

The impact of aging on laboratory fire behaviour in masticated shrub fuelbeds of California and Oregon, USA

Jesse K. Kreye^{A,B,G}, J. Morgan Varner^{B,C}, Jeffrey M. Kane^D, Eric E. Knapp^E
and Warren P. Reed^{A,F}

^APresent address: Department of Forest Resources and Environmental Conservation,
Virginia Tech, Blacksburg, VA 24061, USA.

^BForest and Wildlife Research Center, Mississippi State University, Box 9681, Mississippi State,
MS 39762, USA.

^CUSDA Forest Service, Pacific Northwest Research Station, Pacific Wildland Fire Sciences
Laboratory, Seattle, WA 98103, USA.

^DDepartment of Forestry and Wildland Resources, Wildland Fire Laboratory,
Humboldt State University, Arcata, CA 95521, USA.

^EUSDA Forest Service, Pacific Southwest Research Station, Redding, CA 96002, USA.

^FDepartment of Ecosystem Science and Management, Pennsylvania State University,
University Park, PA 16802, USA.

^GCorresponding author. Email: jkk139@vt.edu

Abstract. Mastication of shrubs and small trees to reduce fire hazard has become a widespread management practice, yet many aspects of the fire behaviour of these unique woody fuelbeds remain poorly understood. To examine the effects of fuelbed aging on fire behaviour, we conducted laboratory burns with masticated *Arctostaphylos* spp. and *Ceanothus* spp. woody debris that ranged from 2 to 16 years since treatment. Masticated fuels that were 10 years or older burned with 18 to 29% shorter flame heights and 19% lower fireline intensities compared with the younger fuelbeds across three different fuel loads (25, 50 and 75 Mg ha⁻¹). Older fuelbeds smouldered for almost 50% longer than the younger masticated fuelbeds. Fuel consumption was 96% in the two higher fuel load categories regardless of fuelbed age, whereas consumption was 77% in the lighter fuel load. Fire intensity in masticated fuels may decrease over time owing to particle degradation, but in dry environments where decomposition is slow, combustion of the remaining fuels may still pose risks for tree mortality and smoke production associated with protracted smouldering.

Additional keywords: fireline intensity, fuel decomposition, fuels treatments, mechanical mastication, smouldering combustion.

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Introduction

Mastication is a mechanical treatment that alters fuel structure through shredding or chipping understorey shrubs and small trees, redistributing fuels from the midstorey to the surface (Kane *et al.* 2009; Kreye *et al.* 2014a). Mastication treatments are increasingly being used in fire-prone environments across the USA (Kane *et al.* 2009; Kobziar *et al.* 2009; Battaglia *et al.* 2010; Menges and Gordon 2010; Brewer *et al.* 2013; Kreye and Kobziar 2015) and elsewhere (Molina *et al.* 2009; Montiel and Kraus 2010; Schiks *et al.* 2015). Mastication often creates heavy but compact fuelbeds composed of shredded woody material with a high proportion of small-diameter particles (Kreye *et al.* 2014b). Compaction of the fuelbed is predicted to change fire behaviour (Knapp *et al.* 2011). Although mastication can lower flame lengths under some burning conditions in comparison with untreated vegetation (Kreye and Kobziar 2015), intense fire

behaviour has also been observed during laboratory (Kreye *et al.* 2011, 2013) and field-based (Bradley *et al.* 2006) burning experiments. Substantial overstorey mortality (Knapp *et al.* 2011) and significant soil heating (Busse *et al.* 2005) can result when masticated fuels are burned. Following treatment, masticated fuels typically remain on site until they decompose or are consumed by subsequent prescribed burning (Reiner *et al.* 2009; Knapp *et al.* 2011). Understanding the fate of these surface fuels and how their combustion properties change over time is essential to determine the efficacy and longevity of mastication.

Laboratory experiments have revealed some of the effects of particle- or fuelbed-scale properties on fire behaviour in masticated fuels (Busse *et al.* 2005; Kreye *et al.* 2011; Kreye *et al.* 2013), but no studies have examined how fuelbed age influences fire behaviour. As masticated woody fuels decompose, reductions in loading should dampen fire behaviour.

