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Drying rates of saturated masticated fuelbeds from Rocky Mountain mixed-conifer stands

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Abstract. Mastication is becoming a popular wildland fuel treatment in the United States but little is known about how masticated fuels dry over time, especially as these atypical fuelbeds age. This report summarises measured drying rates of different-aged masticated fuelbeds built from material collected from sites that were treated using one of four mastication techniques. We recreated three replicates of masticated fuelbeds in wire mesh cages using material collected from 13 sites sampled throughout the US Rocky Mountains. These caged fuelbeds were saturated and then their moisture contents were measured daily as they dried over 10 days in both a controlled growth chamber and outdoors. Relative moisture content after 24 and 96 h of drying and a drying rate were response variables that were analysed across fuel age, drying environment and mastication method. While our sites occurred across different forest types and climates and the mastication equipment used was different, we found that all fuelbeds dried within 3% of the equilibrium moisture contents (3–6%) after ~96 h for both growth chamber and outdoors under moderately dry environments. We also found that mastication method influenced fuelbed drying rates whereas age had little effect. Fire managers may use these drying rates to implement effective prescribed burns to reduce adverse impacts when masticated fuelbeds burn during wildfire conditions.

Additional keywords: fuel drying rate, fuel layers, fuel particles, fuel treatment, mastication, moisture content, ponderosa pine, wildland fuel properties.

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Introduction

Wildland fuel mastication is commonly used for treating canopy and surface fuels in fire hazard reduction projects (Harrod *et al.* 2009; Stephens *et al.* 2012). Fuel mastication has been defined in several ways (Rummer 2006), but in this report, we define mastication as the process of mechanically modifying live and dead surface and canopy biomass by reducing ladder fuels, decreasing canopy bulk density, increasing surface fuel bulk density and raising canopy base height (Kreye *et al.* 2014). Today, there are many methods and techniques for masticating fuels, including chipping, grinding, flailing and cutting (McKenzie and Makel 1991; Halbrook *et al.* 2006; Harrod *et al.* 2009; Jain *et al.* 2012), each of which creates individual fuel particle shapes and sizes that form singular fuelbeds (Battaglia *et al.* 2010; Brennan and Keeley 2015; Jain *et al.* 2018). This wide variety of methods makes mastication a popular choice for fuels treatment across many land-management agencies and locations (Halbrook *et al.* 2006). In some wildland–urban interface areas, mastication may be the only option for reducing canopy fuels because prescribed burning treatments may pose greater threats to adjacent communities, and the public may not be tolerant of smoke from prescribed fires (Berry and Hesseln 2004; Berry *et al.* 2006; Jain *et al.* 2018).

Although mastication has been used since the 1950s (Ritter 1950; Pokela 1972; Lambert and McCleese 1977), there is surprisingly little research into aspects of the longevity of mastication treatments. Specifically, there appears to be two major aspects of mastication that have not been well studied: (1) how fast masticated fuels dry (Kreye and Varner 2007; Kreye *et al.* 2012), and (2) the effect of fuel aging on drying rates (Battaglia 2013). These topics are incredibly important because the greatest ecological damage done by mastication is when these fuelbeds burn under wildfire conditions (Kreye *et al.* 2014; Lyon *et al.* 2018). Although fire behaviour in masticated fuels may not be extreme (Kreye *et al.* 2014; Sikkink *et al.* 2017), these dense and heavy surface fuelbeds have long post-frontal combustion times and may smoulder for hours, pulsing lethal heat deep into the soil (Busse *et al.* 2005; Knapp *et al.* 2011), thereby killing many organisms, especially the residual trees (Battaglia 2013). A better understanding of drying rates and how these change as masticated particles age can help managers develop prescribed burning plans for reducing adverse ecological impacts from wildfires.

Newly masticated fuelbeds consist of amorphous chopped, shredded or crushed woody pieces with sharp edges and high surface area (Kane *et al.* 2009) that may facilitate rapid drying after rainfall (Knapp *et al.* 2011; Kreye *et al.* 2012). The properties of masticated fuel particles, such as shape, size and surface area, are often a direct consequence of the mastication equipment employed and the size, number and species of the trees masticated (Jain *et al.* 2018; Keane *et al.* 2018). However, as masticated fuel particles age, the deposited litter and fractured-wood particles decompose, resulting in major changes in both particle and fuelbed characteristics, such as reductions in particle density, fuel loadings and fuelbed depth, all of which may facilitate faster drying (Harmon *et al.* 1986; Keane 2015). Relatively little is known about how changes in structural, physical and chemical characteristics of masticated fuel particles affect fuelbed moisture dynamics, especially for Rocky Mountain sites, but the assumption is that older fuels will dry faster. Kreye and Varner (2007) and Kreye *et al.* (2012) evaluated moisture loss rates in masticated fuels and found that there were no significant differences between fractured particles and intact particles, but they did not explore the drying rates over different-aged fuels. Kreye *et al.* (2016) explored the effects of aging on fire behaviour and Battaglia (2013) examined changes in soil nitrogen and loading over time; however, neither of these studies investigated the changes in particle properties over time and their relationship to drying.

