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Effects of particle fracturing and moisture content on fire behaviour in masticated fuelbeds burned in a laboratory

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Abstract. Mechanical mastication is a fuels treatment that converts shrubs and small trees into dense fuelbeds composed of fractured woody particles. Although compaction is thought to reduce fireline intensity, the added particle surface area due to fracturing could also influence fire behaviour. We evaluated effects of particle fracturing and moisture content (ranging from 2.5 to 13%) on fire behaviour in fuelbeds composed of masticated *Arctostaphylos manzanita* Parry and *Ceanothus velutinus* Dougl. shrubs in the laboratory. Fuelbeds composed of fractured particles did not burn with greater intensity than fuelbeds composed of intact particles, as hypothesised. Flame heights ranged from 54 to 95 cm and fireline intensity from 50 to 140 kJ s^{-1} m^{-1}, approximating values observed in field experiments. Masticated fuelbeds burned with shorter flame heights and longer flaming duration under higher fuel moistures, but duration of lethal heating (>60°C) above fuelbeds did not differ across the range of fuel moistures, averaging 12 min over a 0.1-m^2 area. Our results suggest that expected fire behaviour increases due to particle fracturing may be overwhelmed by fuelbed bulk density. The long-duration heating of burning masticated fuels may require managers to mitigate effects to trees and soils when fuel loads are high.

Additional keywords: *Arctostaphylos*, *Ceanothus*, fire intensity, fuels management, mechanical fuels treatment.

Introduction

Throughout fire-prone landscapes, a multitude of fuels treatment methods have been implemented to reduce surface fuels, alter canopy characteristics, and disrupt vertical fuel continuity (Agee and Skinner 2005). Goals of fuels management may include moderating potential fireline intensity, reducing torching and crown fire potential, and restoring historical stand structure (Mutch *et al.* 1993; Graham *et al.* 1999). Fuels treatments may slow the spread of fire or enable suppression activities in areas where direct attack was difficult before treatment (Green 1977; Moghaddas and Craggs 2007). One fuels treatment that has become increasingly common is mechanical mastication (Busse *et al.* 2005; Glitzenstein *et al.* 2006; Hood and Wu 2006; Kane *et al.* 2009). Mastication is a process by which shrubs and small trees are shredded via front-end or boom-mounted rotating drums with cutters that chop live or standing dead vegetation and disperse it over the ground. Fractured particles created by mastication typically remain on the soil surface following treatment, and form a compact fuelbed composed of dead woody material (Hood and Wu 2006; Kane *et al.* 2009). By redistributing live vertical shrub and small tree fuels, mastication can potentially lower the probability of crown ignition and reduce fireline intensity.

Although mastication treatments are being widely implemented, several questions remain regarding their potential effects (Kane *et al.* 2009; Sharik *et al.* 2010). Among these, understanding resulting fuelbed characteristics and their effects on fire behaviour are of primary importance. Although mastication is often the sole treatment (with fuels decaying over time on the ground), masticated sites are occasionally treated with prescribed fire as a follow-up (Kobziar *et al.* 2009; Knapp *et al.*, in press). In recent studies in masticated fuelbeds (Busse *et al.* 2005; Bradley *et al.* 2006; Knapp *et al.*, in press), observed fire behaviour and effects, including tree mortality, show potential consequences that may be contrary to fuels treatment objectives. Such consequences have been unexpected and even unpredictable (Knapp *et al.*, in press). Long-duration soil heating (Busse *et al.* 2005), as well as aboveground radiant and convective heating (Knapp *et al.*, in press), may potentially contribute to tree mortality from the burning of masticated fuelbeds. Predicting fire behaviour and effects from the burning of fuels resulting from mastication is needed to fully understand their potential efficacy as an effective management tool.

In addition to poor fire effects prediction, Kane (2007) found that several mechanically masticated sites in northern California and southern Oregon did not readily fit available fire behaviour

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fuel models. Despite heavy loads of smaller-diameter (1-h and 10-h timelag) fuels, the fuelbed is generally compact, making masticated fuelbeds unique. In addition, the fracturing of particles not only increases the quantity of smaller-average-diameter particles, but also alters particle shape into a more irregular, non-cylindrical form (Kane *et al.* 2009), changing particle surface area-to-volume (SAV). At the particle level, high SAV can influence fire behaviour directly owing to increased heat transfer rates elevating woody tissues to combustion temperatures more quickly, as well as indirectly from rapid drying rates that may increase time that fuel particles are available for combustion. The fractured edges of fuel particles from mastication may increase the total area in which moisture is exchanged with the atmosphere during drying or is vaporised during combustion. In contrast, the high bulk density of fuelbeds created from masticated particles (Kane *et al.* 2009) may slow the combustion process (Rothermel 1972) and reduce rates of moisture loss, especially for the lower layers (Kreye and Varner 2007). Low rates of moisture loss in compact fuelbeds (Kreye and Varner 2007) may lessen the daily or seasonal proportion of fuels available for combustion, but it also may indicate that the rate of moisture being evaporated during combustion is slow. This potential dampening effect on fire intensity or spread rate may be greater at higher moisture contents though, and may not play much of a role in environments where long seasonal drying will ultimately result in very dry fuelbeds. The influence of particle-level fracturing relative to fuelbed-level compaction may therefore be more of a consequence in drier fuelbeds. Fracturing, re-sizing, and compacting woody fuels all have the potential to alter the process of combustion, evoking a need for research to elucidate the behaviour of fire in these increasingly common fuelbeds.

Although the influence of fuel moisture on fire behaviour is well understood, the influence of fuel moisture on fire behaviour in masticated fuel beds, and the interaction between fuel moisture and particle fragmentation, has not been studied. To fill these knowledge gaps, we formulated the following objectives: (i) to investigate how particle shape influences fire behaviour at two disparate fuel moisture contents, by comparing burning characteristics and duration of heating between fuelbeds composed of fractured particles and those composed of intact (relatively cylindrical) particles, and (ii) to evaluate the effects of fuel moisture on burning characteristics and duration of heating within compact masticated fuelbeds composed of variously fractured as well as intact particles. Our hypotheses were that: (1) fractured particles will burn with greater fireline intensity than intact particles; (2) fireline intensity will decrease while flaming and smouldering time will increase as fuel moisture content increases in masticated fuels; and (3) duration of heating above the fuelbed (20 cm) will differ with fuel moisture and particle structure (fractured *v.* intact). We tested these hypotheses using the masticated fuels derived from two common shrubs (*Arctostaphylos manzanita* and *Ceanothus velutinus*), species that are commonly masticated in California and Oregon (Busse *et al.* 2005; Perchemlides *et al.* 2008; Kane *et al.* 2009; Kobziar *et al.* 2009). These findings should ultimately help us to more fully understand the potential effects that fire in masticated fuelbeds may have on soil heating and residual tree mortality following mastication in these shrub systems.

