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Moisture desorption in mechanically masticated fuels: effects of particle fracturing and fuelbed compaction

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Abstract. Mechanical mastication is increasingly used as a wildland fuel treatment, reducing standing trees and shrubs to compacted fuelbeds of fractured woody fuels. One major shortcoming in our understanding of these fuelbeds is how particle fracturing influences moisture gain or loss, a primary determinant of fire behaviour. To better understand fuel moisture dynamics, we measured particle and fuelbed drying rates of masticated *Arctostaphylos manzanita* and *Ceanothus velutinus* shrubs, common targets of mastication in fire-prone western USA ecosystems. Drying rates of intact and fractured particles did not differ when desorbing at the fuelbed surface, but these particles did dry more rapidly than underlying fuelbeds. Average response times of 10-h woody particles at the fuelbed surfaces ranged from 16 to 21 h, whereas response times of fuelbeds (composed of 1-h and 10-h particles) were 40 to 69 h. Response times did not differ between fuelbeds composed of fractured woody particles and fuelbeds composed of intact particles ($P = 0.258$). Particle fracturing as a result of mastication does not affect the drying rate, but the longer-than-expected response times of particles within fuelbeds underscores the needs to better understand fuel moisture dynamics in these increasingly common fuels.

Additional keywords: *Arctostaphylos*, *Ceanothus*, mechanical fuel treatment, moisture dynamics, timelag.

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Introduction

Mechanical mastication is a fuel treatment aimed at reducing fire hazard by disrupting the vertical continuity of shrub and small-tree fuels (Kane *et al.* 2009; Reiner *et al.* 2009). Mastication, sometimes referred to as 'chipping' (Glitzenstein *et al.* 2006), 'mowing' (Menges and Gordon 2010), 'mulching' (Battaglia *et al.* 2010), or other terminology, is the process by which living shrubs and small trees are reduced into a highly compacted surface fuelbed composed of small-diameter fractured particles via mechanical shredding (Kane *et al.* 2009). Although mastication projects are increasingly being implemented across the western United States (Busse *et al.* 2005; Stephens and Moghaddas 2005; Bradley *et al.* 2006; Hood and Wu 2006; Perchemlides *et al.* 2008; Fontaine *et al.* 2009; Kane *et al.* 2009; Kobziar *et al.* 2009; Battaglia *et al.* 2010; Knapp *et al.* 2011), the south-eastern United States (Glitzenstein *et al.* 2006; Menges and Gordon 2010) and internationally (Molina *et al.* 2009; Castro *et al.* 2010), there is little known regarding the effects of mastication on subsequent fire behaviour or the ecological effects of their implementation (Sharik *et al.* 2010). In order to fully understand the effectiveness and potential consequences of this extensively used, but fairly novel, fuel treatment, establishing fundamental information required for predicting both fire behaviour and fire effects in these treatments is very much needed.

Prescribed fires have been conducted within masticated sites resulting in unexpected fire behaviour (Bradley *et al.* 2006). Laboratory and small-scale field burning in masticated fuelbeds reveals long-duration heating and high fuel consumption (Busse *et al.* 2005; Knapp *et al.* 2011; Kreye *et al.* 2011). Past research (Kobziar *et al.* 2009; Knapp *et al.* 2011; Kreye *et al.* 2011) and observations by managers (Reiner *et al.* 2009) highlight substantial underestimates of both fire behaviour and effects. For example, Kobziar *et al.* (2009) observed greater fire intensity, flame lengths, rate of spread and fire size than predicted by fire modelling during field experiments. Kreye *et al.* (2011) observed 0.95-m flame lengths, 94% consumption and long-duration (12 min) lethal surface heating from burning fuelbeds in laboratory experiments that were not predicted to burn using the BehavePlus fire modelling system (Andrews *et al.* 2005) based on Rothermel's (1972) commonly used fire spread model (J. Kreye, unpubl. data). And Knapp *et al.* (2011) observed substantially greater crown scorch during experimental field burning than model predictions.

One possible reason that masticated fuels burn differently than expectations may be due to alteration in drying properties when fuel particles are fractured. A survey of 10 masticated sites in northern California and southern Oregon showed that masticated fuelbeds were between 4.6 and 8.0 cm deep with >80% of loading composed of pieces in the 1-h and 10-h timelag categories. Many of the particles were fractured by mechanical mastication, which decreased average particle diameter and generated irregular shapes (Kane *et al.* 2009), changes that may accelerate the rate at which fuels respond to diurnal or seasonal changes in moisture conditions. Fuel moisture is a primary predictor of surface and ground fire intensity (Byram 1963) and spread (Rothermel 1972; Frandsen 1987). If these hypothesised changes in moisture dynamics occur, mastication could abbreviate the lag in early-season drying and post-rain availability of fuels for ignition, potentially increasing the intensity and spread rate of fires in treated areas. However, fuelbed compaction could counter effects of particle-level fracturing within the fuelbed and increase response time to environmental fluctuations. High bulk densities have been observed in masticated fuelbeds, ranging between 46 and 218 kg m^{-3} (Kane *et al.* 2009), substantially more compact than typical woody fuelbeds, which range from 0.5 to 18.4 kg m^{-3} (Anderson 1982), and even greater than litter beds (37–48 kg m^{-3}, Gould *et al.* 2011; 16–147 kg m^{-3}, Anderson 1990). Although fractured surface particles may dry quickly in response to diurnal increases in temperature and decreases in humidity (increasing potential for ignition), particles embedded within compact fuelbeds may remain moist and inhibit consumption of fuels during fires. Estimating drying rates in these fuelbeds will be important to predict the availability of masticated fuels for combustion, ultimately aiding in the prediction of fire behaviour and effects in prescribed and wild fires.