Dead fuel moisture dynamics are mostly governed by the water vapour pressure difference (dry to wet) between the atmosphere and the fuel particle (Viney 1991). This difference is primarily driven by temperature, relative humidity and the presence of water on the particle surface (Matthews 2013). If vapour pressure deficit is positive (high temperature; low relative humidity; fuel is wet), then water is lost from the particle into the atmosphere through a process known as desorption (Anderson 1985; Droin-Josserand *et al.* 1988). The free water in the intercellular space evaporates into the atmosphere, but the vapour pressure deficit (humidity difference between cell spaces and air) must be large enough to drive bound water from the cell walls (Peters and Bruch 2003). Adsorption occurs when atmospheric humidity increases and the dry fuel particles gain moisture as water molecules move from the atmosphere to adhere to the particle surface (Simard 1968; Viney 1991). If there is rain, then free water on the particle surface can be directly absorbed by the particle until the fuel particle has reached the fibre saturation point (fully saturated with water) or precipitation stops and free water on the particle surface evaporates. Water absorption and desorption in fuel particles are slow processes, especially for large woody fuels, because they are governed by many factors, including initial moisture content, particle condition (decay status, degree of fragmentation), and type and size of particle (wood, grass, needle litter) (Keane 2015). In this paper, we use the term 'drying rates' to capture both absorption and desorption.

In 2013, a comprehensive study called MASTIDON (MASTIcated fuelbed Decomposition Operational Network) was undertaken to evaluate fire behaviour, fuel properties, fuel and soil moisture dynamics, soil heating and smouldering combustion of masticated fuelbeds with different time since the last treatment (different aged) (Sikkink *et al.* 2017; Keane *et al.* 2018; Heinsch *et al.* 2018). Critical to MASTIDON objectives was the measurement of the diverse physical and chemical characteristics of masticated particles, fuel components and entire fuelbeds across sites of different times since treatment to provide context for understanding the changes in masticated fuelbed characteristics and fire behaviour over time. Masticated fuelbed properties measured in MASTIDON (Keane *et al.* 2018) were compared with time since treatment to determine if there were significant changes over time that might influence fire behaviour (Sikkink *et al.* 2017) and smouldering combustion dynamics (Reardon *et al.* 2019). Here, we present a small but important part of the MASTIDON project: the relationship of drying rates to fuelbed age and mastication method.

Study objectives

The primary objectives of this study were to describe how fast masticated fuelbeds dry over time and to determine if drying rates are related to fuelbed age (i.e. time since mastication treatment). Managers could use these drying rates to plan prescribed burns in masticated treatment areas and to determine threats to masticated areas from wildfire after rainfall (Keane *et al.* 2018). We determined drying rates at the fuelbed level and not at the particle level, which is somewhat different from past fuel moisture studies (Kreye *et al.* 2012), because we believed that the wide variety of individual fuel particles and their characteristics within masticated fuelbeds would make it difficult to interpret the subtle differences in drying between fuelbed ages and mastication method.

Methods

Study sites

A spatial chronosequence approach was used to select sites in this study to represent different treatment ages or years after treatment (Table 1) in mixed-coniferous forests of the Rocky Mountains in the western United States (Keane *et al.* 2018). After an intensive evaluation process, 15 sites were selected for the MASTIDON study based on treatment date; these sites represented seven different times since treatment (i.e. treatment dates) from 1 to 10 years. However, to get this wide range of ages, we had to accept sites that were treated by different mastication methods (MMs) and that encompassed both moist and arid mixed-conifer forests (Keane *et al.* 2018). We recognise that this introduced additional variability into the study, but it was unavoidable owing to the paucity of mastication treatments of suitable ages in only one treatment and stand type. Two sites (DC1 and UI) had to be removed for this study because we failed to gather enough material to perform the drying experiment.

