana</i>	Understorey shrubs/midstorey trees/small conifers
15	VAN	<i>Q. garryana</i> , <i>Q. kelloggii</i>	Understorey shrubs
16	SFR	<i>P. jeffreyi</i> , <i>P. ponderosa</i>	Understorey shrubs
17	ERR	<i>C. decurrens</i> , <i>P. ponderosa</i> , <i>P. menziesii</i> , <i>Q. kelloggii</i>	Understorey shrubs/small conifers
18	SPR11	<i>A. menziesii</i> , <i>C. decurrens</i> , <i>P. ponderosa</i> , <i>P. menziesii</i> , <i>Q. kelloggii</i>	Understorey shrubs/small conifers
19	EOW12	<i>A. concolor</i> , <i>C. decurrens</i> , <i>P. lambertiana</i> , <i>P. ponderosa</i> , <i>P. menziesii</i>	Understorey shrubs
20	DLB	<i>A. concolor</i> , <i>P. jeffreyi</i> , <i>P. lambertiana</i> , <i>Pinus monticola</i>	Small conifers
21	EMB	<i>A. concolor</i> , <i>P. jeffreyi</i> , <i>P. lambertiana</i>	Small conifers
22	SLT13	<i>A. concolor</i> , <i>Pinus contorta</i> , <i>P. jeffreyi</i> , <i>Purshia tridentata</i>	Small conifers
23	FLL07	<i>Artemesia tridentata</i> , <i>A. concolor</i> , <i>P. jeffreyi</i> , <i>P. tridentata</i>	Small conifers
24	STA	<i>P. ponderosa</i>	Understorey shrubs
25	JD09	<i>C. decurrens</i> , <i>P. lambertiana</i> , <i>P. ponderosa</i> , <i>Q. chrysolepsis</i>	Small conifers

**Fig. 3.** (a) Diagram of sampling frame and metal pins for estimating fuel depth. (b) Photograph of 0.5 × 0.5-m sampling frame and pins in masticated fuels.

The relationship of litter and duff over time since treatment was also fitted with non-transformed simple linear models as it was unclear whether decomposition or deposition might predominate.

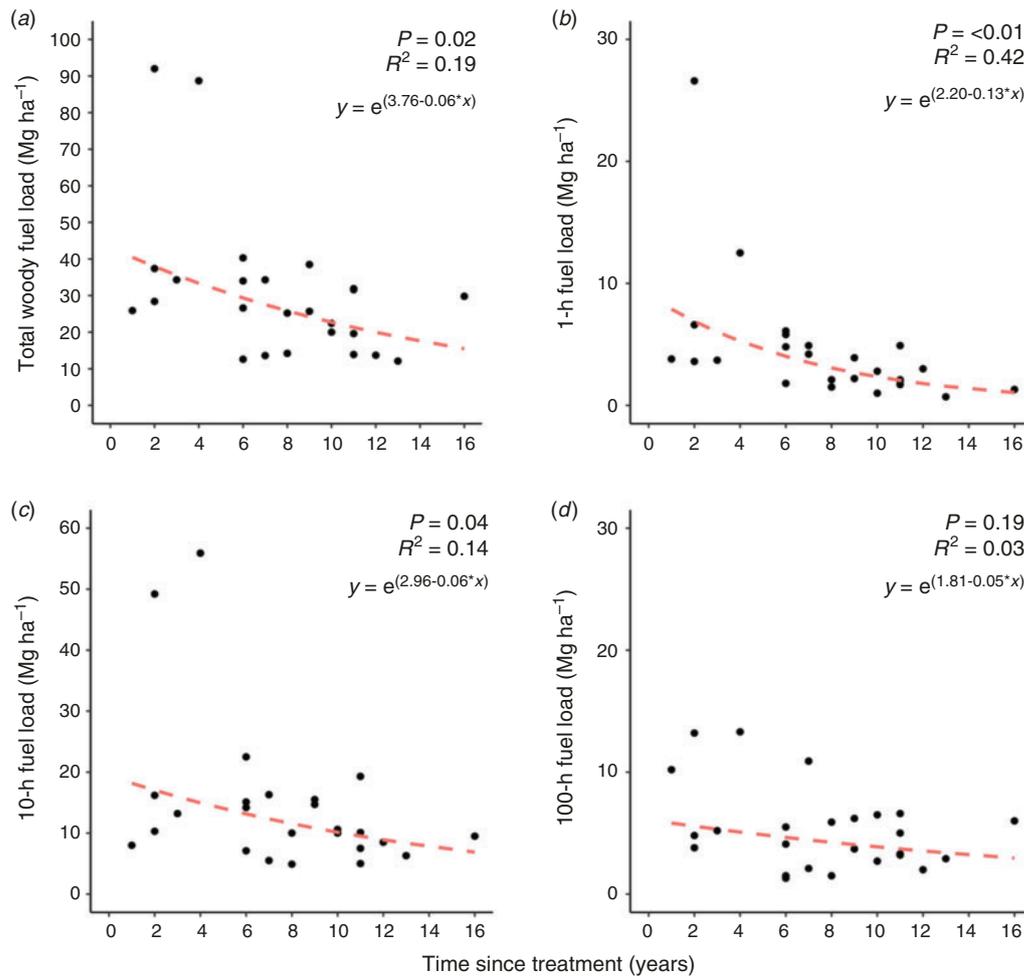
To overcome some of the issues with chronosequence or space-for-time studies, we capitalised on 7 of the 25 sites that were previously measured by Kane *et al.* (2009). At these seven sites, paired comparisons were made between data collected in 2005 or 2006, and then again in 2014. Changes in woody fuel particle specific gravity, loading (by timelag category), and depths were compared among the seven sites using one-tailed *t*-tests, assuming a reduction due to decomposition. For litter and duff loading, a

two-tailed *t*-test was used based on the assumption that additional inputs occurred since treatment, maintaining the possibility of detecting changes in two directions (post-treatment inputs *v.* losses due to decomposition). Statistical significance for all analyses was determined using  $\alpha \leq 0.05$ .

## Results

### Twenty-five sites across the region

Overall woody fuel loading and loading by timelag class varied widely across the 25 sites. Total downed woody fuel loading



**Fig. 4.** The relationship between (a) total woody fuel load; (b) 1-h woody fuel load; (c) 10-h woody fuel load; (d) 100-h woody fuel load, and time since mastication across 25 sites in northern California and southern Oregon.