With decomposition, physical properties of fuels such as particle density, lignin : cellulose ratio and mineral content also change (particularly in the more rapidly decomposing fine fuels; Carlton and Pickford 1982; Erickson *et al.* 1985; Zhao *et al.* 2014; Keane 2015). And as particles become less dense and finer particles are more rapidly lost, fuelbed properties such as packing ratio (Rothermel 1972) and average particle surface area : volume may also change. These altered fuel properties may change fire behaviour in ways beyond simple reductions in total fuel loading. Understanding how these fuelbed age factors contribute to the intensity and duration of energy release while burning will provide important information regarding post-treatment fire behaviour and aid in developing fuel models to better predict fire behaviour and effects (Kreye *et al.* 2014b).

The objective of the present study was to quantify, through laboratory experiments, the effects of fuelbed age on energy release (fireline intensity), flame height, flaming duration and smouldering duration in masticated debris collected from sites ranging from 2 to 16 years since mastication. Our specific aim was to understand how changes in the physical properties of particles and alterations in fuelbed composition would influence fire behaviour beyond the expected changes in fuel load. We hypothesised that fuelbeds composed of material collected from older masticated sites would burn with lower fireline intensities and shorter flame lengths and for a longer duration as a result of particle-level degradation. We tested the combined effects of physical changes to masticated particles, by collecting *in situ* material, and changes to fuelbed composition, by altering 1-h (<0.64 cm) and 10-h (0.64–2.54 cm) fuel proportions according to field measurements at sites of varying fuelbed age. We conducted burning experiments using three levels of fuel loading that approximated high-loading sites in the field.

Methods

Fuel collection sites

Masticated woody fuels were collected from four treatment areas to evaluate the effect of fuelbed age on fire behaviour during controlled laboratory burn experiments. Mastication treatments were conducted in 2012 (Six Rivers National Forest, California), 2010 (Shasta–Trinity National Forest, California), 2004 (Shasta–Trinity National Forest) and 1998 (Applegate Valley, Bureau of Land Management, Oregon). All sites are located within the Klamath Mountains–California High Coast Range Level III ecoregion (United States Environmental Protection Agency 2013). The maximum distance between sites is 272 km. Although overstorey conditions varied, the midstorey vegetation that was targeted for mastication was dominated by *Arctostaphylos* spp. and *Ceanothus* spp. shrubs at all sites. Composition of masticated woody debris (i.e. proportion by size class) and specific gravity of masticated particles were evaluated across these sites by Reed (2016) as part of a larger study examining fuel dynamics following mastication in the region.

Experimental burning

Collected woody fuels were used to create laboratory-scale (25 × 25-cm) fuelbeds for burning experiments. The proportion of fuel by size class (1- and 10-h) was consistent with regional changes over time observed by Reed (2016). Because 100-h

fuels were less common across sites (only 12–20% by mass), we only used 1- and 10-h fuels for experimental burns, similarly to previous burning experiments (Kreye *et al.* 2011). As collected material from each site was used for experimental burns, our fuelbeds reflected changes to particle density and other chemical and physical changes. We did not mimic total fuel loading across the sites from which fuel was collected, but rather tested the effect of fuelbed age as reflected in fuelbed composition and fuel particle density across three total fuel loads (25, 50 and 75 Mg ha⁻¹) that spanned the upper range observed in masticated sites across the region (Kane *et al.* 2009; Reed 2016). Therefore, our laboratory experiments allowed us to isolate effects of particle degradation as fuelbeds age, such as a reduction in particle density and the loss of 1-h woody particles. Fuel composition (percentage 1-h by weight) varied by fuelbed age to reflect fuelbed degradation observed by Reed (2016) with 2-, 4-, 10- and 16-year-old fuels resulting in 36, 32, 24 and 16% 1-h fuels respectively. Specific gravity of the 2-, 4-, 10- and 16-year-old fuels averaged 0.69, 0.69, 0.51 and 0.52 for 10-h particles and 0.67, 0.59, 0.49, 0.45 for the 1-h particles (Reed 2016).

Fuelbeds were burned within combustion boxes (25 × 30 × 15 cm inside dimensions, Fig. 1) lined with 13-mm-thick cement



Fig. 1. Laboratory burning of masticated shrub fuelbeds. Fuelbeds were ignited along one edge utilising a flat paraffin-soaked wick (visible along the right edge of fuelbed) and flame heights ocularly estimated during burning (rule gradations are in cm). Mass loss was recorded via a bench scale interfaced with a computer. Insert: smouldering and glowing combustion followed flaming.

board along the bottom and sides. Fuelbeds were arranged against one edge of the combustion box, leaving 5 cm of open space along which ignition occurred. Masticated particles within sites were randomly selected and composited to create fuelbeds. For each site, fuelbeds were created with three fuel load treatments: 156, 313 and 469 g of fuel, corresponding to total loads of 25, 50 and 75 Mg ha⁻¹ respectively. Bulk density (kg m⁻³) of fuelbeds was calculated from fuelbed depth and total fuel mass. Fuels were at laboratory moisture conditions (5.9 ± 0.6% gravimetric moisture content across all fuel sizes, based on 22 random samples) when burned. Experiments were replicated three times within each fuel load and fuelbed age combination, for a total of 36 burns.