Each of the remaining 13 sites had a unique set of mastication treatments that we grouped into four major MMs (Table 1) (Fig. 1). Five of the sites were cut with a rotating head with fixed teeth that was boom-mounted on a vertical shaft (VS1). Two of the sites were cut with a vertical shaft with swinging knives and front-end mounted (VS2). A horizontal shaft cutting head with fixed teeth that was both boom- and front-end mounted was used

Table 1. Characteristics of study sites sampled in the MASTIDON project (adapted from Keane *et al.* 2018)

Tree species include ponderosa pine (PP), Douglas-fir (DF), western hemlock (WH), western larch (WL), western white pine (WWP) and western red cedar (WRC). Locations: six experimental forests (EFs), one national forest (NF) and one national preserve (NP) in either the PP or PP/DF stands (dry) or the moist mixed-species stands (moist). The mastication method (MM) used these machines: horizontal shaft (HS) and vertical shaft (VS) that have either fixed teeth (FT) or swinging knives (SK) and were boom-mounted (BM) or front-end mounted (FEM) with or without a rotating head (RH). Four mastication methods are identified in this study based on the equipment used: VS1, vertical shaft fixed-teeth boom mounted on rotating head masticator; VS2, vertical shaft swinging knives front-mounted on mowing masticator; HS, horizontal shaft fixed-teeth front mounted on masticator; and CHIP, chipper. Note the DC1 and UI in the Keane *et al.* (2018) paper were not included in the drying experiment because of lack of material

Location	Study site	Mixed-conifer climate type	Dominant species	Treatment date	Age (years)	Mastication method (MM)
Boise Basin EF, Idaho	Amber	Dry	PP	2004	10	VS, FT, BM (= RH) = VS1
Manitou EF, Colorado	MEFChip	Dry	PP, DF, *Symphoricarpos albus*, *Juniperus communis*	2004	10	Chipped = CHIP
Manitou EF, Colorado	MEFWS	Dry	PP, DF, *Arctostaphylos uva-ursi*	2005	9	VS, FT, FEM (= RH) = VS1
Santa Fe NF, New Mexico	LG	Dry	PP, bunchgrass	2006	8	HS, FT, FEM = HS
Priest River EF, Idaho	PRCC1	Moist	WWP, WH, WL, *Clintonia uniflora*	2007	6	VS, FT, BM (= RH) = VS1
Valles Caldera NP, New Mexico	VC1	Dry	PP, sedge, bunchgrass	2007–08	6	HS, FT, FEM = HS
Boise Basin EF, Idaho	Amber-New	Dry	PP, DF, *Purshia tridentata*, *Symphoricarpos albus*	2010	4	VS, FT, BM (= RH) = VS1
San Juan NF, Colorado	Skelton	Dry	PP, DF, *Artemisia tridentata*	2010–11	3	VS, FT, FEM (= RH) = VS1
Priest River EF, Idaho	PR3	Moist	WRC, WH, WWP, WL	2011	2	HS, FT, FEM = HS
Black Hills EF, South Dakota	BHMix	Dry	PP, *Arctostaphylos uva-ursi*	2012	2	VS, SK, FEM (Mow) = VS2
Black Hills EF, South Dakota	BHMow	Dry	PP, *Arctostaphylos uva-ursi*, *Symphoricarpos albus*	2012	2	VS, SK, FEM (Mow) = VS2
Santa Fe NF, New Mexico	PAL	Dry	PP, sedge	2011–12	2	HS, FT, FEM = HS
Valles Caldera NP, New Mexico	VC2	Dry	PP, bunchgrass	2012	2	HS, FT, FEM = HS

on another five sites (HS) and one site was chipped (CHIP). It was difficult to ensure that mastication methods were evenly represented across all ages represented in this study because there were a limited number of sites across the western US that met all four of our selection criteria as listed above.

Eleven of the selected sites were composed of mixed ponderosa pine (*Pinus ponderosa*) and Douglas-fir (*Pseudotsuga menziesii*) stands; the remainder were composed of mixed western hemlock (*Tsuga heterophylla*), western larch (*Larix occidentalis*), western white pine (*Pinus monticola*) and western red cedar (*Thuja plicata*). All of these stands were dense, pole-size or mature stands with high fire hazard (Keane *et al.* 2018). The 13 sites in the present study were distributed from northern Idaho to New Mexico in the US Rocky Mountains and to South Dakota in the mixed-conifer forests of the Great Plains (Fig. 2). All sites were on flat ground. Pretreatment stand summaries were not available for many of these sites.