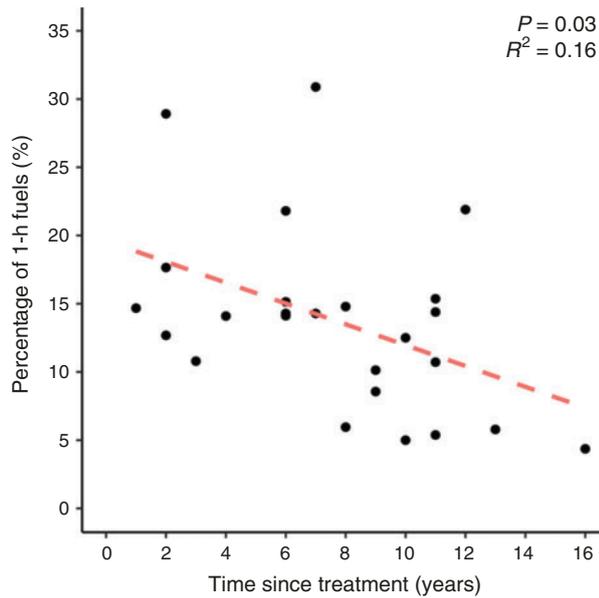
ranged from 12.1 to 91.9 Mg ha<sup>-1</sup> and averaged 30.6 Mg ha<sup>-1</sup>. Two of the 25 sites, Van Duzen (VAN) and Shasta Lake (SHL), had particularly high fuel loading (88.7 and 91.9 Mg ha<sup>-1</sup>) whereas the remaining 23 sites were considerably lower (12.1 to 40.3 Mg ha<sup>-1</sup>; Appendix 1). The 1-h fuel loads varied by two orders of magnitude, ranging from 0.7 to 26.6 Mg ha<sup>-1</sup>, while the 10-h fuels ranged from 5.0 to 55.9 Mg ha<sup>-1</sup> across the 25 sites. The 100-h fuels were somewhat less abundant than the other size classes, ranging from 1.3 to 13.3 Mg ha<sup>-1</sup>. As is commonly found within masticated fuelbeds, 1000-h fuels were somewhat rare and highly variable. The 1000-h fuels ranged from 0.1 to 21.5 Mg ha<sup>-1</sup> at the 25 sites. Litter and duff loading followed similar patterns and had substantial variation across study sites. Litter ranged from 4.8 to 22.0 Mg ha<sup>-1</sup> while duff ranged the widest of any individual category from 1.7 to 68.3 Mg ha<sup>-1</sup> (Appendix 1).

Total fuel loading across all sites was significantly and negatively related to time since treatment, as expected, but the relationship explained only a small portion of the variation ( $P = 0.02$ ,  $R^2 = 0.19$ ). From this model of total fuel loads, we infer a 6% year<sup>-1</sup> loss on average of the initial fuel mass (Fig. 4a). When we attempted to explain potential causes of the variation in fuel loading among sites by including mean annual temperature

and mean annual precipitation and their interaction as covariates in the model, none of the additions were significant ( $P = 0.81$ , 0.76, 0.69 respectively) or improved model fit.

Following the overall trend, loading within the 1-h woody time lag fuels was negatively related to time since treatment and this relationship explained the most variance of any fuel size class ( $P < 0.01$ ,  $R^2 = 0.42$ ). The trend of 10-h fuel woody loading followed a similar pattern and decreased with time since treatment ( $P = 0.04$ ,  $R^2 = 0.14$ ). The 100-h fuels did not demonstrate a decrease in woody fuel mass over time since treatment ( $P = 0.12$ ) (Fig. 4).

As smaller woody particles are expected to decay faster than larger ones, another measure of decay is a change in the relative proportion among size classes over time. The proportion of 1-h woody fuels within fuelbeds declined as time since mastication increased ( $P = 0.03$ ,  $R^2 = 0.16$ ; Fig. 5). The specific gravity of fuels across the 25 sites was also hypothesised to decrease with decay over time. Surprisingly, the relationship between specific gravity and time since treatment was not statistically significant for any of the fuel size classes, although 1-h fuels approached significance ( $P = 0.05$ , 0.50 and 0.32 for 1-, 10- and 100-h fuels respectively).



**Fig. 5.** Percentage of 1-h fuels in fuel beds and time since mastication across 25 sites in northern California and southern Oregon.

Woody and litter fuelbed depths were measured collectively at all sites and averaged 7.3 cm and ranged from 3.9 to 12.5 cm. Counter to the hypothesised trend that total fuelbed depths would decrease as time since mastication increased, no significant relationship between fuelbed depth and time since treatment was found ( $P = 0.19$ ). The depth of duff averaged 2.3 cm and ranged from 0.3 to 4.6 cm.

#### Changes in masticated fuels 2005 to 2014: Remeasured sites

In the seven remeasured sites, total masticated woody fuel loads lost 20% of their mass over the 8- to 9-year period between sampling, or  $\sim 2\%$  year<sup>-1</sup> but the rate of loss varied with particle size. Within sites, 1-h fuels decreased by an average of 7.1 Mg ha<sup>-1</sup>, reflecting a 69% reduction over time, or  $\sim 8\%$  year<sup>-1</sup>; all seven sites decreasing significantly (Table 3). The 10-h fuel loading decreased by 5.7 Mg ha<sup>-1</sup>, corresponding to a 33% reduction, or  $\sim 4\%$  year<sup>-1</sup>. Although 10-h loading numbers became smaller over time at all sites, only the decreases at SFR and WHI were statistically significant (Table 3). In the 100-h size class, no differences in loading were detected between 2005 and 2014 sampling efforts (Table 3).

In contrast to results from the 25-site chronosequence, specific gravity of all woody particle sizes was markedly reduced between 2005 and 2014, with rates of loss highest for the smaller size classes (Fig. 6). On average, the specific gravity of 1-h fuel particles decreased by 23% ( $t = 12.13$ ,  $P < 0.01$ ), 10-h fuel particles decreased by 20% ( $t = 12.91$ ,  $P < 0.01$ ), and 100-h fuel decreased by 13% ( $t = 2.93$ ,  $P < 0.01$ ). Specific gravity declines were significant for all particle sizes at all sites, with the exception of the 100-h fuels at APP and TAY ( $P = 0.76$ , 0.79 respectively).