Moisture dynamics of wildland fuels are described by the timelag concept developed by Byram (1963). Timelag mathematically describes the moisture response of wildland fuels subjected to changes in environmental conditions using the parameter τ, referred to here as the response time (Viney and Catchpole 1991; Nelson 2001), derived from a simple theoretical exponential model (Byram 1963). This model has provided the foundation for research aimed at modelling fuel moisture content for fire behaviour prediction and fire danger rating systems (Lancaster 1970; Deeming *et al.* 1978).

By converting fuel moisture content to relative moisture content (Fosberg 1970) (Eqn 1), desorption rates can be compared and the response time of various fuels estimated.

$$E = \frac{(m_t - m_f)}{(m_i - m_f)} \tag{1}$$

where E is the relative moisture content, m_t is the moisture content at time t, m_f is final moisture content and m_i is initial moisture content. Relative moisture content (E) is the remaining fraction of moisture that is evaporable at a specific time during desorption from an initial moisture content to an equilibrium moisture content following a change in temperature or relative humidity. As explained by Nelson (1969), the timelag parameter is the result of physical and chemical processes that follow an exponential decay function and E could be described in terms of the response time (τ) by:

$$E = Ke^{-\frac{t}{\tau}} \tag{2}$$

where $K = 1$ when $t = 0$, $m_t = m_i$; t is in hours; τ is response time (h) for which $1 - 1/e$ (63.2%) of water loss (or gain) during desorption (or adsorption) towards m_f has occurred. By differentiating the logarithmic form of Eqn 2, the rate of change in relative moisture content can be calculated as a linear function of response time (τ):

$$\frac{d}{dt}(\ln E) = -\frac{1}{\tau} \tag{3}$$

Response time can then be calculated by solving Eqn 3 for τ.

Empirical studies have been uncertain in confirming a negative exponential response of forest fuels during moisture desorption. Van Wagner (1982) observed drying response in needle litter that closely fitted an exponential decay, whereas others (Nelson 1969; Mutch and Gastineau 1970; Anderson 1990; Nelson and Hiers 2008) have shown that moisture response in forest fuels deviates from it in various ways. Different techniques have been used to describe response times (τ) throughout desorption and adsorption processes because of such deviations. Although response time under the theoretical negative exponential model is the time required for 63.2% ($1 - 1/e$) of the total change to occur as moisture is adsorbed or desorbed from an initial stable state to that of equilibrium at another stable state, this response time can fluctuate throughout the process. When moisture response does not follow a pure exponential decay function, the derivative of the true function will be non-linear and its instantaneous slope therefore not constant.

In several studies, relative moisture content (E) has been plotted as a function of time (t) on a semi-logarithmic axis, with the resulting curves partitioned into linear sections and response time calculated for each. Nelson (1969) described two timelags, or response times τ_1 and τ_2, representing the initial and final stage of drying, but these were separated by a curvilinear portion. Mutch and Gastineau (1970) reported two linear sections, without the curvilinear portion, occurring during both desorption and adsorption in reindeer lichen (*Cladina rangiferina*). It is unclear from the literature why deviations from the theoretical negative exponential occur for some fuels. However, in comparing drying rates between fuels, Nelson and Hiers (2008) have used the response time of the initial drying period, exclusively, for comparisons. Even where significant deviations from exponential drying occur in the above studies, the initial drying response is generally linear before ~63.2% ($1 - 1/e$) of evaporable moisture loss has occurred. Although the physical basis for shifts in moisture response rates during drying is not clear, late-stage drying tends to occur when changes in moisture content are small as equilibrium is being approached. In the field, fuels are constantly adjusting to changes in environmental conditions and never reach a true equilibrium. Therefore, comparison of initial desorption responses across various types of forest fuels is likely appropriate to compare how differing fuels will react to changes of environmental moisture conditions in the field. In this study, we used a statistical procedure to partition the logarithm of relative moisture content (E) as a function of time (t) into two linear portions and focussed on the estimated response time of the initial period as the basis for our comparisons.

To address potential effects of mastication on moisture dynamics, we evaluated fuel moisture during desorption experiments in masticated fuels. Our objectives were to determine whether: (1) particle fracturing influences moisture desorption at either the fuel particle or fuelbed scale and (2) fuelbed desorption differed from that of particle desorption at the fuelbed surface. Experiments were conducted in a laboratory using *Arctostaphylos* and *Ceanothus* shrubs, two of the dominant genera in masticated treatments in northern California and southern Oregon (Kane *et al.* 2009). We hypothesised that (i) the response time of fractured particles would be shorter than the response time of intact particles and (ii) because of high fuelbed bulk density, response time of 10-h particles at the upper surface of fuelbeds would be shorter than the response time of entire fuelbeds. We tested the first hypothesis at two scales – comparing fractured and unfractured particles at the surface of fuelbeds and entire fuelbeds comprising either fractured or unfractured particles. Effects of fracturing on particle surface area-to-volume ratios were isolated from effects on particle size distributions by controlling for size effects. Our results should address potential effects of mastication-caused particle fracturing and fuelbed compaction on moisture dynamics and may help clarify moisture relationships in other non-uniform fuels.