Fuelbeds were ignited using a flat 2.5 × 20-cm lamp wick soaked in 99% pure paraffin wax along the open edge (Fig. 1), as in Kreye *et al.* (2011); wicks burned for ~10 s. During burn experiments, we recorded maximum flame height (cm), observed against a vertically oriented ruler (Fig. 1); flaming time (s, time elapsed from ignition to flame extinction); and smouldering time (s, time elapsed from the end of flaming to the end of glowing combustion that was visible under darkened conditions). Following smouldering combustion, we weighed the remaining fuel mass and calculated percentage consumption. To estimate energy release, burns were conducted on top of a bench scale connected to a computer (RS232 interface) and weight was recorded throughout burning at 5-s intervals. Energy release was calculated as fireline intensity (kW m⁻¹) by multiplying mass loss (g) per 5-s interval by a representative heat content (19.2 kJ g⁻¹; Countryman 1982) divided by the width (0.25 m) of the fuelbed, as described in Kreye *et al.* (2011). All 36 experimental burns were conducted in a randomised order.

Data analysis

Fire behaviour metrics (peak fireline intensity, flame height, flaming duration, smouldering duration and fuel consumption) were each compared across fuelbed age and total fuel load category (25, 50, 75 Mg ha⁻¹) using a general linear model

(GLM) analysis of variance. Main effects and their interactions were examined. Although burns were conducted in a laboratory, ambient conditions varied somewhat; air temperature ranged from 21.5 to 24.5°C and relative humidity ranged from 42 to 52%. Both temperature and relative humidity were tested as covariates in each analysis. Relative humidity was a significant covariate for flame heights ($P < 0.001$), and GLM analysis of covariance subsequently used, but not for any other fire behaviour metric. Air temperature was not a significant covariate in any analysis. Fuelbed bulk density was confounded with fuelbed age and fuel load treatments (see *Results*); we therefore report bulk density values, but do not evaluate it as a dependent variable. Differences among the means were examined using the Tukey–Kramer post-hoc multiple comparison test. Significance for all analyses was tested at $\alpha = 0.05$. Normality of residuals and homoscedasticity (GLM assumptions) were confirmed for each analysis using the Shapiro–Wilk test and modified Levene test respectively.

Fireline intensity was evaluated throughout the duration of flaming combustion using LOESS (locally weighted regression scatter-plot smoothing) curve-fitting across replicated burns. Whereas peak fireline intensity indicates the maximum energy output within one 5-s interval for each burn, the LOESS regression provides weighted average fireline intensities throughout burning across replicates (Kreye *et al.* 2011).

Results

Bulk densities across all fuelbeds averaged 82.8 kg m⁻³ (18.9 s.d.) with differences only detected between the lowest fuel load (25 Mg ha⁻¹), averaging 66.7 kg m⁻³, and the two highest fuel loads ($P < 0.001$), which averaged 85.8 and 95.8 kg m⁻³ for the 50 and 75 Mg ha⁻¹ fuelbeds respectively; and between the 4- and 16-year-old fuels ($P = 0.001$), which averaged 71.1 and 92.2 kg m⁻³ respectively. Maximum flame heights of the masticated fuelbeds ranged from 15 to 80 cm and peak fireline intensities from 31 to 138 kW m⁻¹ across the 36 experimental burns. As expected, flame heights and peak fireline intensities

Table 1. Fire behaviour metrics during laboratory experimental burning of 25, 50 and 75 Mg ha⁻¹ of masticated fuelbeds collected from sites with varying fuelbed ages (2, 4, 10 and 16 years)

Values shown are adjusted means for each level of the main effects (fuel age and fuel load) from general linear modelling (GLM) analysis of variance. Different superscript letters within fuel age or fuel load, for each burn metric separately, indicate significant differences based on Tukey–Kramer post-hoc multiple comparison tests. No interactions between main factors (fuel age, fuel load) were significant for any burning metric