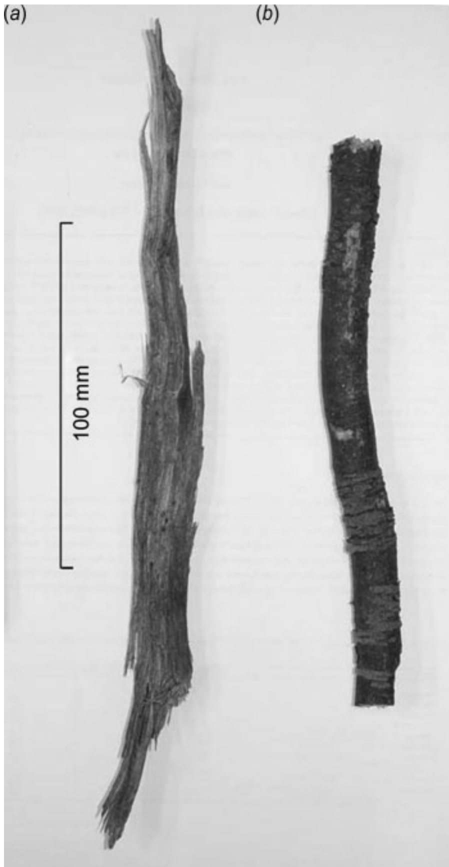

Fig. 1. Examples of the masticated shrub (*Ceanothus velutinus*) particle fuel types: fractured (*a*) and intact (*b*).

Methods

Masticated fuels used in laboratory burning experiments were collected from two sites in north-western California, USA, that were dominated by shrubs before mastication treatments. One site was a fuel break in the Six Rivers National Forest near Mad River, California, which was dominated by dense *Arctostaphylos manzanita* (common manzanita) before mastication in December 2004. The other site was a fuel break on Taylor Ridge in the Klamath National Forest near Cecilville, California, which was dominated by *Ceanothus velutinus* (snowbrush) before the May 2005 mastication. Woody fuels were collected from the surface down to mineral soil at each site to create fuelbeds for laboratory burning. Dates of fuel collection were 18 and 14 months after mastication at the Mad River and Taylor Ridge sites respectively.

Effect of particle fracturing on fire behaviour

To address potential effects of mechanical fracturing caused by mastication on fire behaviour (objective (i)), 32 fuelbeds were created using fuels collected from both sites. Sixteen fuelbeds were composed of *Arctostaphylos manzanita* from Mad River and 16 were composed of *Ceanothus velutinus* from Taylor Ridge. Prior to fuelbed construction, fuels were separated into particles that remained intact and particles that were fractured as a result of mastication (Fig. 1). Intact particles were those not

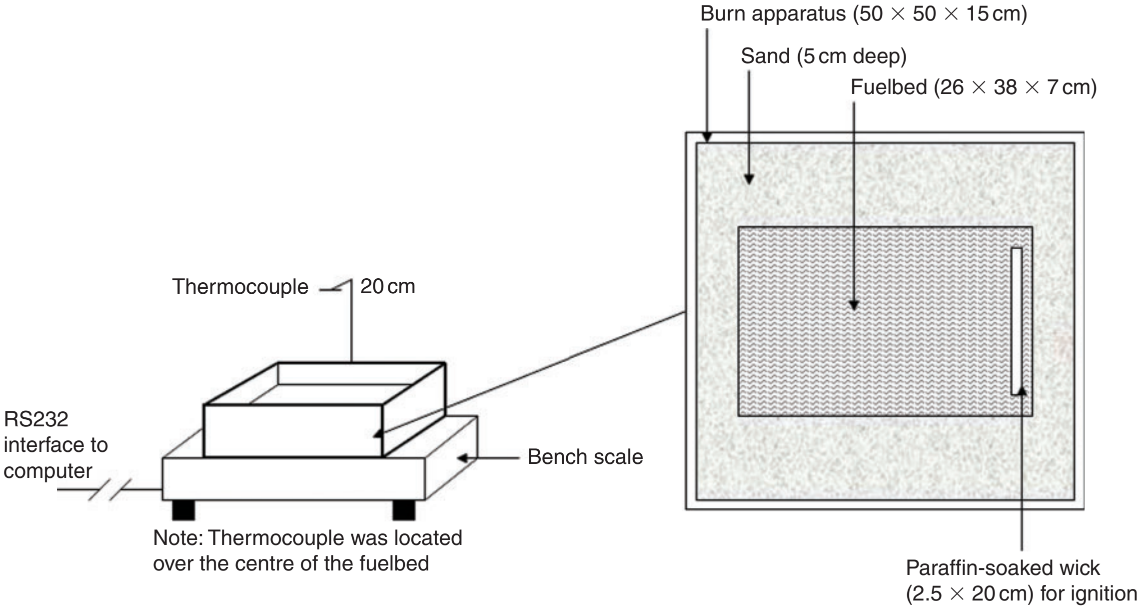

Fig. 2. Burning apparatus used for combustion experiments with masticated fuelbeds.

fractured longitudinally. Of the 16 *A. manzanita* fuelbeds, eight were composed of fractured particles exclusively. The remaining eight fuelbeds were created using *A. manzanita* from the same site that had been hand-cut from live shrubs at the time of mastication and piled separately from the mastication treatment. Fuels within the hand pile were subsequently cut into particles of lengths similar to the collected masticated particles. Smaller-diameter particles were cut into shorter lengths (mostly ~3 to 10 cm) whereas larger-diameter particles were cut into longer lengths (~20 cm), to match field observations. This method was used because there was limited availability of intact particles within the masticated treatment unit. The 16 *Ceanothus velutinus* laboratory fuelbeds built with woody material from the Taylor Ridge fuel break were constructed in the same manner, except there were sufficient intact particles available within the masticated site to be used for the eight intact fuelbeds.