Methods

Fuels for laboratory moisture experiments were collected from two masticated fuelbreaks in north-western California, USA, the midstorey of which was formerly dominated by shrubs. Both sites were located in north-western California: Mad River (Fig. 1), in the Six Rivers National Forest, was dominated by dense *Arctostaphylos manzanita* (common manzanita) shrubs before mastication in December 2004; Taylor Ridge, in the Klamath National Forest, was dominated by *Ceanothus velutinus* (snowbrush) before mastication in May 2005. Woody fuels were collected 18 and 14 months after mastication at the Mad River and Taylor Ridge sites respectively.

To evaluate effects of particle fracturing at the surface layer of fuelbeds (objective 1, hypothesis i) and the effect of compacted fuelbeds on desorption rates (objective 2, hypothesis ii), 24 fuelbeds (12 of each species) were created in 26×38-cm pans (Fig. 1). For all fuelbeds, the same proportion of particles in the 1-h (<6.4 mm diameter) and 10-h (6.4 to 25.4 mm diameter) fuel categories were used. Fuels >25.4 mm in diameter were excluded from experimentation because they composed a minor fraction of loading in these two sites (8.0% at Mad River and 5.7% at Taylor Ridge; Kane *et al.* 2009). Fuelbeds were constructed of 294 g of 1-h fuels and 435 g of 10-h fuels. Constructed fuelbeds were ~7 cm deep, resulting in a fuelbed bulk density of ~100 kg m^{-3}, comparable with field values observed by Kane *et al.* (2009).

Within each fuelbed, three 'fractured' and two 'intact' 10-h woody fuel particles were randomly selected and marked with wire and metal tags. 'Intact' particles escaped fracturing along their longitudinal axis during the mastication process and were relatively cylindrical (Fig. 2). Average diameter was estimated for each particle from the arithmetic mean of four measurements: the minimum and maximum diameter at one-third and two-thirds of the distance along the longitudinal axis from one end of the particle to the other. All marked particles were placed at the upper layer of their respective fuelbeds so that the upper surface of each particle was exposed to the atmosphere directly above the fuelbed.

To compare desorption of field-collected particles with particles of known size and volume, ponderosa pine and maple dowels (12.5 mm in diameter × 127 mm long) were also wired, tagged and added to all fuelbeds. Ponderosa pine dowels are used as standard fuel moisture indicators for estimating fuel moisture in the field (Gisborne 1933; Cramer 1961). Maple dowels were added because their particle specific gravity is more similar to *Arctostaphylos manzanita* and *Ceanothus velutinus* compared with ponderosa pine dowels (Kreye and Varner 2007). Although conducted under similar laboratory conditions (see below), desorption of 12 *C. velutinus* fuelbeds and the 12 *A. manzanita* fuelbeds were conducted separately in time and were therefore analysed as separate experiments.

All constructed fuelbeds were submerged in a water bath for 7 days, drained and placed in a temperature and humidity-controlled room (4.5 × 3.2 × 2.5 m) for desorption. Relative humidity (RH) and temperature were controlled (*Arctostaphylos manzanita*: RH 30.9% (±3.5), temperature 24.1°C (±1.0); *Ceanothus velutinus*: RH 28.7% (±2.4), temperature 28.4°C (±0.6)) by sealing off ventilation and running a Comfort-Aire BHD-301 electronic dehumidifier (Heat Controllers, Inc., Jackson, MI) continuously for the 336-h (14-day) drying experiment. Pans were elevated on wooden slats to allow excess moisture to drain throughout desorption via 2-mm holes punctured throughout the pans. Fuelbeds and tagged particles were weighed periodically throughout the experiment, with more frequent sampling (every 4 h) early during desorption when the rate of moisture loss was highest. Following desorption, fuelbeds and particles were oven-dried at 60°C for 72 h and weighed to obtain oven-dry mass. Specific gravity of marked masticated particles and dowels was measured by submersion of individual oven-dry particles (g) in water and measuring the resulting buoyant force (g) as recorded on a balance (ASTM 2002) whereby

$$\text{Specific gravity} = \text{oven dry weight}/\text{buoyant force} \quad (4)$$

Weight was recorded immediately following submersion to avoid overestimating density from potential water absorption.

Fuel moisture content (Eqn 5) and relative moisture content (Eqn 1) values were calculated for marked particles and fuelbeds for each time period that particles and fuelbeds were weighed during desorption. Moisture content (m) at time t was calculated by:

$$m_t = (\text{fuel weight}_t - \text{oven dry weight})/\text{oven-dry weight} \quad (5)$$

Fuel moisture content was converted to relative moisture content (E, Eqn 1) to compare desorption rates and to estimate response time. Piecewise polynomial curve fitting (Seber and

Fig. 1. Photographs of: the masticated fuelbed at the Mad River fuelbreak, Six Rivers National Forest, California (upper left); examples of a dowel (*a*), fractured (*b*) and intact (*c*) particle (upper right); and the constructed experimental fuelbeds used to quantify moisture dynamics in masticated fuelbeds (bottom).

Wild 1989) was conducted to separate curves of the natural log of relative moisture content ($\ln E$) as a function of drying time t into first and second timelag sections using linear-linear piecewise models in *NCSS* (Hintze 2007). Using Eqn 3, response time τ for all marked particles, dowels and entire fuelbeds was then calculated for both timelag sections (τ_1 and τ_2).

To determine if intact particles, fractured particles, pine dowels, maple dowels and entire fuelbeds differed in desorption rates, first timelag period response times (τ_1) were compared using general linear model (GLM) analysis of variance (GLM ANOVA) followed by a conservative Tukey–Kramer post-hoc multiple comparison of the means (Sokal and Rohlf 1995). Specific gravity was also compared across fuel types using GLM analysis of variance. Normality and equal variance assumptions were tested using the Shapiro–Wilk W-test and the modified Levene test respectively.