Field sampling

A detailed documentation of the field sampling methods for the MASTIDON study is presented by Keane *et al.* (2018). In summary, field sampling was conducted within a 30 × 50-m macroplot at each study site that was located in an area of the treatment unit that broadly represented the general conditions of the mastication treatment. Within each macroplot, 20 microplots were established on two 30-m transects at 5-m increments using the Hood and Wu (2006) methods for sampling masticated materials. Microplots were 1 × 1 m in size and oriented along the slope (up- and down-hill). All organic material down to mineral soil was collected from the 20 microplots, but only 10 of the microplots were used in this study. The material from the other 10 microplots was used to test burn characteristics (Sikkink *et al.* 2017; Heinsch *et al.* 2018). The material from each of the 10 microplots was sorted into three fuelbed components in the field (duff, masticated fuel and litter components) and transported to the laboratory for various MASTIDON experiments (Table 2). Keane *et al.* (2018) summarised 27 properties that were measured from the collected fuel particles.

Laboratory tasks

We constructed 39 wire cages that were 25 × 25 × 12 cm and, inside these cages, we recreated the masticated fuelbed conditions by layer (litter and woody – no duff) as found at each of the 13 masticated sites for three replicates (39 total fuelbeds) (Fig. 3). The cages were constructed from hardware cloth wired together to form five of the six sides in the desired fuelbed volume; the sixth side (top) was left open. On the bottom of the cage, we placed muslin fabric that prevented fine materials from falling through the cage. We then constructed masticated fuelbeds in each cage that resembled those masticated fuelbeds measured in the field.

Target fuel loadings for each fuel component for each cage were taken from the measured fuel loadings for the litter, duff and woody materials for the 13 sites (Table 2). High total fuel loadings were found in all masticated fuelbeds for most sites (2.6 to 9.7 kg m^{-2}). Most of the fuels were in the woody masticated layer (28 to 83%, averaging 52%), compared with litter and duff layers. Several sites contained heavy duff loadings

Fig. 1. There are two primary equipment types most commonly used for mastication (also referred to as mulching) treatments. Cutting tools placed on either a (*a*) vertical shaft (VS) (photo from amacocei.com, accessed 9 October 2018), or (*b*) horizontal shaft (HS) (photo from txbrushcutter.com, accessed 9 October 2018) using different configurations, such as (*c*) fixed teeth, swinging hammers (photo from rockhound.com, accessed 9 October 2018), and (*d*) Kut Kwick bushmaster fire mower (photo from forestfireequipment.com, accessed 9 October 2018).

(e.g. 4.6 kg m^{-2} on LG and 4.2 kg m^{-2} on VC1), but these sites also had the heaviest fuelbed loads. The greatest total fuelbed loadings were often found in the moist, northern Idaho sites (PR3 and PRCC1, with heavier than 5.0 kg m^{-2}) and the Valles Caldera sites (VC2 and VC1, with greater than 6.0 kg m^{-2}) (Keane *et al.* 2018).

We conditioned the 39 replicate fuel cages for 5 days inside a fuel warehouse at 25°C and ~30% relative humidity to reach an equilibrium moisture content. We found it was impossible to condition the fuels to a target moisture content because of the wide variety of material in each cage. The conditioned fuel cages were then placed under a set of water sprinklers and wet for 25 h (Fig. 4). We assumed that most fuel particles in the fuelbeds attained water saturation during this soaking period and validated this with occasional *ad hoc* fuel moisture measurements on the large fuel particles. The cages were weighed directly after sprinkling and placed on a solid shelf in a drying environment (DE) that consisted of an environmental chamber (chamber treatment) that was set at 26.6°C and 30% relative humidity to represent average summer conditions. We weighed all 39 cages every 24 h until either the cages reached equilibrium moisture content (i.e. weight did not change within 1% of previous measurement) or 168 h had elapsed.

To replicate moisture loss under field conditions, we designed a second experiment exactly as described above but placed the saturated fuelbeds outside in the open in the parking lot at the Missoula Fire Sciences Laboratory and weighed them every 2 h for the first 10 h, then at 24 h, and every 24 h thereafter up to 600 h (outdoor treatment, DE). The daily maximum temperatures during this time averaged 30°C and minimum temperatures averaged ~10°C with relative humidity ranging from 90% at night to 20% at 1700 hours each day. This second DE was included to evaluate the influence of desorption (drying during the day) and adsorption (water gained at night). All weight measurements for chamber and sunlit DEs were entered into a spreadsheet for analysis.