To construct fuelbeds, fuel particles were separated into 1-h (<6.35 mm diameter) and 10-h (6.36 to 25.4 mm diameter) timelag categories (Lancaster 1970). The segregation of particles into timelag categories was established using the minimum thickness that spanned at least 50% of the particle's length (Kane *et al.* 2009). Fuels >25.4 mm in diameter were excluded from experimentation because they composed a minor fraction of loading at both sites (Mad River 8.0% and Taylor Ridge 5.7%) and from most treated sites in the region (Kane *et al.* 2009). Little mineral soil was mixed in with the fuel we collected and any attached mineral soil was brushed off during fuel separation. Each 26 × 38 × 7-cm fuelbed was constructed in aluminium pans using 294 g of 1-h fuels and 435 g of 10-h fuels to approximate the high end of loading and bulk density at Mad River. Mad River contained the highest fuel loading of 10 masticated sites described in northern California and southern Oregon (Kane *et al.* 2009). A second pan was held upside down on top of the fuelbed pan and fuels were shaken for ~30 s to mix fuel particles.

To vary fuelbed moisture conditions, all fuelbeds were soaked in a water bath for 7 days and then drained and allowed to dry under laboratory conditions (25°C ± 0.1° and 29 ± 0.3% relative humidity). Sixteen fuelbeds (eight *Arctostaphylos manzanita*: four intact and four fractured; and eight *Ceanothus velutinus*: four intact and four fractured) dried until they reached 13% fuel moisture content (FMC), whereas the remaining 16 fuelbeds dried until they reached 5% FMC. Fuel moisture content is defined here as the ratio of water weight to fuel oven-dry weight expressed as a percentage.

After reaching treatment FMC, fuelbeds were burned beneath a 3 × 3-m exhaust hood in the laboratory. Each fuelbed was placed on a 5 cm-deep layer of screened and washed fine sand within a custom burning apparatus (50 × 50 × 15 cm inside dimensions). The inside surfaces of the apparatus were lined with fire shelter material (Cleveland Laminating Corp., Cleveland, OH) and aluminium flashing before filling with sand. The burning apparatus was placed on a bench scale to measure changes in fuelbed mass during combustion (Fig. 2). The bench scale was connected to a computer and mass was recorded every second through the experiment. An insulated iron–constantan (Type J; Omega GG-J-30-500, Omega Engineering, Stamford, CT) thermocouple, attached to a CR1000 datalogger (Campbell Scientific Inc., Logan, UT), was placed 20 cm above the fuelbed–sand interface (Fig. 2). Temperature from each thermocouple was recorded every second during flaming and glowing combustion.

Fuelbeds were ignited using a 2.5 × 20-cm lamp wick soaked in 99% pure liquid paraffin wax. For each burn, a wick was placed along the edge of the fuelbed (Fig. 2) and ignited. A flaming front thus moved through the fuelbed perpendicular to the ignition axis. Maximum flame height was measured as the height above the fuelbed–sand interface throughout the duration of flaming combustion, estimated using video footage recorded for each burn. Flaming time was recorded as the elapsed time between initiation of flaming and the completion of flaming combustion. Smouldering time was measured as the time that elapsed between the extinction of flaming and the time that visible glowing combustion ceased. Mass loss rate ($g\,s^{-1}$) (Rothermel 1972) was calculated as the average change in fuelbed mass at 5-s intervals from recorded bench scale data using the following equation:

$$\frac{dM}{dt} = \frac{(M_t - M_{t-5})}{5} \tag{1}$$

where M, mass (g); t, time (s).

Mass loss rate was then converted to energy output using heat content values for *Arctostaphylos patula* ($19.20\,kJ\,g^{-1}$) and *Ceanothus velutinus* ($19.21\,kJ\,g^{-1}$) from Countryman (1982), weighted by fuel load and diameter class, using the following equation:

$$E = \frac{dM}{dt}(h) \tag{2}$$

where dM/dt, mass loss rate ($g\,s^{-1}$); and h, heat content ($kJ\,g^{-1}$).

The energy output is similar to Rothermel's (1972) reaction intensity, but does not include the unit area of the fire front, but rather the total energy being released throughout flaming and glowing combustion within the entire fuelbed at any point in time. Energy output was then converted to fireline intensity (Byram 1959) by dividing energy output by the width of the fuelbed perpendicular to the spread direction of the flaming front (Fig. 2).

$$I = E/w \tag{3}$$

where I, fireline intensity ($kJ\,s^{-1}\,m^{-1}$); E, energy output ($kJ\,s^{-1}$); and w, fuelbed width (m).

Fuel consumption was calculated as the percentage of the initial mass, before burning, that was lost during combustion.

Maximum flame height, flaming time, smouldering time, and consumption were all compared between fuel moisture contents (5 and 13%) and particle fuel types (intact *v.* fractured) in a 2×2 factorial design, for each species (*Arctostaphylos manzanita* and *Ceanothus velutinus*), using GLM (general linear modelling) analysis of variance. Curves of mean heating duration at 20 cm above the fuelbed–sand interface were created across fuel moisture treatment and fuel type for both species. Duration of heating above 60°C was compared across fuel moisture and fuel type, for both species, using GLM analysis of variance. Two-way interactions were tested to evaluate if differences in burning characteristics between fuel types varied between fuel moisture contents. Normality and equal variance assumptions were tested using the Shapiro–Wilk W-test and the modified Levene test respectively. A non-parametric Kruskal–Wallis test on ranks was used in the event of failure of either of these tests.

Effect of fuelbed moisture on fire behaviour

Sixteen additional fuelbeds were created, to address objective (ii), using masticated *Arctostaphylos manzanita* particles from the Mad River fuel break to quantify fire behaviour across a gradient of FMCs. These fuelbeds were created using the same methods described above, except that fuels were not separated into fractured and cylindrical particles. Masticated fuelbeds on site contain some cylindrical particles that were not fractured by the machinery (Kane *et al.* 2009). All 1-h and 10-h particles collected from plots within the Mad River fuel break were used here regardless of the level of fracturing, therefore more closely representing fuelbeds resulting from mastication.

To create the fuelbed moisture treatments, 12 fuelbeds were soaked in a water bath for 7 days and then drained and allowed to desorb moisture under laboratory conditions (24 ± 0.07°C and 34 ± 0.29% relative humidity) until the fuel moisture contents of the fuelbeds reached 11, 9 and 7% ($n = 4$ per treatment). The four remaining fuelbeds were oven-dried at 60°C for 3 days and then allowed to adsorb moisture until they reached 2.5% FMC. After the fuelbeds reached treatment moisture content, they were transferred to the combustion platform and burned using the same methods described above.

Maximum flame height, flaming time, smouldering time, consumption and duration of heating above 60°C were all compared among fuel moisture treatments (2.5, 7, 9 and 11%) using GLM analysis of variance and a Tukey–Kramer post-hoc multiple comparison of the means (Sokal and Rohlf 1995). Although FMC treatments were randomly assigned to fuelbeds, all replicates within an FMC treatment were burned before burning of subsequent FMC treatments owing to the method of allowing fuelbeds to dry until treatment FMC was reached. Relative humidity and temperature were recorded in the laboratory for all burns and did not differ among FMC treatments ($P = 0.11$ and 0.24 respectively).