To address potential effects of particle shape on drying rates at the fuelbed level (objective 1, hypothesis i), 32 additional fuelbeds were created using fuels collected from both fuelbreaks. Particles of both species were separated based on whether they were fractured or not. Because mastication at Mad River site was thorough, the availability of intact particles was limited. Therefore, intact *Arctostaphylos manzanita* particles were cut from shrubs that had been hand-cut and piled adjacent to the site at the time of mastication. Mastication at Taylor Ridge resulted in a greater proportion of intact pieces, and *Ceanothus velutinus* particles were collected from within the treated area. All 32 fuelbeds were constructed with the same methods as described above ($26 \times 38 \times 7$ cm; 294 g of 1-h fuels, 435 g of 10-h fuels); the only difference was that no particles were marked nor were dowels placed within fuelbeds because response of the entire fuelbed was measured.

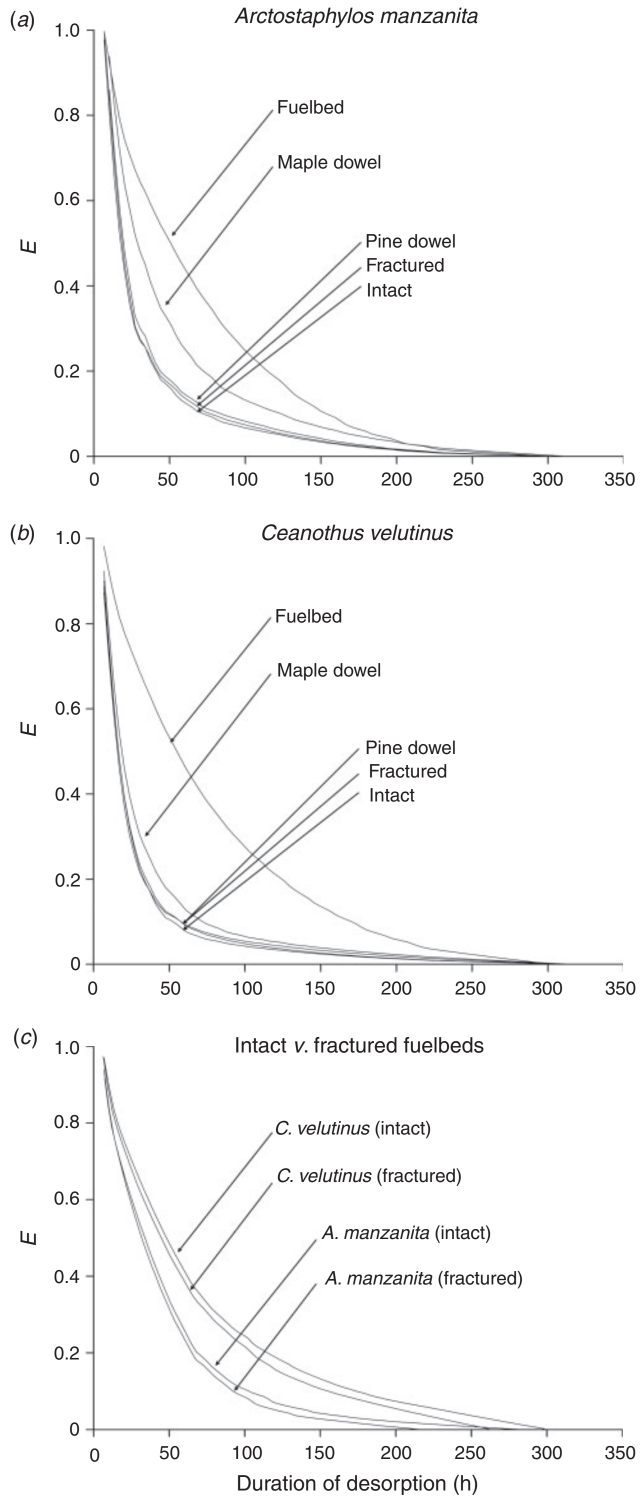

Fig. 2. Relative moisture content (E) during desorption of masticated *Arctostaphylos manzanita* fuelbeds and particles marked and placed at the upper surface of fuelbeds (a); *Ceanothus velutinus* fuelbeds and particles marked and placed at the upper surface of fuelbeds (b); and intact and fractured *Ceanothus velutinus* and *Arctostaphylos manzanita* fuelbeds (c) under laboratory conditions. LOESS curves were developed using 40% of the dataset at each LOESS calculation.

Fuelbeds were soaked in a water bath for 7 days and subsequently drained and allowed to desorb moisture under the laboratory conditions described above. Temperature and relative humidity were maintained throughout the experiment at 25.1°C (±2.0) and 28.9% (±6.1), respectively. Initial timelag period response times (τ_1) were compared across fuel types (intact *v.* fractured) and species (*Arctostaphylos manzanita* and *Ceanothus velutinus*) using a GLM analysis of variance, including both main effects and their interaction. Normality and equal variance assumptions were tested using the Shapiro–Wilk W-test and the modified Levene test respectively. Statistical significance for all analyses was assumed to be $\alpha = 0.05$.