Litter and duff changes in the remeasured masticated sites were less pronounced than changes in woody fuels. Litter loading at the seven sites increased by an average of 2.8 Mg ha<sup>-1</sup> across sites (Table 4). Litter loading increases were significant at four of the

**Table 3.** Mean surface 1-, 10- and 100-h fuel loading ( $\pm$ s.e.) changes over a period of 9 years (8 at STA) at seven remeasured sites treated with fuel mastication

For each site and sampling period, averages were calculated from 15 microplots. %  $\Delta$  represents the percent change; \* designates statistical significance

Site	1-h 2005–06 (Mg ha <sup>-1</sup> )	1-h 2014 (Mg ha <sup>-1</sup> )	$\Delta$ (Mg ha <sup>-1</sup> )	% $\Delta$	$t$ ratio	$P$ value
APP	12.3 (2.8)	2.2 (0.4)	-10.1	-82%	3.56	0.0015*
IMR	6.2 (1.7)	2.1 (0.5)	-4.1	-66%	2.29	0.0175*
MFR	4.7 (1.1)	2.0 (0.6)	-2.7	-57%	2.20	0.0190*
SFR	5.2 (0.9)	1.7 (0.3)	-3.5	-67%	3.53	0.0014*
STA	15.7 (1.7)	4.8 (1.2)	-10.9	-69%	5.13	0.0001*
TAY	13.2 (2.9)	3.9 (0.8)	-9.3	-70%	3.12	0.0033*
WHI	11.8 (2.4)	3.0 (0.7)	-8.8	-75%	3.55	0.0013*
Average	7.7 (0.8)	2.2 (0.2)	-7.1	-69%		

Site	10-h 2005–06 (Mg ha <sup>-1</sup> )	10-h 2014 (Mg ha <sup>-1</sup> )	$\Delta$ (Mg ha <sup>-1</sup> )	% $\Delta$	$t$ ratio	$P$ value
APP	24.6 (4.9)	14.7 (3.4)	-9.9	-40%	1.65	0.0559
IMR	13.8 (4.0)	10.1 (2.3)	-3.7	-27%	0.80	0.2151
MFR	8.2 (2.2)	7.5 (2.1)	-0.7	-9%	0.23	0.4109
SFR	11.1 (2.3)	5.0 (1.1)	-6.1	-55%	2.43	0.0123*
STA	25.0 (3.3)	19.4 (4.1)	-5.6	-22%	1.07	0.1481
TAY	21.7 (4.4)	15.5 (5.6)	-6.2	-29%	0.87	0.1968
WHI	16.4 (2.9)	8.5 (1.7)	-7.9	-48%	2.35	0.0139*
Average	13.4 (1.3)	9.0 (1.1)	-5.7	-33%		

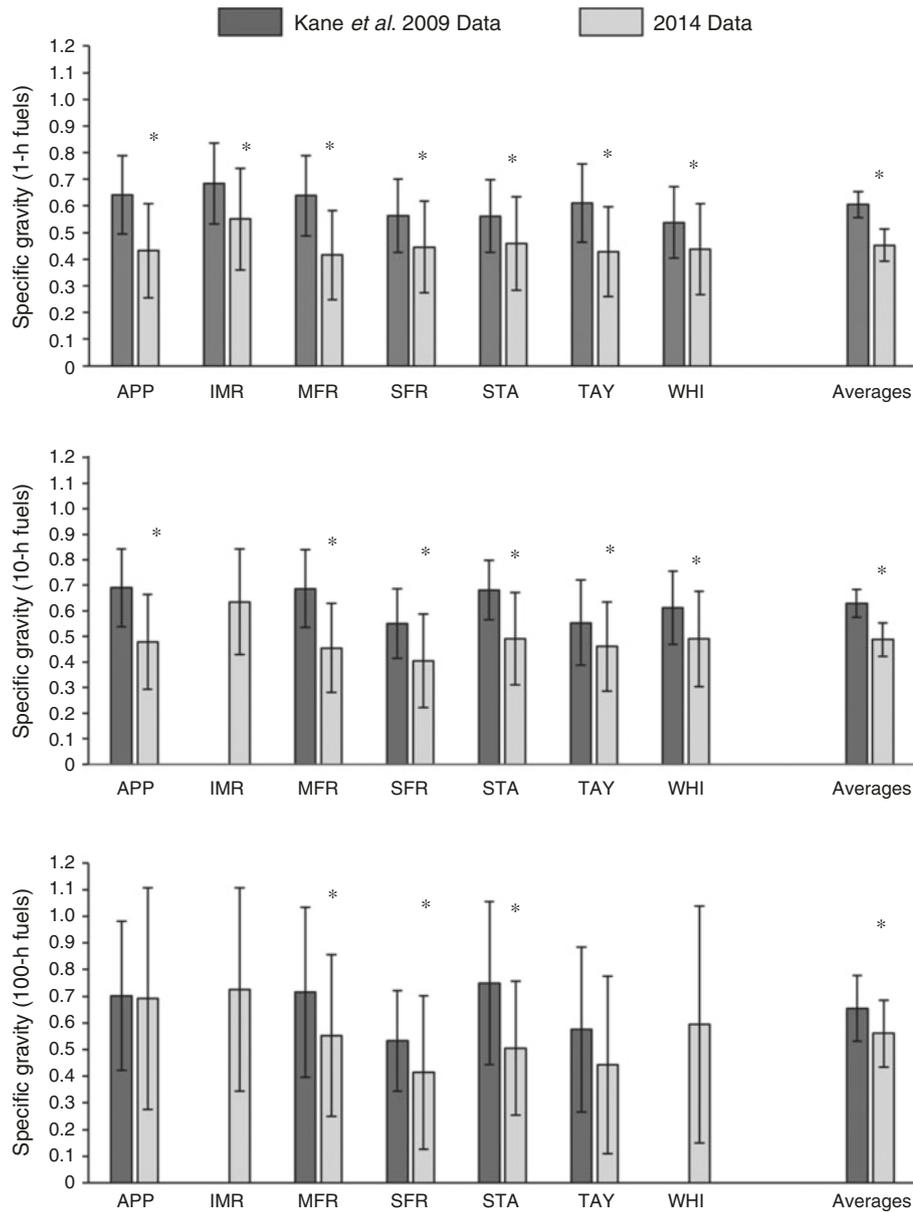
Site	100-h 2005– 06 (Mg ha <sup>-1</sup> )	100-h 2014 (Mg ha <sup>-1</sup> )	$\Delta$ (Mg ha <sup>-1</sup> )	% $\Delta$	$t$ ratio	$P$ value
APP	8.6 (4.8)	6.4 (2.7)	-2.2	-26%	0.44	0.6686
IMR	3.6 (1.6)	5.0 (2.0)	+1.6	+44%	-0.56	0.7104
MFR	1.3 (2.2)	3.2 (1.4)	+1.9	+146%	-1.23	0.8839
SFR	6.6 (2.9)	3.3 (1.8)	-3.3	-50%	0.95	0.1753
STA	4.8 (1.6)	6.6 (3.0)	+1.8	+38%	-0.54	0.7019
TAY	2.1 (0.8)	3.7 (2.4)	+1.6	+76%	-0.61	0.7235
WHI	3.5 (1.5)	2.0 (1.2)	-1.5	-43%	0.79	0.2187
Average	3.4 (0.7)	3.3 (0.6)	-0.2	+26%		