Results

Effect of particle fracturing on fire behaviour

Laboratory burning of *Arctostaphylos manzanita* showed that maximum flame height, ranging from 53 to 91 cm, differed significantly ($P < 0.001$) between fractured *v.* intact fuel types, and fuel moisture treatments ($P = 0.002$) (Table 1). Maximum flame heights were 36% higher in the intact fuelbeds compared with fuelbeds composed of fractured particles and 25% higher in the drier (5% FMC) fuelbeds compared with the wetter (13% FMC) fuelbeds. Differences were also detected in duration of flaming between FMC ($P = 0.009$) and fuel type ($P = 0.042$), with flaming times being longer (21.1 min) in wetter fuelbeds (13% FMC) than in the drier fuelbeds (15.6 min) and longer in fractured particles (20.4 min) than intact particles (16.3 min) (Table 1). There was no interaction between FMC and fuel type with regard to flame height or flaming time (Table 1). Smouldering time did not differ across FMC or fuel type, but averaged 47.6 min (Table 1). Maximum flame height and flaming time were inversely correlated ($r = -0.70$, $P < 0.001$). Fuel consumption was high across all scenarios (range 94.3 to 98.6%). Although fuel type had a significant effect on consumption ($P = 0.001$), there was some evidence of the effect of FMC ($P = 0.073$), but no significant interaction (Table 1).

Laboratory burning of *Ceanothus velutinus* showed a similar trend in direction of mean flame heights across FMC and fuel type as *Arctostaphylos manzanita*, but differences were not statistically significant (Table 2). Flaming time was longer (22.1 min) in wetter fuelbeds (13% FMC) versus drier (5%

Table 1. Effects of fuel fracturing and moisture content (FMC) on laboratory burning in masticated *Arctostaphylos manzanita* fuelbeds
Values in parentheses are ±s.e. in the units indicated above

Factors included		Flame height (cm)		Flaming time		Smouldering time (min)		Heating duration		Consumption (%)	
		Mean (s.e.)	*P*	Mean (s.e.)	*P*	Mean (s.e.)	*P*	Mean (s.e.)	*P*	Mean (s.e.)	*P*
All		72 (3.9)		18.3 (1.2)		47.6 (2.6)		14.0 (0.6)		96.4 (2.1)	
FMC (%)	5	80 (5.0)	0.002	15.6 (1.0)	0.009	43.1 (2.6)	0.072	12.6 (0.4)	0.012	95.8 (0.7)	0.073
	13	64 (4.6)		21.1 (1.7)		52.1 (4.1)		15.5 (0.9)		97.1 (0.7)	
Fuel type	Fractured	61 (3.9)	<0.001	20.4 (1.9)	0.042	46.7 (4.6)	0.707	14.6 (0.9)	0.253	94.9 (0.5)	0.001
	Intact	83 (4.2)		16.3 (1.1)		48.5 (2.8)		13.5 (0.7)		97.9 (0.5)	
FMC × Fuel type	5/Fractured	70 (3.5)	1.000	17.4 (1.6)	0.819	37.9 (2.5)	0.087	12.9 (0.9)	0.605	94.3 (0.7)	0.898
	5/Intact	91 (5.5)		13.8 (0.3)		48.2 (2.9)		12.3 (0.3)		97.2 (0.7)	
	13/Fractured	53 (3.8)		23.3 (2.8)		55.5 (6.4)		16.3 (1.1)		95.5 (0.6)	
	13/Intact	75 (2.9)		18.8 (1.4)		48.8 (6.4)		14.6 (1.3)		98.6 (0.8)	

Table 2. Effects of fuel fracturing and moisture content (FMC) on laboratory burning in masticated *Ceanothus velutinus* fuelbeds
Values in parentheses are ±s.e. in the units indicated above

Factors included		Flame height (cm)		Flaming time		Smouldering time (min)		Heating duration		Consumption (%)	
		Mean (s.e.)	*P*	Mean (s.e.)	*P*	Mean (s.e.)	*P*	Mean (s.e.)	*P*	Mean (s.e.)	*P*
All		62 (2.7)		19.6 (1.1)		57.4 (2.8)		13.9 (0.6)		94.7 (0.6)	
FMC	5	64 (2.1)	0.466	17.2 (0.9)	0.032	59.1 (2.6)	0.577	14.6 (0.5)	0.314	95.3 (1.7)	0.195
	13	59 (5.0)		22.1 (1.7)		55.8 (5.0)		13.3 (1.1)		94.1 (2.7)	
Fuel type	Fractured	60 (2.7)	0.600	19.4 (1.5)	0.838	60.6 (3.7)	0.288	14.2 (0.6)	0.629	93.4 (2.6)	0.012
	Intact	63 (4.8)		19.8 (1.8)		54.3 (4.0)		13.6 (1.1)		96.0 (0.7)	
FMC × Fuel type	5/Fractured	63 (2.5)	0.916	16.2 (0.9)	0.459	64.1 (3.5)	0.536	14.6 (0.7)	0.618	94.5 (1.1)	0.237
	5/Intact	65 (3.5)		18.1 (1.5)		54.1 (1.8)		14.6 (0.7)		96.1 (0.3)	
	13/Fractured	58 (4.8)		22.6 (1.4)		57.2 (6.6)		13.9 (0.9)		92.2 (1.3)	
	13/Intact	61 (9.7)		21.5 (3.4)		54.5 (8.4)		12.6 (2.1)		95.9 (0.5)	

FMC) fuelbeds (17.2 min) and consumption differed between intact and fractured fuelbeds (Table 2). Consumption of intact particles was ~3% higher than fractured particles (Table 2, which was similar to that found in *A. manzanita* (Table 2).