Results

Drying rates of intact and fractured *Arctostaphylos manzanita* particles at the upper surface layer of fuelbeds were similar throughout desorption (Fig. 2*a*, Table 1), contrary to our hypothesis. Relative moisture content (E) throughout desorption (Fig. 1) and calculated response times (Table 1) for fuelbeds and marked particles are presented. Initial timelag period response (τ_1) of fractured *A. manzanita* particles (20.8 h), intact *A. manzanita* particles (19.2 h) and pine dowels (21.5 h) all of the same size did not differ; however, response time in maple dowels was longer (36.5 h) than pine dowels and *A. manzanita* particles (intact and fractured) at the upper layer of fuelbeds (Table 1). Moisture loss from entire fuelbeds (composed of both 1-h and 10-h *A. manzanita* particles; 68.5 h) was substantially slower than tagged 10-h particles at the surface of fuelbeds (19.2 to 36.5 h) (Fig. 2*a*, Table 1).

Similar results were observed during desorption in *Ceanothus velutinus* where drying rates were similar between fractured and intact *C. velutinus* particles (10-h size class) at the surface of fuelbeds, whereas drying rates of entire fuelbeds were substantially slower (Fig. 2*b*, Table 1). Response times (τ_1) of particles at the upper surface of fuelbeds did not differ between fractured *C. velutinus* particles (16.7 h), intact *C. velutinus* particles (15.8 h) or pine dowels (17.2 h) of the same size, but response time in maple dowels (24.0 h) was 40% longer than all other particles (Table 1). Response time of *C. velutinus* fuelbeds was slower (87.2 h) than all of the measured particles.

Fuel particle density differed across species, but these differences did not correspond to differences in moisture loss by species. Specific gravity of *Arctostaphylos manzanita* particles and maple dowels (0.67) was denser than *Ceanothus velutinus* (0.59), which in turn was denser than pine dowels (0.47; $F = 82.4$, $P < 0.001$).

In the experiment comparing fuelbeds composed entirely of either fractured or intact particles, drying rates throughout desorption did not differ between fractured and intact particles ($P = 0.258$) for both species (Fig. 2*c*, Table 2); however, moisture loss in *Ceanothus velutinus* fuelbeds was 57% slower than *Arctostaphylos manzanita* fuelbeds ($P < 0.001$), regardless of fracturing. No interaction was found between species and fuel type ($P = 0.820$).

Relative moisture contents (E) throughout desorption are presented for all replicates in this study in Appendices 1 and 2. In addition, whereas initial timelag period response times (τ_1) were used to compare drying rates across fuels (Nelson and

Table 1. Desorption response time (τ_1) from experimental *Arctostaphylos manzanita* and *Ceanothus velutinus* fuelbeds assembled from masticated fuels and from maple and pine dowels and intact and fractured particles of the same species as the bed
Values in parentheses are ±s.e.

A. manzanita			*C. velutinus*		
Fuel	*n*	τ_1 (h)	Fuel	*n*	τ_1 (h)
Fuelbed[B]	12	68.5 (3.7)A[A]	Fuelbed[B]	12	87.2 (2.2)A[A]
Maple dowels[C]	24	36.5 (1.9)B	Maple dowels[C]	12	24.0 (1.5)B
Pine dowels[C]	24	21.5 (1.3)C	Pine dowels[C]	12	17.2 (1.8)C
Fractured particles[D]	38	20.8 (1.1)C	Fractured particles[D]	36	16.7 (1.0)C
Intact particles[D]	22	19.2 (1.2)C	Intact particles[D]	24	15.8 (0.7)C

[A]Values with like notation within columns did not differ ($\alpha = 0.05$) using GLM (general linear model) analysis of variance and the Tukey–Kramer post-hoc multiple comparison of the means.
[B]Fuelbeds composed of woody debris (1- and 10-h particles) collected from mastication treatments.
[C]Individual 10-h dowels placed at the surface of the fuelbeds.
[D]Individual 10-h intact and fractured particles of the same species as the underlying fuelbed.

Table 2. Desorption response time (τ_1) from experimental fuelbeds composed of intact *v.* fractured *Arctostaphylos manzanita* and *Ceanothus velutinus* particles
Values in parentheses are ±s.e.

Factor	*n*	τ_1 (h)	*P*
Species			<0.001
A. manzanita (intact and fractured)	16	41.8 (2.6)	
C. velutinus (intact and fractured)	16	65.6 (3.1)	
Fuel type			0.258
Intact (both species)	16	56.1 (4.0)	
Fractured (both species)	16	51.4 (4.3)	
Species × fuel type			0.820
A. manzanita (intact)	8	43.7 (3.9)	
A. manzanita (fractured)	8	39.9 (3.6)	
C. velutinus (intact)	8	68.5 (3.0)	
C. velutinus (fractured)	8	62.8 (5.4)	

Hiers 2008), final timelag response times (τ_2) and the transition times (*J*) between τ_1 and τ_1, are reported for all comparisons in Appendices 3 and 4.

Discussion

A major concern with the increasing use of mastication is that it increases drying rates and, thus, results in more fuel consumption and more intense fire behaviour. (Glitzenstein *et al.* 2006; Kane *et al.* 2009; Knapp *et al.* 2011). In contrast to our hypothesis and manager concerns, moisture desorption rates did not differ between fractured particles and intact particles of the same size class in masticated fuelbeds. The lack of an effect of particle fracturing on desorption rates was evident at both the fuelbed and the particle level. Our results do, however, support the notion that the compact fuelbeds that result from mastication lose moisture slowly (Anderson 1990). The physical shape of masticated particles alone does not control fuel moisture desorption; rather, fuelbed properties appear to dominate moisture dynamics.