seven sites (IMR, SFR, MFR, WHI), with increases ranging from 96 to 524% over the period between sampling. There were no changes in duff loading over time at any of the seven sites. Fuelbed depth (litter and woody measured together) increased significantly in three of the seven remeasured sites (MFR, SFR, and STA) and did not change in the remaining four (Table 5).

## Discussion

### Site level fuel loading

Mastication treatments have become more widely used in fire-prone landscapes to mitigate fire hazard and fire spread. The conversion of live fuels to dead woody surface fuels, however, may pose a management concern (Knapp *et al.* 2011; Kreye *et al.* 2014a), particularly where these fuels persist for long durations. Results from the present study corroborate previous findings of highly variable and in many cases heavy downed woody fuel loading across 25 sites that spanned up to 16 years since treatments (12.1 to 92.0 Mg ha<sup>-1</sup>). Some of the variability across sites was attributed to time since treatment, suggesting



**Fig. 6.** Mean site-level changes in fuel particle specific gravity  $\pm$  s.e. of the mean from remeasured sites. Absence of bars represents missing data: (a) 1-h; (b) 10-h; (c) 100-h fuels.

potential mass loss to decomposition. In other western coniferous forests, masticated fuel loading has been reported to range from 15.3 to 63.4 Mg ha<sup>-1</sup> (Hood and Wu 2006; Kane *et al.* 2009; Reiner *et al.* 2009; Battaglia *et al.* 2010). Research in south-eastern US pine forests reported even wider ranges in fuel loading, from 9.6 up to 192.4 Mg ha<sup>-1</sup> (Glitzenstein *et al.* 2006; Kreye *et al.* 2014b; Stottlemeyer *et al.* 2015). Despite differences in overall loading, fuel loads across those studies were generally concentrated in the finer 1- and 10-h fuel size classes, similarly to our results.

The wide variation in loading and composition of masticated woody surface fuels was likely due to differences in the species targeted for mastication, site productivity, mastication method

and time since last disturbance. Degree of shading by overstorey trees may also have been a factor, both by influencing the volume of shrubs and other understorey vegetation before treatment (many of the targeted shrubs are intolerant of shade), and the environment for decomposition post treatment. Sampling methodologies also vary across studies, which could potentially explain some of the differences, e.g. planar intercept sampling may not be as accurate as destructive sampling of masticated fuels (Kane *et al.* 2009). The results from the current study, however, are generally consistent with other findings where surface fuel loads resulting from mastication are variable, but often heavy, and are primarily composed of finer fuels (litter, 1-h, and 10-h fuels).

**Table 4. Mean surface litter and duff fuel loading ( $\pm$ s.e.) changes at seven remeasured sites treated with fuel mastication**

For each site and sampling period, averages were calculated from 15 micro-plots. %  $\Delta$  represents the percent change; \* designates statistical significance

Site	Litter 2005–06 (Mg ha <sup>-1</sup> )	Litter 2014 (Mg ha <sup>-1</sup> )	$\Delta$ (Mg ha <sup>-1</sup> )	% $\Delta$	<i>t</i> ratio	<i>P</i> value
APP	10.3 (2.8)	6.9 (1.3)	-3.4	-33%	1.07	0.1473
IMR	2.6 (0.6)	5.1 (0.9)	+2.5	+96%	-2.17	0.0394*
MFR	2.1 (1.8)	13.1 (2.0)	+11.0	+524%	-4.95	0.0001*
SFR	5.4 (1.5)	10.6 (1.4)	+5.2	+96%	-2.56	0.0161*
STA	9.9 (1.0)	8.2 (1.0)	-1.7	-17%	1.24	0.2269
TAY	6.2 (1.3)	8.2 (1.3)	+2.0	+32%	-1.08	0.2908
WHI	3.3 (0.7)	7.2 (1.4)	+3.9	+118%	-2.57	0.0179*
Average	5.8 (0.6)	8.5 (0.5)	+2.8			

Site	Duff 2005–06 (Mg ha <sup>-1</sup> )	Duff 2014 (Mg ha <sup>-1</sup> )	$\Delta$ (Mg ha <sup>-1</sup> )	% $\Delta$	<i>t</i> ratio	<i>P</i> value
APP	6.7 (3.1)	4.4 (0.8)	-2.3	15.95	0.73	0.4770
IMR	7.5 (3.1)	9.1 (3.1)	+1.6	27.99	-0.36	0.7212
MFR	15.0 (3.7)	13.7 (2.4)	-1.3	23.75	0.28	0.7827
SFR	5.7 (2.1)	13.7 (3.9)	+8.0	21.64	-1.80	0.0866
STA	25.9 (4.0)	21.6 (3.6)	-4.3	27.77	0.80	0.4317
TAY	32.7 (7.3)	45.2 (12.0)	+12.5	23.25	-0.89	0.3831
WHI	7.0 (1.5)	6.1 (1.4)	-0.9	27.77	0.42	0.6778
Average	14.4 (1.8)	16.3 (2.3)	+1.9			

**Table 5. Mean woody and litter depth ( $\pm$ s.e.) changes at seven remeasured sites treated with fuel mastication**

For each site and sampling period, averages were calculated from 15 micro-plots. \* designates statistical significance