Factor	Maximum flame height (cm)	Flaming duration (min)	Smouldering duration (min)	Fuel consumption (%)	Peak fireline intensity (kW m ⁻¹)
Fuel age (years)					
2	55 ^a	14.8 ^a	51 ^a	89 ^a	85.3 ^{ab}
4	52 ^{ab}	13.0 ^a	62 ^{ab}	91 ^a	92.2 ^a
10	45 ^{bc}	13.2 ^a	73 ^{bc}	87 ^a	76.8 ^b
16	39 ^c	15.4 ^a	74 ^{bc}	87 ^a	73.4 ^b
Fuel load (Mg ha ⁻¹)					
25	27 ^a	13.4 ^a	49 ^a	77 ^a	48.6 ^a
50	51 ^b	14.6 ^a	66 ^b	93 ^b	84.5 ^b
75	65 ^c	14.2 ^a	79 ^b	96 ^b	112.6 ^c

were also strongly correlated ($P < 0.001$, $r = 0.862$). Flaming and smouldering durations ranged from 8.7 to 21.3 and 35 to 121 min respectively. Fuel consumption across the chronosequence ranged from 51 to 97%.

Fuelbed age had a negative influence on maximum flame height ($P < 0.001$) and peak fireline intensity ($P = 0.004$), but positively affected smouldering time ($P = 0.010$) across all fuel loads (Table 1, Fig. 2). Flame heights were shorter in the two oldest (10- and 16-year) fuels compared with the youngest (2-year-old) fuels. Four-year-old fuels also burned with taller flames compared with the oldest (16-year) masticated fuels and peak fireline intensities were greater in the 4-year-old fuels compared with both the older (10- and 16-year) fuels. Although fuelbed age did not affect flaming duration ($P = 0.345$), these older fuels smouldered for $\sim 50\%$ longer than the most recently masticated debris (Table 1). Fuelbed age did not affect fuel consumption ($P = 0.846$), which averaged 89%.

Flame heights and peak fireline intensities differed across all fuel loads ($P < 0.001$), with heavier fuelbeds burning with taller flames and greater fireline intensity (Table 1, Fig. 2). Flaming duration, however, did not differ among fuel loads ($P = 0.660$), but the lighter 25-Mg ha⁻¹ fuelbeds smouldered for shorter durations and were less consumed compared with the heavier 50- and 75-Mg ha⁻¹ fuelbeds ($P < 0.001$). No interactions were detected between fuelbed age and fuel load on flame heights ($P = 0.981$), flaming duration ($P = 0.910$), smouldering duration ($P = 0.269$), fuel consumption ($P = 0.591$) or peak fireline intensity ($P = 0.281$).

Fireline intensity throughout burning (based on LOESS regression curves) also trended towards diminished energy release in the older fuels across all three fuel load categories (Fig. 3). The 4-year-old fuels, however, consistently burned with greater intensity than younger 2-year-old fuels. Similar results were apparent in peak fireline intensities observed during burning of the 50- and 75-Mg ha⁻¹ loads (Fig. 2), but these differences were not significant in a Tukey–Kramer post hoc comparison of the means.

Discussion

The present study revealed a reduction in fireline intensity with fuelbed age following mastication of shrub-dominated fuels. Recently masticated fuels burned similarly in flame height, fireline intensity and consumption to that of other recently masticated *Arctostaphylos* spp. and *Ceanothus* spp. fuels from a previous study (Kreye *et al.* 2011). Changes in particle-level properties and the relative loss of 1-h particles in fuelbeds over time both likely contributed to fuelbed age dampening fire behaviour (Rothermel 1972). These factors are confounded in the present study, however, and the mechanisms involved may be complex. As average particle surface area : volume decreases with losses in 1-h fuels, combustion rates are likely to decrease (Rothermel 1972). But reductions in particle density and increases in fuelbed bulk density, characteristics of older fuelbeds in the current study, both increase fuelbed packing ratio. And reaction intensity has been shown to increase with packing ratio to an optimum beyond which intensity then decreases (Rothermel 1972). It is unknown what the optimum packing ratio may be for these masticated fuels. Reduced particle