Whether moisture dynamics are controlled at the fuelbed or particle level may depend on fuelbed characteristics such as packing ratio, fuelbed depth and distribution of fuel load by diameter class. The relative dominance of fuelbed properties *v.* particle properties on moisture desorption was recently examined in experiments conducted with pine litter, where increasing packing ratio and orienting fuels horizontally both reduced drying rates (Nelson and Hiers 2008). Anderson (1990) also showed that moisture response in litter fuelbeds was slower with higher packing ratio and lower fuelbed depth and that the litter beds dried more slowly than 1.27 × 1.27-cm square pine (*Pinus ponderosa*) sticks. Individual fuel particles and litter or duff fuelbeds have been represented by cylinders and slabs respectively during theoretical moisture simulations (Viney 1992) and although such representations may be adequate, dense fuelbeds created by mechanical mastication may dry in a way that would place them somewhere between these two models.

In this study, the response times of 10-h fuel particles drying at the surface of fuelbeds (16 to 21 h) were at the upper end of the expected response times for similar fuels drying independently of fuelbeds (e.g. 12 to 13 h; Kreye and Varner 2007). Response times of particles within the fuelbeds were even longer (40 to 87 h), even though fuelbeds consisted of both 10-h (435 g) and 1-h (294 g) particles. If fuelbed properties are disregarded, moisture response time of fuelbeds would be the weighted average, by mass, of their timelag classes (6.37 h in the present study). Isolated fuel particles under desorption should react primarily to the surrounding atmosphere in response to surface tension forces or gradients in bound water and partial vapour pressure (Nelson 2001). Although masticated fuelbeds are composed of woody particles, they may dry more like dense litter beds (e.g. up to 31.6 h response time; Nelson and Hiers 2008). Increasing compaction of woody fuels in masticated fuelbeds probably creates microclimates where moisture may transfer from particle to particle and relative humidity within the fuelbed pore space may be higher than the atmosphere above the fuelbed during drying. Factors associated with water vapour flux between a dense mulch-like layer and the adjacent atmosphere (Bristow *et al.* 1986; Bussière and Cellier 1994) are likely important in these fuels. Our results suggest that masticated fuelbed characteristics affect moisture desorption more strongly than particle-level characteristics. This is at least apparent when dense fuelbeds are composed of small-diameter (1- and 10-h) fuels. Further work varying fuelbed bulk density, fuel load and fuelbed depth in moisture dynamics experiments would be necessary to address the levels at which these characteristics are influencing moisture response in compact woody fuelbeds.

The slow rate of moisture loss from masticated fuelbeds may potentially mitigate particle- or stand-scale effects (i.e. canopy reduction) that might otherwise increase drying rates following fuel treatments. Although reducing the forest and shrub canopy during fuel treatments may result in increased solar radiation or surface winds, potentially increasing surface drying (Agee and Skinner 2005), the mulching effect of compact masticated fuelbeds may mitigate their effects. Resistance of compact particle beds to vertical moisture conductance has been described in agricultural mulches (Bristow *et al.* 1986; Bussière and Cellier 1994) and dense forest litter (Matthews 2005) and may also apply to masticated fuelbeds, creating a gradient in moisture conductance with depth. In dense eucalyptus litter, vertical conductance near the litter-bed surface was shown to increase greatly under higher winds, yet the influence of wind on vertical conductance lower in the fuelbed profile was much reduced (Matthews 2005). Similarly to this work, high fuelbed bulk densities in shallow beds have been reported in other mastication-type fuel treatments: Hood and Wu (2006) in Jeffrey pine–white fir (155 kg m^{-3} and 3 cm), ponderosa pine–oak (136 kg m^{-3} and 3 cm) and pinyon–juniper (218 kg m^{-3} and 3 cm); Kane *et al.* (2009) across 10 sites in northern CA and south-western OR (46 to 115 kg m^{-3} and 5 to 8 cm); and Reiner *et al.* (2009) in ponderosa pine (125 kg m^{-3} and 4–12 cm). The slow moisture response in densely compacted fuelbeds is important to consider when evaluating the effectiveness of mastication fuel treatments.

The ability to accurately measure fuel moisture is important in fire danger rating (Deeming *et al.* 1978; Van Wagner 1987) and for predicting fire behaviour and effects when conducting prescribed burns. Results from the present study and others (e.g. Estes *et al.* 2012) suggest that the use of individual moisture indicator stick data (e.g. from remote automatic weather stations) may drastically overestimate the drying rates of masticated fuelbeds and underestimate fuel moisture content following the drying process. This may be the case not only for masticated fuels, but for any fuelbed with a high bulk density, especially as fuel moisture indicator sticks are commonly elevated above the ground. Elevated fuel-moisture indicator sticks may overestimate probability of ignition and surface fire rate of spread even for particles at the surface of masticated beds, given that our observed response times for surface particles (~20 h) were at the upper limit of their 10-h timelag range (2–20 h). Fire danger rating systems operate at scales larger than typical mastication treatments and purposefully overestimate fire danger to provide insight about the 'worst-case scenario' in wildfire situations (Deeming *et al.* 1978). For prescribed burning operations, however, drastic underestimation of fuelbed moisture content may mean that goals and objectives (e.g. fuel consumption) are not met. In order for managers to balance the potential consequences of burning masticated fuels at low fuel moisture (Busse *et al.* 2005; Kreye *et al.* 2011) against obtaining low consumption at high fuel moisture, we not only need to fully understand the effects of burning masticated fuels at various fuel moisture contents, but also be able to predict fuel moisture in these novel fuelbeds.