Site	Litter and woody depth 2005–06 (cm)	Litter and woody depth 2014 (cm)	<i>t</i> ratio	<i>P</i> value
APP	6.9 (0.8)	7.6 (0.5)	-0.7025	0.4892
IMR	4.9 (0.8)	5.1 (0.7)	-0.1993	0.8435
MFR	3.0 (0.4)	6.4 (0.5)	-5.7252	<0.0001*
SFR	3.1 (0.5)	6.0 (0.6)	-3.7425	0.0009*
STA	5.2 (0.5)	10.1 (0.6)	-6.0663	<0.0001*
TAY	5.0 (0.6)	6.0 (0.7)	-1.0751	0.2915
WHI	5.8 (0.6)	7.7 (0.8)	-1.9655	0.0650

### Downed woody fuel loading over time

Brennan and Keeley (2015) noted a significant negative relationship between fuel loading and time across 148 masticated sites in southern California chaparral ranging 0 to 8 years since treatment, and though we sampled fewer sites, our study lengthens this monitoring duration. In our study, woody particle size categories at seven remeasured sites lost between 2 and 8% of their weight year<sup>-1</sup> over an 8–9-year period. The lowest percentage loss was for all woody fuel combined, suggesting that some of the losses from larger fuel particle categories may have been due to further fracturing into smaller particles over time. The 16-year, 25-site time-since-treatment chronosequence suggested a 6% year<sup>-1</sup> loss for all masticated woody fuels combined. Although numbers from both the 25 sites and the 7

site remeasurement were in a similar range, the loss rate from the chronosequence is hampered by additional sources of variability besides time, and the seven-site comparison by relatively low sample size. In the chronosequence, two sites with the highest fuel loading disproportionately impacted this relationship (Appendix 1). Had the duration of the chronosequence been long relative to the rate of decay, a stronger relationship might have been expected. That older sites still contained abundant woody surface fuels illustrates the slow process of decay in these seasonally dry Mediterranean climate landscapes and the long duration over which elevated surface fuel loading resulting from mastication might remain a concern. The estimate of 2–6% loss of all masticated woody material combined per year for the two approaches, although imperfect, is still a useful range for these plant communities, soils and climate.

Comparisons between plots sampled in both 2005–2006 (Kane *et al.* 2009) and 2014 reveal a strong relationship between particle size and decomposition rate, with the 1-h fuel size class losing ~8% year<sup>-1</sup> and the 10-h fuel size losing ~4% year<sup>-1</sup>. This reduction was due to both a decline in number of fuel particles and decline in specific gravity of those remaining. Both particle number and specific gravity losses were highest for smaller particles and lowest for larger particles, as expected. This is in contrast to what others have found in regard to the decomposition of logging slash. Across multiple forest types in Washington, USA, Erickson *et al.* (1985) reported faster decomposition in larger particles, possibly because they retained moisture longer into the warm and dry season. Wood decomposition is generally most rapid when conditions are warm and moist (Edmonds *et al.* 1986). Differing observations in masticated fuelbeds compared with intact and unshredded particles may be attributed to numerous factors. In a laboratory study, Kreye *et al.* (2012) found that fuelbed compaction caused by mastication slowed the rate of moisture loss. Moisture retention could make water (a limiting factor for decomposition) more available during the late spring and early summer when temperatures rise. Masticated fuelbeds in the present study were also composed of smaller-diameter particles, and therefore expected to dry more rapidly after rainfall events than the slash fuelbeds studied by Erickson *et al.* (1985). As fuel particle size decreases, the surface area-to-volume ratios increase (Fasth *et al.* 2011), setting the stage for more biotic and chemical interactions required for decomposition on the particle substrate. Additionally, the fractured nature of masticated particles could play a larger role than was explored within this study. The novelty of this aspect of masticated fuelbeds has been noted by others (Keane *et al.* 2018). The limited research on and management relevance of decomposition dynamics of masticated fuels highlight an important research need in the region and beyond (Kreye *et al.* 2014a).

Although fuel loading in the 25-site chronosequence decreased significantly over time, a substantial amount of variability remained unexplained, illustrating the challenges associated with space-for-time or chronosequence approaches (Johnson and Miyanishi 2008) especially across highly variable landscapes and among fuel complexes that differ for many reasons other than time. Increasing the sample size and increasing the duration of the chronosequence would further improve estimates of decomposition rates. The changes seen in the seven

remeasured sites are likely more definitive and strengthen the conclusions.

The species targeted for mastication likely contribute to variability in both fuel loading (Kane *et al.* 2009) and decomposition rates. At some sites, the masticated vegetation consisted mainly of shrubs, whereas at other sites, conifer ladder fuels were primarily targeted. The wood of shrubs and conifers varies in specific gravity and rates of decomposition. Higher lignin concentrations have been associated with slower rates of leaf litter decomposition (Gartner and Cardon 2004) and high lignin : nitrogen ratios have been found to stall or inhibit litter and wood decomposition processes (e.g. Melillo *et al.* 1982; Edmonds 1987). Variation in lignin concentration and initial wood density of different masticated species may play a role in masticated woody fuelbed decomposition as well. More long-term studies where vegetative volume is documented by species both pre- and post-mastication treatment, and the stoichiometry as well as specific gravity of targeted vegetation quantified, will increase our understanding of the persistence and decomposition of these novel fuelbeds.

#### *Management implications*

Although masticated fuel loads decreased over time, these woody fuels are slow to decompose in summer dry environments like the ones studied here. Findings from the majority of sites suggest that high surface fuel loads can remain for many years following treatment. Management goals that include reducing vertical fuel continuity to avoid crown fire initiation may be met with masticated treatments alone, but the trade-off of persistent surface fuels could limit effectiveness for improving forest resilience to wildfire (Busse *et al.* 2005; Knapp *et al.* 2011), at least in the short to intermediate term. In particular, where shrubs resprout or tree regeneration occurs quickly following treatments, the combination of recovering understorey vegetation growing over persistent high dead surface fuel loading may pose a fire hazard (Kane *et al.* 2010; Brennan and Keeley 2015). Past fire effects modelling for wildfires burning under typical dry summer conditions have predicted that substantial overstorey tree mortality is probable in masticated treatments. The average fuel loading of 30.6 Mg ha<sup>-1</sup> in mastication-only sites found in this study was similar to loadings reported for untreated long-unburned stands of California yellow pine and mixed-conifer forests (34.0 Mg ha<sup>-1</sup>) that experienced stand-replacing severity in wildfires (Safford *et al.* 2012). In the latter study, adjacent stands with reduced fuel loading (14.1 Mg ha<sup>-1</sup>) as a result of mechanical treatment in combination with prescribed fire or pile burning experienced far lower severities. Until the woody material decomposes, masticated treatments may be more effective at moderating fire spread rates and improving access for firefighters than increasing stand resilience (Knapp *et al.* 2011).