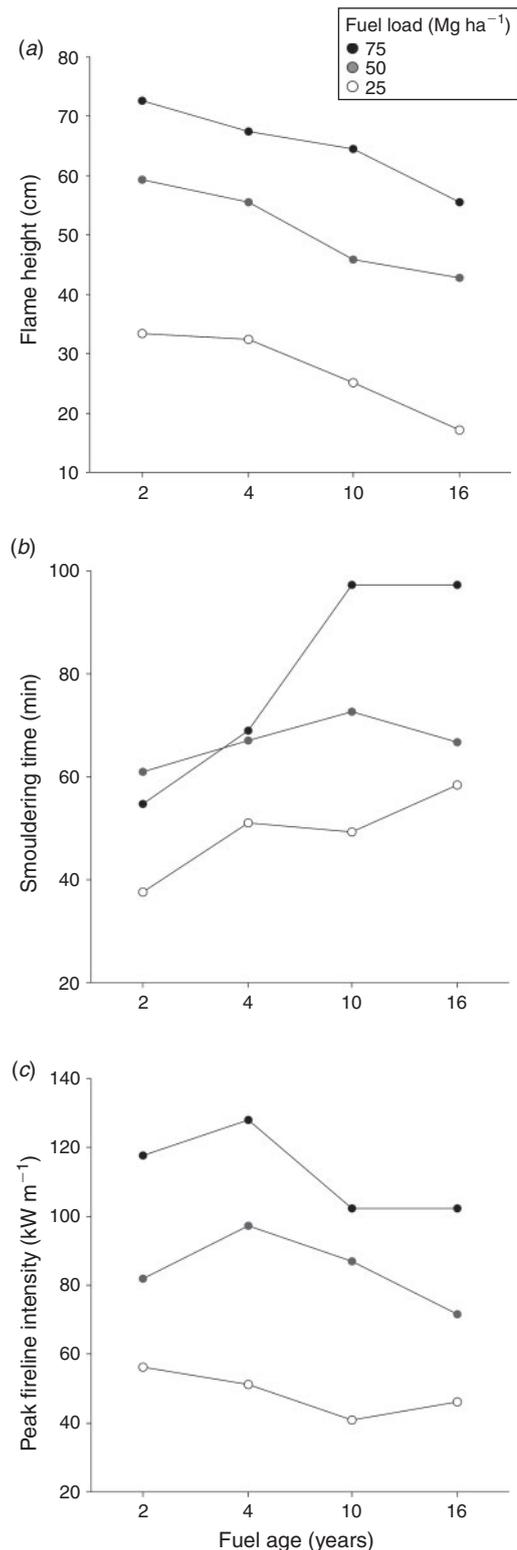


Fig. 2. The effect of fuelbed age on maximum flame height (a); smouldering duration (b); and peak fireline intensity (c) during laboratory burning masticated fuel loads of 25, 50 and 75 Mg ha⁻¹. Data are adjusted means from each GLM (general linear model).

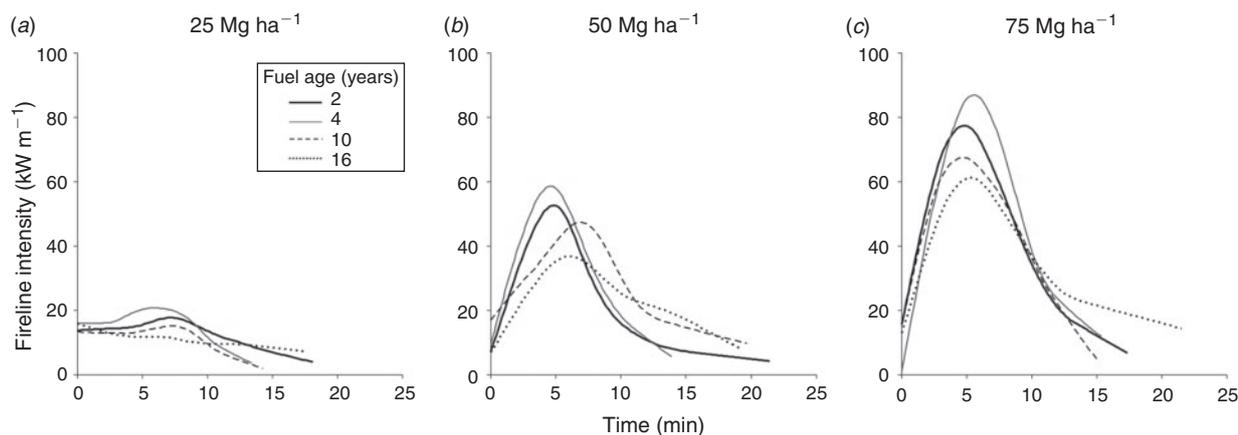


Fig. 3. Effects of fuelbed age on fireline intensity (kW m^{-1}) during burning of masticated debris collected from sites ranging in fuel age from 2 to 16 years. Burning experiments were conducted using three different fuel loads: 25 (a); 50 (b); and 75 (c) Mg ha^{-1} . Data presented are LOESS curves (using 40% of data at each LOESS regression calculation) across replicated burns ($n = 3$).