It appears from this study that the fractured shape of particles does not affect drying rates over and above the effect of fracturing on particle size and that the high bulk density of fuelbeds created from the mastication of shrubs and small trees dominates moisture response whereas particle level control has a small effect. Although differences in moisture drying rates were observed between two shrub species commonly masticated in California and southern Oregon, USA, the dominance of fuelbed control over moisture dynamics was observed in both. Future work on moisture dynamics in masticated fuels should be focussed on the level of control caused by fuelbed properties over a spectrum of fuel loading, fuelbed bulk density and fuelbed depth in order to develop fuel moisture prediction models to be used by fire managers in these types of fuels. Additionally, in order to scale these results to field conditions, *in situ* fuel moisture evaluation should be compared with predictions by fuel moisture models such as the Fine Fuel Moisture Code (FFMC) and Duff Moisture Code (DMC) of the Canadian Forest Fire Weather Index (Van Wagner 1987) and that of the US National Fire Danger Rating System (NFDRS) (Deeming *et al.* 1978).

Masticated fuelbeds differ in several ways from fuels described by currently used fuel models (Kane *et al.* 2009). The high fuel loading of 1- and 10-h fuels and high bulk density found in masticated sites are uncharacteristic of natural or other activity fuels. Further research into the disparity between observations and fire behaviour predicted using current fire behaviour models is warranted given observed fire behaviour (Bradley *et al.* 2006) and effects (Knapp *et al.* 2011) in these types of fuel treatments as well as fire behaviour observed under laboratory conditions (Kreye *et al.* 2011). The ability to accurately predict fire behaviour in these fuel treatments will be important for land managers as mastication treatments continue to be implemented across fire-prone forest and shrub ecosystems.

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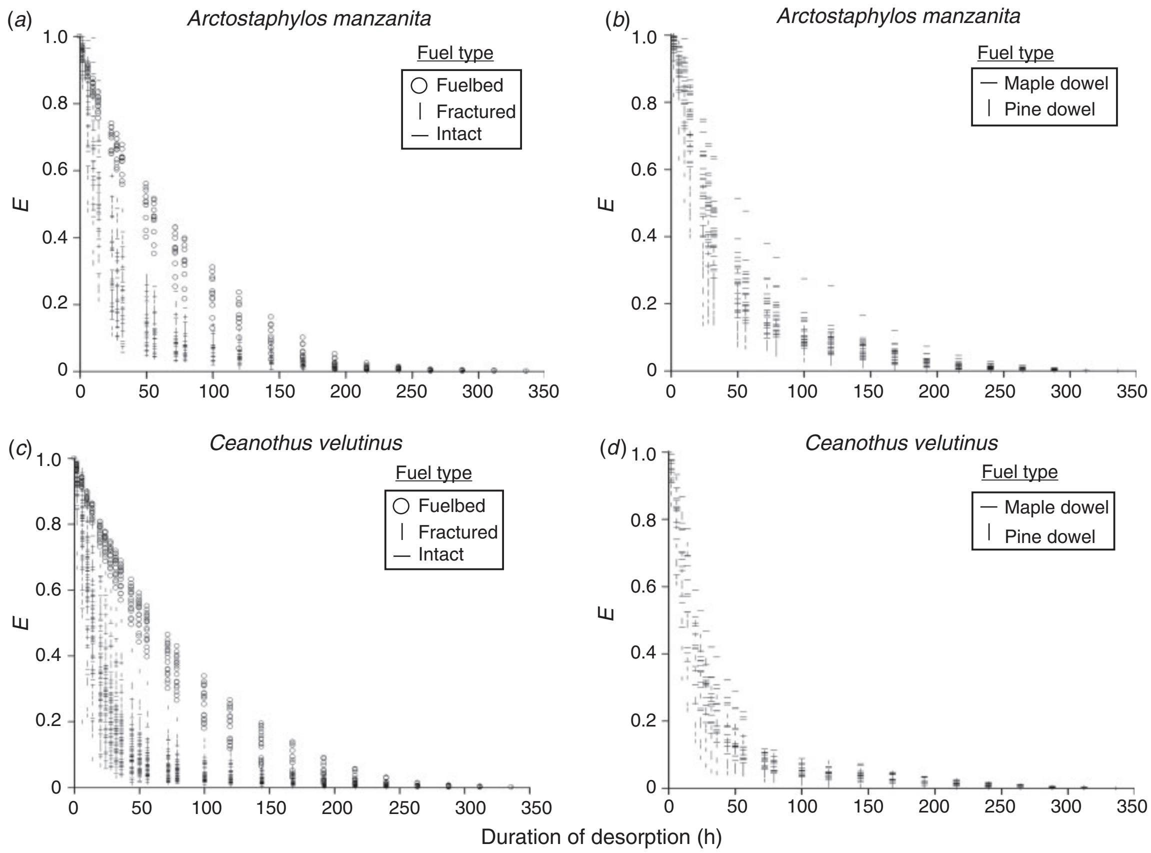
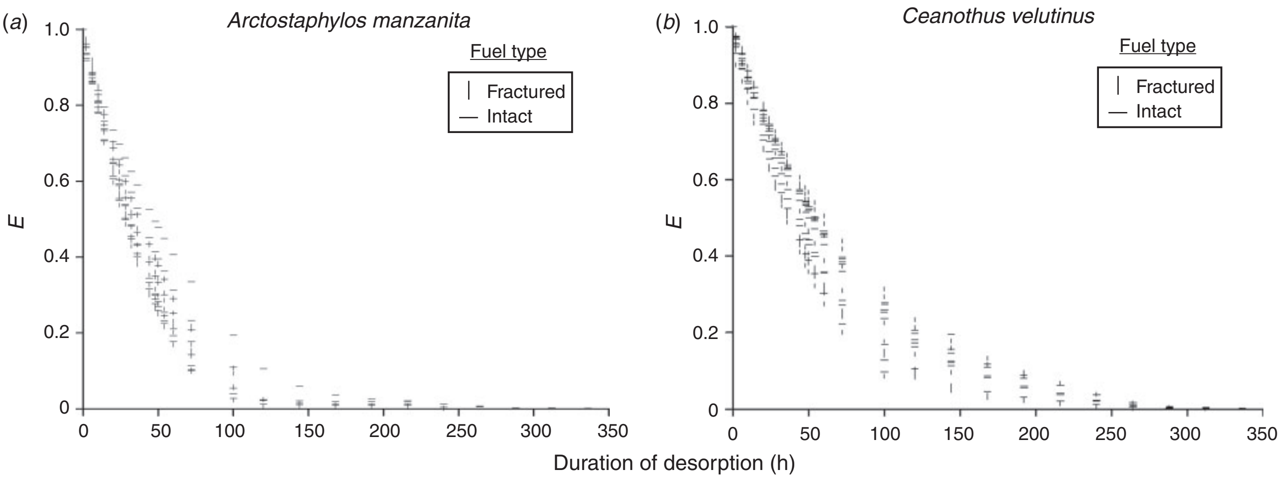
Appendix 1. Relative moisture content (*E*) data from all replicates of experimental fuelbeds, assembled from masticated *Arctostaphylos manzanita* and *Ceanothus velutinus* shrubs, and marked particles placed at the surface of the beds during moisture desorption