Fig. 3 shows fireline intensity (kJ s^{-1} m^{-1}), from mass loss data, during the first 30 min of all laboratory burns. Replicate burns within each graph are shown to include the variation between burns within treatment combinations. Fuelbeds composed of intact *Arctostaphylos manzanita* particles burned with greater intensity than did those created with fractured particles, and fuelbeds at 5% FMC burned with greater intensity than did fuelbeds at 13% FMC (Fig. 3). Peak fire intensity, from mass loss data (Fig. 3), was correlated with observed maximum flame heights across all burns for both *A. manzanita* ($r = 0.92$) and *Ceanothus velutinus* ($r = 0.64$). The average time in which cessation of flaming combustion occurred across replicates is indicated with a vertical line within each graph. Elevated fireline intensity, during flaming combustion, occurred for longer durations within burns with lower peak fireline intensities (Fig. 3). Differences in peak fireline intensities across treatment combinations are not apparent in *C. velutinus* fuelbeds, but the duration of elevated intensity during flaming combustion is easily observed to be longer in the wetter (13% FMC) fuelbeds. The highest fireline intensities occurred during flaming combustion (Fig. 3) where 86–97% of all energy output occurred (from integration of each curve up to the time of flaming cessation). During the phase of exclusively smouldering combustion, fireline intensity dropped below 20 kJ s^{-1} m^{-1} (Fig. 3). In the *C. velutinus* fuelbeds burned at 13% FMC (bottom of Fig. 3), there was one fuelbed of intact particles and one fuelbed of fractured particles that burned at intensities >20 kJ s^{-1} m^{-1} beyond the average time of flaming cessation. Flaming time within these two burns were 31.2 and 26.6 min respectively, and following the cessation of flaming combustion within these individual burns, fireline intensity was <20 kJ s^{-1} m^{-1}.

Generally, negative curvilinear relationships between heating duration and temperatures occurred across fuel type and FMC treatment for both species (Fig. 4) where, as expected, higher temperatures occurred for shorter durations. Duration of lethal heating (>60°C) from burning *Arctostaphylos manzanita* fuelbeds ranged from 12.3 to 16.3 min at 20 cm above the fuelbed, but differences were only found between FMCs. Burning the wetter fuelbeds caused longer durations (15.5 min) of lethal heating than the drier fuelbeds (12.6 min) (Table 1). There were no differences in duration of lethal heating (range 12.6–14.6 min) across FMC or fuel type (intact *v.* fractured) during the burning of *Ceanothus velutinus* fuelbeds (Table 2).

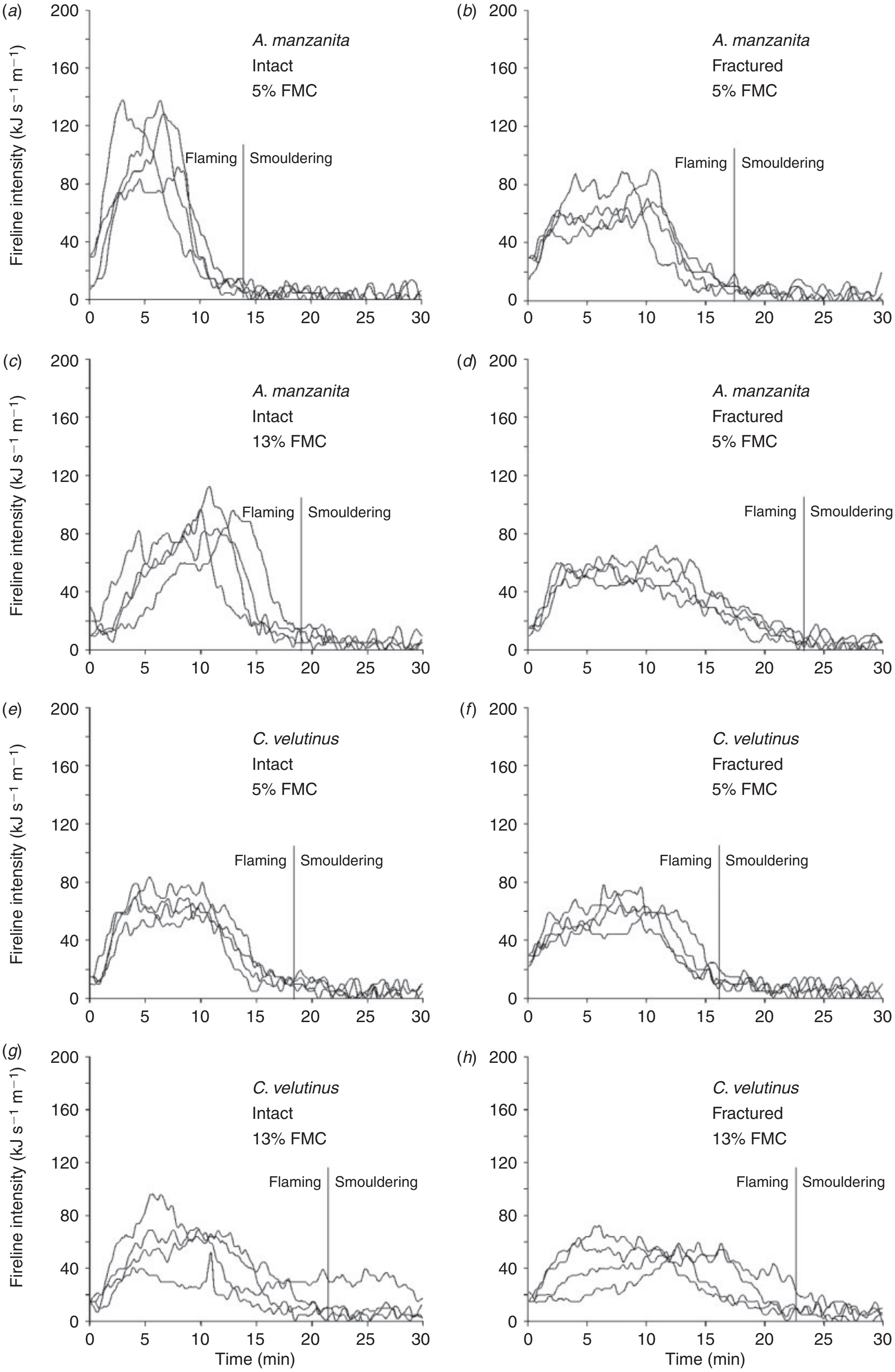

Fig. 3. Fireline intensity (kJ s^{-1} m^{-1}) by fuel type (intact or fractured particles) in *Arctostaphylos manzanita* (*a–d*) and *Ceanothus velutinus* (*e–h*) fuelbeds in small-scale burning experiments at 5% (*a–b*, *e–f*) and 13% (*c–d*, *g–h*) fuel moisture content (FMC). All four replicates are shown within each graph as separate time traces. The vertical line indicates the mean time in which flaming combustion ceased across replicates. Smouldering combustion continued for an additional 38–64 min following flaming cessation, but graphs are truncated after 30 min total burn time.