It is presumed that the decay of masticated woody fuels and the assumed compaction that transpires will diminish potential fire behaviour in masticated fuelbeds over time (Kreye *et al.* 2014a). Results from the 25-site chronosequence and the 7-site remeasurement comparisons show that the smaller the fuel particle diameter, the faster the rate of decomposition. However, some of the re-measured sites experienced substantial increases

in litter and fuelbed depth over time, which could potentially partially negate the expected dampening effect of fine fuel decomposition. Fine litter fuels over the top of a masticated fuelbed can increase rates of fire spread and lead to a wide flaming zone, which has the potential to increase crown scorching (Knapp *et al.* 2011; Kreye *et al.* 2013). This may be especially important in sites with residual pine overstories, where substantial annual needle cast would be expected.

Because masticated woody fuels may persist for long periods, especially in dry forests and woodlands, future treatments may benefit from tailoring operational or mechanical aspects of mastication to increase decomposition rates or by using supplemental fuels treatments such as prescribed fire. The size class distribution of masticated fuel particles is generally a function of the vegetation treated, the prescription (i.e. spatial arrangement and intensity of treatment), equipment used and operator effort (Kane *et al.* 2009; Vitorelo *et al.* 2009). Results from the present study suggest that masticated fuelbeds that are proportionally composed of more 1-h fuels are likely to have an accelerated rate of decomposition, reducing fuel loads and alleviating wildfire risk to residual forest in a shorter period of time. However, tailoring mastication prescriptions to produce smaller-diameter fuels can lead to higher operational costs (Lyon *et al.* 2018). Follow-up prescribed fire treatments would eliminate the dependence on decomposition to more fully alleviate fire hazard.

#### **Conflicts of interest**

The authors declare no conflicts of interest.

#### **Acknowledgements**

An earlier draft of the manuscript benefitted from feedback provided by C. Copenheaver. We are grateful for the helpful comments from the three anonymous reviewers that helped improve this manuscript. This research was supported in part by funds provided by the USDA and the USDI Joint Fire Science Program (Project 12-1-03-31). Assistance with field data collection was provided by G. Hamby, C. Keller and J. Tobia. We appreciate the cooperation of the Sierra, Stanislaus, Tahoe, Lake Tahoe Basin Management Unit, Shasta-Trinity and Klamath National Forests as well as the Medford Bureau of Land Management office for assistance with selecting study sites and providing information about how treatments were implemented. J. Kane provided logistical support and numerous conversations through project development from which this study benefited.

#### **References**

- Abatzoglou JT, Williams AP (2016) Impact of anthropogenic climate change on wildfire across western US forests. *Proceedings of the National Academy of Sciences of the United States of America* **113**, 11770–11775. doi:10.1073/PNAS.1607171113
- Agee JK, Skinner CN (2005) Basic principles of forest fuel reduction treatments. *Forest Ecology and Management* **211**, 83–96. doi:10.1016/J.FORECO.2005.01.034
- ASTM (2002) Standard test methods for specific gravity of wood and wood-based materials, D2395-02. In 'Annual book of ASTM standards', Vol. 4.10, pp. 357–364. (American Society for Testing and Materials: Conshohocken, PA, USA)
- Battaglia MA, Rocca ME, Rhoades CC, Ryan MG (2010) Surface fuel loadings within mulching treatments in Colorado coniferous forests. *Forest Ecology and Management* **260**, 1557–1566. doi:10.1016/J.FORECO.2010.08.004