density, resulting from decomposition, has been shown to increase ignitability of individual dead twigs, but without effects on heat release (Zhao *et al.* 2014). Fuel heat content may also change with decomposition, likely a result of increased relative lignin concentration and mineral content (via decay of cellulose; Hyde *et al.* 2011). As we did not quantify heat content, we used a constant across fuel age categories to estimate fireline intensity. Although fireline intensity may have been slightly underestimated in older fuels, where higher lignin concentrations may have increased heat content, intensity was still strongly correlated with flame height, as expected. And although cellulose more readily volatilises to support flaming combustion, lignin content, along with mineral content and high packing ratio, promotes smouldering combustion (Johnson and Miyanishi 2001), which was prolonged in these older fuelbeds.

Although consumption did not decrease with fuelbed age during burning, smouldering combustion increased, presumably owing to fuel particle (e.g. density and lignin:cellulose; Shafizadeh and Bradbury 1979; Costa and Sandberg 2004) or fuelbed property (e.g. increased bulk density) changes with fuelbed age. Reduced fire intensity over time may enhance long-term treatment efficacy, but longer durations of smouldering combustion may have unintended ecological or health (e.g. smoke emissions) consequences when older masticated fuels are burned (Ottmar 2014). Long-duration smouldering fires may prolong lethal heating near the base of trees or in underlying mineral soils (Busse *et al.* 2005), exacerbating duff combustion and potentially causing unforeseen overstorey tree mortality (Ryan and Frandsen 1991). Smouldering also tends to be a less efficient form of combustion compared with flaming, and increases in smoke production and changes to smoke chemistry (e.g. increased CO concentration, particulate matter and decreased visibility) are typically associated with smouldering fires (Sandberg *et al.* 2002; Ottmar 2014).

Fuel load, moisture content and the species composition of fuel burned may be the best predictors of fire behaviour in masticated fuels (Kreye *et al.* 2011, 2013; Brewer *et al.* 2013), but fuel degradation will contribute to how fuels burn over time.

As masticated fuels decompose, decreases in fuel load reduce potential energy for combustion, but our results highlight that effects of fuel aging on particle density, fuelbed composition and potentially chemistry may affect fire behaviour beyond simple reductions in fuel load. Aging fuels burned with lower fire intensity, but smouldered for longer durations even when total fuel loads were held constant. Laboratory studies with recently masticated fuels have shown the propensity for fuelbeds to burn for long durations (Busse *et al.* 2005), but our work is the first to reveal how these patterns change over time. Several factors may influence decomposition rates of masticated debris, but moisture is likely to be of primary importance (Enriquez *et al.* 1993; Prescott *et al.* 2004). In dry environments, slow decomposition rates may prolong post-mastication hazards. But even as fuels decay, prolonged smouldering may pose additional risks associated with long-duration heating or emissions.

Although our results show a reduction in fire intensity over time in masticated fuels, these predictions are complicated by site-level factors that will be important in determining how treatments may burn during wildfires or prescribed burns. Litter, duff or other surface fuels (Kobziar *et al.* 2009; Knapp *et al.* 2011; Kreye *et al.* 2013) that may remain on site since the time of mastication, or are deposited on top of the masticated fuels over time also contribute to fire behaviour. And the influence of recovering understorey and midstorey vegetation on post-treatment fire behaviour may be even more important (Kreye and Kobziar 2015). Although our results highlight the influence of fuel age on combustion, fire behaviour measurements at the laboratory scale may differ from what is observed in the field where steady-state rate of fire spread and fireline intensity may differ. The longevity of the contribution of masticated woody fuels to fire behaviour (Kreye *et al.* 2014b) and effects (Busse *et al.* 2005; Reiner *et al.* 2009; Knapp *et al.* 2011) will likely rely on how much debris was initially created (Kane *et al.* 2010; Kreye *et al.* 2014a) and how long it takes to decompose (Reed 2016). Understanding the many factors that influence fire behaviour in masticated fuels will be required to fully evaluate the efficacy of these widely used treatments.

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