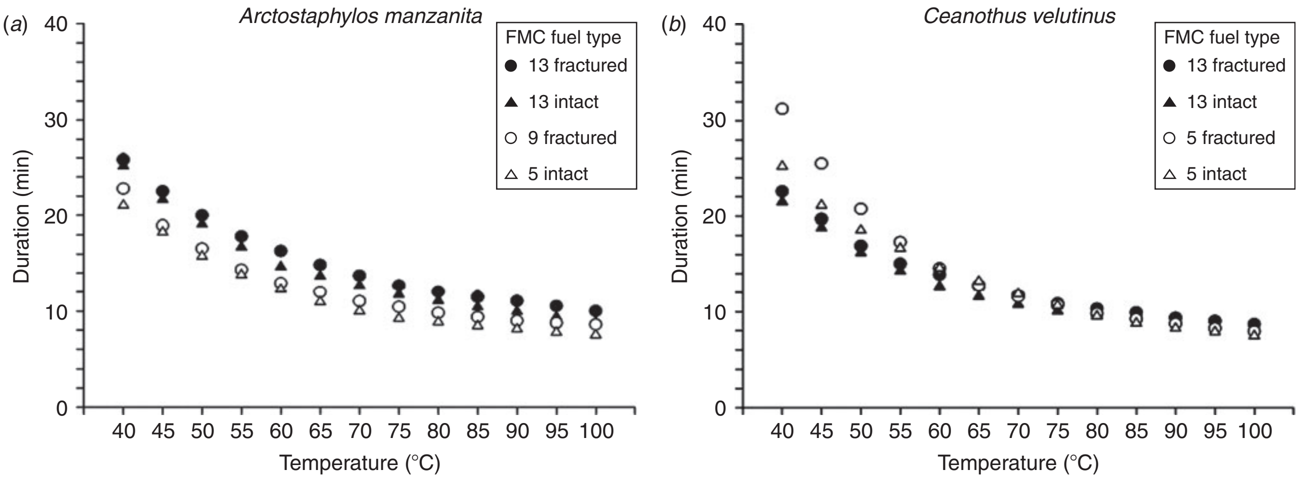

Fig. 4. Mean duration (min) exceeding a range of temperatures (°C) at 20 cm above the fuelbed–sand interface from the laboratory burning of *Arctostaphylos manzanita* (*a*) and *Ceanothus velutinus* (*b*). Open and solid symbols represent 5 and 13% fuel moisture content (FMC) respectively. Circles and triangles represent fractured and intact particles respectively.

Table 3. Fire behaviour characteristics and duration of lethal heating during laboratory burning of masticated *Arctostaphylos manzanita* fuelbeds compared across fuel moisture treatments

Values in parentheses are ±s.e. Values with similar superscripts (within columns) did not differ using the Tukey–Kramer post-hoc multiple comparison

Fuel moisture content (%)	*n*	Flame height (cm)	Flaming time (min)	Smouldering time (%)	Heating duration >60°C	Fuel consumption (%)
2.5	4	95 (6.5)^{a}	13.2 (1.2)^{a}	57.2 (7.5)^{a}	11.38 (0.69)^{a}	94.2 (1.13)^{a}
7	4	79 (5.9)^{ab}	17.3 (1.8)^{ab}	70.1 (9.6)^{a}	12.17 (0.68)^{a}	94.2 (1.24)^{a}
9	3	77 (3.3)^{ab}	17.4 (0.6)^{ab}	68.3 (3.5)^{a}	11.83 (0.60)^{a}	94.7 (0.20)^{a}
11	4	69 (1.6)^{b}	22.3 (1.0)^{b}	48.8 (4.3)^{a}	12.44 (1.54)^{a}	93.3 (1.44)^{a}

Effect of fuel moisture on fire behaviour

During the burning of masticated *Arctostaphylos manzanita*, maximum flame heights differed ($P = 0.017$), but only between the driest (2.5% FMC; 95 cm) and wettest (11% FMC; 69 cm) treatments; flame heights with FMC of 7 and 9% were intermediate (Table 3). Also, as fuel moisture increased, total duration of flaming combustion increased, but significant differences ($P = 0.003$) were only detected between the driest (2.5% FMC; 13.2 min) and the wettest (11% FMC; 22.3 min) fuel moisture treatments (Table 3). Smouldering time ranged from 48.8 to 70.1 min among FMC treatments, but differences were not significant ($P = 0.170$). Fuel consumption did not differ ($P = 0.869$) among fuel moisture treatments, and was high across all scenarios ($\bar{x} = 94.1\%$). Among FMC treatments, maximum flame height and flaming time were inversely related ($r = -0.86$, $P < 0.001$).

Although there was variation among burn replicates within fuel moisture treatments (Fig. 5*a*–*d*), maximum fireline intensity was higher (up to 118 kJ s^{-1} m^{-1}) and peaked earlier with the driest fuelbeds (FMC 2.5%; Fig. 5*a*). At 7 and 9% FMC, peak fireline intensity was lower (100 and 90 kJ s^{-1} m^{-1} maximum respectively) than the 2.5% FMC treatment, but was sustained at high intensity for a longer duration (Fig. 5*b*, *c*). For example, average fireline intensities >20 kJ s^{-1} m^{-1} were sustained for ~17 min at 7 and 9% FMC whereas the same intensities were sustained for only 14 min at 2.5% FMC. The highest fuel moisture treatment (11%) resulted in the lowest peak fireline intensity (60 kJ s^{-1} m^{-1} maximum), but elevated intensities occurred for longer durations (Fig. 5*d*). Fireline intensities >20 kJ s^{-1} m^{-1} occurred for ~22 min in fuelbeds at 11% FMC. These durations (>20 kJ s^{-1} m^{-1}) correspond well with the average flaming time measured during burning (Table 3). Between 89 and 96% of the total energy released during burning occurred during this flaming phase. Following the cessation of flaming, where smouldering combustion occurred exclusively, fireline intensity remained less than 20 kJ s^{-1} m^{-1} (Fig. 5).

Temperatures above the fuelbeds were elevated across all moisture treatments and as expected, negative curvilinear relationships between heating duration and specified temperatures occurred (Fig. 6). Duration (min) of lethal heating (>60°C) did not differ between fuel moisture treatments (Table 3, $P = 0.881$). Our hypothesis that fireline intensity decreases and combustion time increases with higher FMC in masticated fuelbeds was supported, but there was no support that differences in FMC, ranging from 2.5 to 11%, cause differences in duration of lethal heating at 20 cm above the fuelbed.