Fuelbeds (*a*, *c*), marked particles (intact and fractured) (*a*, *c*) and maple and pine dowels (*b*, *d*) placed at the fuelbed surface. Fuelbeds composed of woody debris (1- and 10-h particles) collected from mastication treatments. Individual 10-h intact and fractured particles of the same species as the underlying fuelbed. Individual 10-h dowels placed at the surface of the fuelbeds. Separate figure shown to enhance the clarity of replicate data



Appendix 2. Relative moisture content (*E*) data from all replicates of fuelbeds during desorption experiments of *Arctostaphylos manzanita* (*a*) and *Ceanothus velutinus* (*b*) shrubs

For both species, experimental fuelbeds were composed exclusively of either fractured or intact particles



Appendix 3. Initial response time (τ_1), final response time (τ_2) and the transition time (J) between τ_1 and τ_2 from desorption experiments of laboratory created fuelbeds composed of masticated *Arctostaphylos manzanita* and *Ceanothus velutinus* shrubs

Response time phases were partitioned by piecewise polynomial curve fitting (see Methods). Values in parentheses are ±s.e.

Fuel	*n*	τ_1 (h)	τ_2 (h)	*J* (h)
A. manzanita				
Fuelbed[A]	12	68.5 (3.7)	63.4 (3.9)	60.6 (7.5)
Maple dowels[B]	24	36.5 (1.9)	74.9 (7.0)	54.9 (2.8)
Pine dowels[B]	24	21.5 (1.3)	142.3 (34.6)	41.2 (3.0)
Fractured particles[C]	38	20.8 (1.1)	93.3 (13.6)	38.7 (2.3)
Intact particles[C]	22	19.2 (1.2)	85.1 (6.5)	41.5 (3.2)
C. velutinus				
Fuelbed[A]	12	87.2 (2.2)	75.6 (3.0)	38.4 (3.6)
Maple dowels[B]	12	24.0 (1.5)	92.4 (35.2)	46.4 (4.1)
Pine dowels[B]	12	17.2 (1.8)	74.3 (28.5)	37.4 (3.5)
Fractured particles[C]	36	16.7 (1.0)	1234.4 (837.7)	43.1 (2.4)
Intact particles[C]	24	15.8 (0.7)	206.9 (83.4)	49.0 (2.6)

[A]Fuelbeds composed of collected debris (1- and 10-h particles) from mastication treatments.
[B]Individual 10-h dowels at the surface of fuelbeds.
[C]Individual 10-h intact and fractured particles of the same species as the underlying fuelbed.

Appendix 4. Initial response time (τ_1), final response time (τ_2) and the transition time (J) between τ_1 and τ_2 from desorption experiments of laboratory created fuelbeds composed *Arctostaphylos manzanita* and *Ceanothus velutinus* shrubs

For both species, fuelbeds were created that were composed of either intact or fractured particles exclusively. Mean values between species, between fuel type (intact or fractured) and across species × fuel type combinations are shown. Response time phases were partitioned by piecewise polynomial curve fitting (see Methods). Values in parentheses are ±s.e.

Factor	*n*	τ_1 (h)	τ_2 (h)	*J* (h)
Fuelbeds				
Species				
A. manzanita (intact and fractured)	16	41.8 (2.6)	49.0 (5.5)	94.4 (15.1)
C. velutinus (intact and fractured)	16	65.6 (3.1)	43.5 (4.3)	129.3 (19.3)
Fuel type				
Intact (both species)	16	56.1 (4.0)	47.7 (5.0)	109.1 (17.5)
Fractured (both species)	16	51.4 (4.3)	44.9 (5.0)	114.6 (16.2)
Species × fuel type				
A. manzanita (intact)	8	43.7 (3.9)	48.0 (9.2)	97.5 (25.7)
A. manzanita (fractured)	8	39.9 (3.6)	50.1 (6.8)	91.4 (17.6)
C. velutinus (intact)	8	68.5 (3.0)	47.4 (4.8)	120.7 (24.8)
C. velutinus (fractured)	8	62.8 (5.4)	39.6 (7.2)	137.8 (31.0)