- Black DE, Arthur MA, Leuenberger W, Taylor DD, Lewis JF (2019) Alteration to woodland structure through midstory mastication increased fuel loading and cover of understory species in two upland hardwood stands. *Forest Science* **65**, 344–354. doi:10.1093/FORSCI/FXY066
- Bradley T, Gibson J, Bunn W (2006) Fire severity and intensity during spring burning in natural and masticated shrub woodlands. In 'Fuels management – how to measure success'. (Eds PL Andrews, BW Butler) USDA Forest Service, Rocky Mountain Research Station, Proceedings RMRS-P-41, pp. 419–428. (Fort Collins, CO, USA)
- Brennan T, Keeley J (2015) Effect of mastication and other mechanical fuel treatments on fuel structure in chaparral. *International Journal of Wildland Fire* **24**, 949–969. doi:10.1071/WF14140
- Brown JK (1974) Handbook for inventorying downed woody material. USDA Forest Service, Intermountain Forest and Range Experiment Station, General Technical Report INT-16. (Ogden, UT, USA)
- Busse MD, Hubbert KR, Fiddler GO, Shestak CJ, Powers RF (2005) Lethal soil temperatures during burning of masticated forest residues. *International Journal of Wildland Fire* **14**, 267–276. doi:10.1071/WF04062
- Busse MD, Shestak CJ, Hubbert KR, Knapp E (2010) Soil physical properties regulate lethal heating during burning of woody residues. *Forest Range and Wildland Soils* **74**, 947–955. doi:10.2136/SSSAJ2009.0322
- Coop JD, Grant TA, Magee PA, Moore EA (2017) Mastication treatment effects on vegetation and fuels in pinon–juniper woodlands of central Colorado, USA. *Forest Ecology and Management* **396**, 68–84. doi:10.1016/J.FORECO.2017.04.007
- Edmonds RL (1987) Decomposition rates and nutrient dynamics in small-diameter woody litter in four forest ecosystems in Washington, USA. *Canadian Journal of Forest Research* **17**, 499–509. doi:10.1139/X87-084
- Edmonds RL, Vogt DJ, Sandberg DH, Driver CH (1986) Decomposition of Douglas-fir and red alder wood in clear-cuttings. *Canadian Journal of Forest Research* **16**, 822–831. doi:10.1139/X86-145
- Erickson HE, Edmonds RL, Peterson CE (1985) Decomposition of logging residues in Douglas-fir, western hemlock, Pacific silver fir, and ponderosa pine ecosystems. *Canadian Journal of Forest Research* **15**, 914–921. doi:10.1139/X85-147
- Fasth BG, Harmon ME, Sexton J, White P (2011) Decomposition of fine woody debris in a deciduous forest in North Carolina. *The Journal of the Torrey Botanical Society* **138**, 192–206. doi:10.3159/TORREY-D-10-00009.1
- Gartner TB, Cardon ZG (2004) Decomposition dynamics in mixed-species leaf litter. *Oikos* **104**, 230–246. doi:10.1111/J.0030-1299.2004.12738.X
- Glitzenstein JS, Streng DR, Achtemeier GL, Naeher LP, Wade DD (2006) Fuels and fire behavior in chipped and unchipped plots: implications for land management near the wildland/urban interface. *Forest Ecology and Management* **236**, 18–29. doi:10.1016/J.FORECO.2006.06.002
- Hood S, Wu R (2006) Estimating fuel bed loadings in masticated areas. In 'Fuels management – how to measure success'. (Eds PL Andrews, BW Butler) USDA Forest Service, Rocky Mountain Research Station, RMRS-P-41, pp. 333–340. (Portland, OR, USA)
- Jain T, Sikkink P, Keefe, R, Byrne, J (2018) To masticate or not: Useful tips for treating forests, woodland, and shrubland vegetation. USDA Forest Service, Rocky Mountain Research Station, General Technical Report RMRS-GTR-381. (Fort Collins, CO, USA)
- Johnson EA, Miyaniishi K (2008) Testing assumptions of chronosequences in succession. *Ecology Letters* **11**, 419–431. doi:10.1111/J.1461-0248.2008.01173.X
- Kane JM, Varner JM, Knapp EE (2009) Novel fuelbed characteristics associated with mechanical mastication treatments in northern California and south-western Oregon, USA. *International Journal of Wildland Fire* **18**, 686–697. doi:10.1071/WF08072
- Kane JM, Varner JM, Knapp EE, Powers RF (2010) Understory vegetation responses to mechanical mastication and other fuels treatments in a ponderosa pine forest. *Applied Vegetation Science* **13**, 207–220. doi:10.1111/J.1654-109X.2009.01062.X
- Keane RE, Sikkink PG, Jain TB (2018) Physical and chemical characteristics of surface fuels in masticated mixed-conifer stands of the US Rocky Mountains. USDA Forest Service, Rocky Mountain Research Station, General Technical Report RMRS-GTR-370. (Fort Collins, CO, USA)
- Knapp EE, Varner JM, Busse MD, Skinner CN, Shestak CJ (2011) Behaviour and effects of prescribed fire in masticated fuelbeds. *International Journal of Wildland Fire* **20**, 932–945. doi:10.1071/WF10110
- Kreye JK, Varner JM, Knapp EE (2012) Moisture desorption in mechanically masticated fuels: effects of particle fracturing and fuelbed compaction. *International Journal of Wildland Fire* **21**, 894–904. doi:10.1071/WF11077
- Kreye JK, Kobziar LN, Zipperer WC (2013) Effects of fuel loading and moisture content on fire behaviour and heating in masticated litter-dominated fuels. *International Journal of Wildland Fire* **22**, 440–445. doi:10.1071/WF12147
- Kreye JK, Brewer NW, Morgan P, Varner JM, Smith AMS, Hoffman CM, Ottmar RD (2014a) Fire behavior in masticated fuels: a review. *Forest Ecology and Management* **314**, 193–207. doi:10.1016/J.FORECO.2013.11.035
- Kreye JK, Kobziar LN, Camp JM (2014b) Immediate and short-term response of understory fuels following mechanical mastication in a pine flatwoods site of Florida, USA. *Forest Ecology and Management* **313**, 340–354. doi:10.1016/J.FORECO.2013.10.034
- Kreye JK, Varner JM, Kane JM, Knapp EE, Reed WP (2016) The impact of aging on laboratory fire behaviour in masticated shrub fuelbeds of California and Oregon, USA. *International Journal of Wildland Fire* **25**, 1002–1008. doi:10.1071/WF15214
- Lyon ZD, Morgan P, Stevens-Rumann CS, Sparks AM, Keefe RF, Smith AMS (2018) Fire behaviour in masticated forest fuels: lab and prescribed fire experiments. *International Journal of Wildland Fire* **27**, 280–292. doi:10.1071/WF17145
- Melillo JM, Aber JD, Muratore JF (1982) Nitrogen and lignin control of hardwood leaf litter decomposition dynamics. *Ecology* **63**, 621–626. doi:10.2307/1936780
- PRISM Climate Group (2004) PRISM Climate Data. Northwest Alliance for Computational Science & Engineering at Oregon State University Available at <http://prism.oregonstate.edu> [verified 27 May 2020].
- Quinn-Davidson LN, Varner JM (2012) Impediments to prescribed fire across agency, landscape and manager: an example from northern California. *International Journal of Wildland Fire* **21**, 210–218. doi:10.1071/WF11017
- R Core Team (2018) A language and environment for statistical computing. (R Foundation for Statistical Computing: Vienna, Austria) Available at <https://www.R-project.org>
- Radeloff VC, Hammer RB, Stewart SI, Fried JS, Holcomb SS, McKeefry JF (2005) The wildland–urban interface in the United States. *Ecological Applications* **15**, 799–805. doi:10.1890/04-1413
- Reiner AL, Vaillant NM, Fites-Kaufman J, Dailey SN (2009) Mastication and prescribed fire impacts on fuels in a 25-year old ponderosa pine plantation, southern Sierra Nevada. *Forest Ecology and Management* **258**, 2365–2372. doi:10.1016/J.FORECO.2009.07.050
- Sackett SS (1980) Woody fuel particle size and specific gravity of south-western tree species. USDA Forest Service, Rocky Mountain Forest and Range Experiment Station, Research Note RM-389. (Fort Collins, CO, USA)
- Safford HD, Stevens JT, Merriam K, Meyer MD, Latimer AM (2012) Fuel treatment effectiveness in California yellow pine and mixed-conifer forests. *Forest Ecology and Management* **274**, 17–28. doi:10.1016/J.FORECO.2012.02.013
- Scholl AE, Taylor AH (2010) Fire regimes, forest change, and self-organization in an old-growth mixed-conifer forest, Yosemite