Discussion

The results of this study were counter to our hypothesis that particle fracturing would increase fire intensity. Flame lengths were not greater in fractured particles compared with intact particles in fuelbeds composed of *Ceanothus velutinus*, and

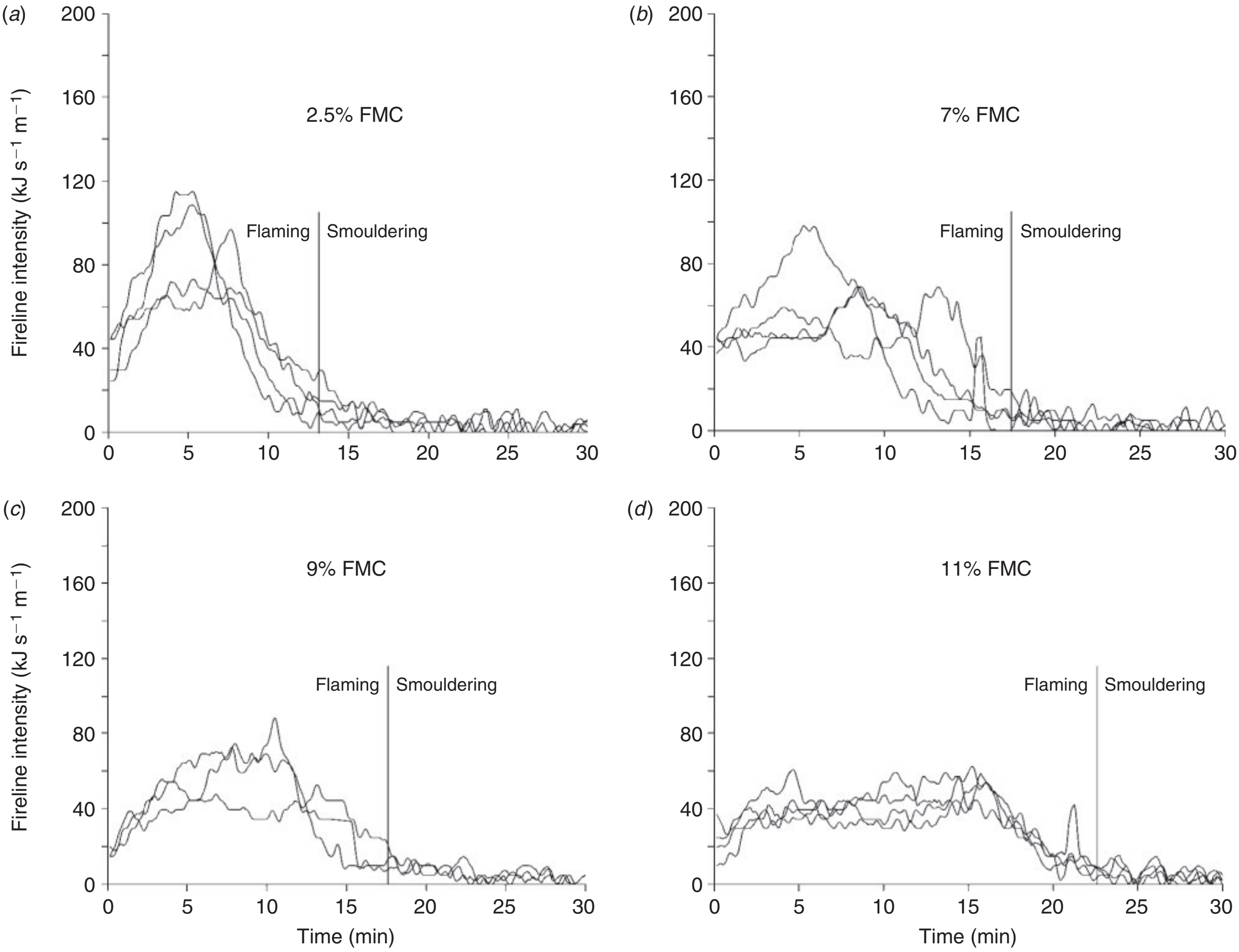

Fig. 5. Fireline intensity (kJ $s^{-1} m^{-1}$) by fuel moisture content (FMC) in *Arctostaphylos manzanita* fuelbeds at fuel moisture contents of 2.5% (*a*), 7% (*b*), 9% (*c*) and 11% (*d*). All four replicates are shown within each graph.

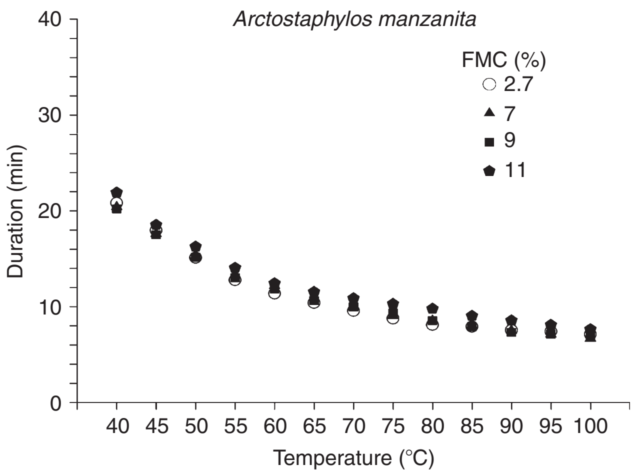

Fig. 6. Mean duration (min) above a range of temperatures (°C) at 20 cm above the fuelbed–sand interface during laboratory burning of masticated *Arctostaphylos manzanita* among fuel moisture content (FMC) treatments.

were actually less in fractured compared with intact particles in fuelbeds composed of *Arctostaphylos manzanita*.

Although fuel loading and fuelbed depth were similar across constructed fuelbeds, other fuelbed or particle properties may have influenced fire behaviour in the *Arctostaphylos manzanita* fuelbeds that we cannot fully explain. The diameter, the shape and the number of particles within a fuelbed can influence heat transfer during combustion (Rothermel 1972; Bradshaw *et al.* 1983). The use of timelag categories minimised variation between particle thicknesses across fuelbeds, but even with the partitioning of fuel mass into timelag categories, the number of particles or the average particle diameter within each size category may have differed slightly between masticated and intact fuels. However, the same methodology was used with *Ceanothus velutinus* fuelbeds as well, and doesn't explain why the differences were found primarily in *A. manzanita*. At the particle level, bark retained on intact *A. manzanita* may have properties that increase flammability and influence fire behaviour characteristics, although this is unknown. Also, because intact particles of *A. manzanita* were collected from a handpile and not from surface fuels, there may have been particle-level differences because they were elevated above ground for the 18 months following treatment whereas fractured particles were lying at the ground surface. *C. velutinus* particles were all collected from the ground surface and at a much higher elevation (1860 m), compared with Mad River (285 m). Site conditions or differences in physical characteristics by species (Countryman 1982) may result in differences in particle degradation that might subdue any effects of particle fracturing on combustion in *C. velutinus*. We cannot fully explain the increased fire intensity with intact fuel particles compared with fractured particles in *A. manzanita*, but the lack of increased fire behaviour in fractured particles compared with cylindrical particles suggests that the fractured shape of masticated particles does not significantly increase the rate of combustion when other fuelbed properties are controlled, at least for these two species.

Although particle fracturing didn't increase fire behaviour, both fractured and unfractured fuelbeds sustained flaming combustion with fireline intensities ranging from 60 to 140 $kJ\,s^{-1}\,m^{-1}$, in spite of fuelbed compactness. The results of these laboratory experiments fit those observed during the burning of masticated *Arcostaphylos* spp. and *Ceanothus* spp. in the field (Bradley *et al.* 2006; Kobziar *et al.* 2009; Knapp *et al.*, in press), providing further evidence that fire in masticated fuels isn't inhibited by their high bulk density. Furthermore, long-duration heating occurred above the fire front for fuelbeds of both species (*Arctostaphylos manzanita* and *Ceanothus velutinus*), regardless of particle fracturing or fuel moisture content.

Although reduced fire intensity and increased flaming time under wetter FMC in our second experiment were both expected, the lack of influence of fuel moisture on heating duration was not. The combined role of fuel moisture subduing fire intensity while prolonging flaming time may account for the lack of significant differences in duration of heating across the 2.5 to 11% fuel moisture treatments. This suggests that both intensity and flame residence time influence heating duration. The only influence of FMC on duration of heating found in this study was in our first experiment, where higher fuel moisture (13%) actually prolonged heating across both intact and fractured *Arctostaphylos manzanita* fuelbeds. Long-duration heating may result in root damage (Swezy and Agee 1991) or cambial damage (Ryan and Frandsen 1991) even under lower fireline intensity owing to extended exposure of vascular tissues to heat fluxes. Developing burn prescriptions that limit potentially detrimental effects will require a better understanding of how masticated fuels burn across varying conditions in the field.

Smouldering duration did not differ among fuel moisture treatments in this study. This may largely be due to the methodology of measuring smouldering time as the time elapsed when glowing combustion can no longer be seen under dark conditions. Smouldering times were often lengthy owing to a small fraction (<1% of fuel particles) glowing for extended periods, as has been observed in other fire experiments (Kane *et al.* 2008). In smouldering duff fuels, moisture content subdues fuel consumption (Frandsen 1987), yet fuel consumption in this experiment was not affected by fuelbed moisture. All fuelbed moisture levels were beneath the threshold at which combustion is limited. Busse *et al.* (2005) did not find differences in consumption in masticated fuels across two disparate moisture treatments (2 and 16% FMC). Busse *et al.* (2005) also suggested that the rapid burning of masticated residues led to relatively little smouldering combustion in comparison with other slash type fuels. Although smouldering times were up to 60 min in the present study, the majority of total combustion (93.5%) occurred during flaming, leaving a relatively small portion of potential energy available during the smouldering phase. Total combustion time (flaming and smouldering) was lengthy for burning such small fuelbeds. Average burning times in our study ranged from 70 to 87 min across fuel moisture treatments. For comparison with other types of surface fuel, Fonda (2001) found total burning time of western USA pine litter in similar-sized fuelbeds and under similar moisture conditions (15 g arrayed in a 35 × 35-cm fuelbed; ~2% FMC) to range from 3.5 to 7 min. Combustion duration may be long in comparison with litter fuels because of higher fuel mass in conjunction with high bulk density, but may be short in comparison with combustion in underlying duff that may burn for several hours following ignition, heating underlying soil and tree roots (Haase and Sackett 1998). Masticated fuelbeds, with high fuel loading, may burn with characteristics dissimilar to either of these common fuel types (litter beds or duff), but somewhere in between.

We observed flaming times between 13 and 22 min, with flame heights ranging from 69 to 95 cm, and fuel consumption of 94% across fuel moisture treatments. For comparison, Busse *et al.* (2005) observed flaming duration of 23–26 min, flame heights of 100–110 cm, and 89–91% fuel consumption from burning larger constructed fuelbeds (90 × 90 × 7.5 cm) of masticated *Arctostaphylos* over a similar range of fuel moisture contents. Although flaming duration is difficult to precisely compare owing to differences in fuelbed size, ignition technique and lack of steady-state fire spread, our flame heights and fuel consumption were comparable, averaging 80 cm and 94% respectively. In prescribed fires in masticated *Arctostaphylos* and *Ceanothus* in northern California, USA, Knapp *et al.* (in press) observed flame lengths to average 35 cm with backing fire and 72 cm with heading fire. Kobziar *et al.* (2009) observed 70- and 110-cm flame lengths during prescribed burning of masticated *Ceanothus cordulatus* (Kellog) and *Arctostaphylos patula* (E. Greene) shrubs, as well as small trees (<23 cm) in the understorey of ponderosa (*Pinus ponderosa*, Dougl. ex P. & C Laws.) and Jeffrey (*Pinus jeffreyi*, Grev. & Balf.) pine plantations in northern California. Glitzenstein *et al.* (2006) prescribed-burned chipped 5- to 15-cm-deep fuelbeds in South Carolina, USA, loblolly pine (*Pinus taeda* L.) flatwoods with a variety of midstorey shrubs and observed 35-cm flame lengths. Fuel moisture contents within these field studies fall within the range of FMCs tested here. Fire behaviour within similar FMCs was consistent across these studies and with our observed fire behaviour under laboratory conditions.

By converting vertically oriented live fuels into dense dead surface fuels, mechanical mastication reduces the potential for canopy ignition in sites containing residual trees, but the resulting fuel complex may lead to unforeseen fire effects when wildfires or prescribed burning occurs. In locations, such as the wildland–urban interface, where creating fire buffers to minimise the risk for canopy fire is important enough to offset these potential effects, mastication may serve as a temporary solution. In this study, flaming combustion and lethal heating occurred at durations that dramatically exceed that of typical litter-driven surface fire. Our laboratory experiments revealed that lethal temperatures occurred for long durations regardless of the fracturing of fuel particles or FMC. The potential that elevated tree mortality occurs following burning masticated fuelbeds (Kobziar *et al.* 2009; Knapp *et al.*, in press) deserves more careful study. This, and other research on mastication treatments, should be a priority as fuels treatments continue to be widely implemented in fire-prone forests and shrublands.

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