- National Park, USA. *Ecological Applications* **20**, 362–380. doi:10.1890/08-2324.1
- Sikkink PG, Jain TB, Reardon J, Heinsch FA, Keane RE, Butler B, Baggett LS (2017) Effect of particle aging on chemical characteristics, smoldering, and fire behavior in mixed-conifer masticated fuel. *Forest Ecology and Management* **405**, 150–165. doi:10.1016/J.FORECO.2017.09.008
- Stottleyer AD, Waldrop TA, Wang GG (2015) Prescribed burning and mastication effects on surface fuels in southern pine beetle-killed loblolly pine plantations. *Ecological Engineering* **81**, 514–524. doi:10.1016/J.ECOLENG.2015.04.076
- Syphard AD, Radeloff VC, Keeley JE, Hawbaker TJ, Clayton MK, Stewart SI, Hammer RB (2007) Human influence on California fire regimes. *Ecological Applications* **17**, 1388–1402. doi:10.1890/06-1128.1
- Vitorelo B, Han HS, Varner JM (2009) Masticators for fuel reduction treatment: equipment options, effectiveness, costs, and environmental impacts. In 'Proceedings of the 2006 Council on Forest Engineering (COFE) meeting', pp. 11. (Lake Tahoe, CA, USA)

**Appendix 1. Fuel loading at 25 masticated fuels treatments across northern California and southern Oregon, USA. Id number corresponds to mapped locations in Fig. 1**

ID	Site	Total woody loading (Mg ha <sup>-1</sup> )	1-h (Mg ha <sup>-1</sup> )	10-h (Mg ha <sup>-1</sup> )	100-h (Mg ha <sup>-1</sup> )	1000-h (Mg ha <sup>-1</sup> )	Litter (Mg ha <sup>-1</sup> )	Duff (Mg ha <sup>-1</sup> )
15	VAN	92.0 (11.3)	26.6 (2.6)	49.2 (7.5)	13.2 (5.2)	3.0	4.8 (1.1)	21.6 (1.4)
9	SHL	88.7 (12.8)	12.5 (2.4)	55.9 (9.6)	13.3 (2.9)	7.0	9.0 (1.9)	8.5 (1.8)
25	JD09	40.3 (7.1)	6.1 (1.4)	22.5 (4.4)	5.5 (2.2)	6.2	13.3 (2.3)	25.2 (4.0)
7	TAY	38.5 (8.6)	3.9 (0.8)	15.5 (5.6)	3.7 (2.4)	15.4	8.2 (1.3)	45.2 (12.0)
19	EOW	37.4 (5.7)	6.6 (1.3)	16.2 (3.4)	4.8 (1.4)	10.0	10.1 (1.8)	21.3 (3.0)
13	HF07	34.3 (6.3)	4.9 (1.3)	16.3 (3.8)	10.9 (3.2)	2.7	7.5 (0.8)	19.3 (2.8)
18	SPR11	34.3 (3.9)	3.7 (0.7)	13.2 (2.5)	5.2 (1.6)	12.2	10.6 (2.1)	46.1 (8.8)
20	DLB	34.0 (3.9)	4.8 (0.8)	15.1 (2.5)	4.1 (1.8)	10.0	22.0 (7.4)	54.9 (10.3)
24	STA	31.9 (6.7)	4.9 (1.2)	19.3 (4.1)	6.6 (3.0)	1.0	8.2 (1.0)	21.6 (3.6)
16	SFR	31.6 (2.5)	1.7 (0.3)	5.0 (1.1)	3.3 (1.8)	21.5	10.6 (1.4)	13.7 (3.9)
5	APP98	29.8 (5.5)	1.3 (0.4)	9.5 (3.4)	6.0 (2.6)	13.0	6.1 (1.8)	3.6 (1.6)
17	ERR	28.4 (3.1)	3.6 (0.9)	10.3 (2.0)	3.8 (1.2)	11.3	13.4 (1.7)	28.5 (5.6)
21	EMB	26.6 (3.7)	5.8 (0.9)	14.2 (2.8)	1.3 (0.8)	5.3	10.0 (1.1)	66.4 (13.2)
22	SLT13	25.9 (9.0)	3.8 (1.0)	8.0 (3.0)	10.2 (5.4)	4.0	15.6 (6.8)	68.3 (18.6)
1	APP	25.7 (5.6)	2.2 (0.4)	14.7 (3.4)	6.2 (2.7)	2.6	6.9 (1.3)	4.4 (0.8)
3	BLM06	25.2 (6.1)	1.5 (0.3)	10.0 (2.4)	5.9 (3.9)	7.8	6.2 (0.8)	11.6 (3.9)
10	SHL2	22.4 (3.6)	2.8 (0.4)	10.6 (2.2)	2.7 (1.5)	6.3	10.6 (2.4)	3.0 (1.1)
2	APP04	20.0 (3.5)	1.0 (0.2)	10.0 (1.8)	6.5 (2.3)	2.5	6.8 (1.1)	4.3 (1.2)
12	IMR	19.6 (4.1)	2.1 (0.5)	10.1 (2.3)	5.0 (2.0)	2.4	5.1 (0.9)	9.1 (3.1)
8	TRN	14.2 (2.0)	2.1 (0.4)	4.9 (1.3)	1.5 (0.9)	5.7	6.4 (1.5)	20.3 (8.1)
11	WHI	13.7 (2.8)	3.0 (0.7)	8.5 (1.7)	2.0 (1.2)	0.1	7.2 (1.4)	6.1 (1.4)
23	FLL07	13.6 (2.7)	4.2 (0.8)	5.5 (1.3)	2.1 (1.0)	1.7	10.3 (1.5)	57.6 (7.2)
6	MFR	13.9 (3.3)	2.0 (0.6)	7.5 (2.1)	3.2 (1.4)	0.4	13.1 (2.0)	13.7 (2.4)
14	HF09	12.6 (2.5)	1.8 (0.4)	7.1 (1.8)	1.5 (0.6)	2.2	10.6 (2.7)	41.1 (11.1)
4	APP01	12.1 (3.6)	0.7 (0.2)	6.3 (1.8)	2.9 (2.5)	2.3	6.2 (2.4)	1.7 (1.5)
	Average	<b>30.6 (4.0)</b>	<b>4.5 (1.0)</b>	<b>14.5 (2.4)</b>	<b>5.2 (0.7)</b>	<b>6.3 (1.1)</b>	<b>9.6 (0.5)</b>	<b>24.6 (1.7)</b>