Analysis

To mitigate effects of different fuel loadings, and different woody fuel particle size and shape distributions across the different-sized woody particles in each cage across the replicates and sites on fuel drying, we calculated the relative weight of each cage with fuel (0–1) by dividing each weight measurement by the pre-wetting weight (Fig. 5 as an example). We subtracted the tared cage weight from each time-step measurement to obtain the weight of just the masticated material.

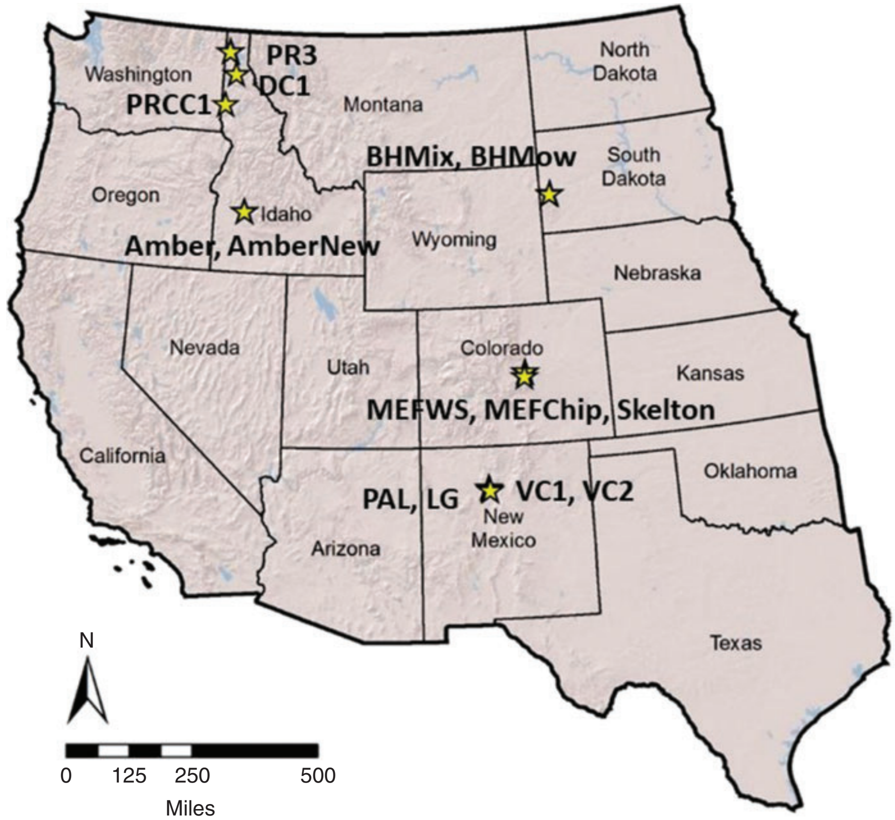

Fig. 2. Geographic distribution of the 15 study sites with definitions of site codes and site description in Table 1 from Keane *et al.* (2018).

We used relativised weights instead of moisture contents to more objectively compare drying rates. A common starting point (25 h of wetting) and ending point (equilibrium) better reflected differences in drying dynamics across replicates. However, a few replicates appeared to stabilise before reaching the prewetting weight owing to changes in local weather, especially humidity, while other samples fell below the pre-wetted weight and then stabilised. In an effort to be consistent, we normalised each relative weight measured over time to the saturated relative weight of each replicate. Equilibrium was then defined as the point at which the relative weight fell within 1% of the relativised ending weight. We calculated the moisture contents of some of the fuelbeds at the end of the elapsed time to determine the equilibrium moisture content.

We fitted a regression line through the time series of the relative weights for each of the three replicates for each site for both chamber and outdoors drying conditions (78 equations: 39 replicates and 2 DEs) after taking the natural log of the relativised weight (dependent variable) and untransformed time (independent variable). The regression equations had the following form (Kreye and Varner 2007):

$$Ln(y) = a + (bt) \quad (1)$$

which is equivalent to the equation:

$$y = \alpha e^{-bt} \quad (2)$$

where y is the relative weight (0–1), α is the intercept (dimensionlesss), b is the rate or β coefficient (BCOEFF variable) (h^{-1}), and t is time (h). All regression equations and goodness-of-fit statistics are shown in Table S.1 in the Supplementary Material by DE for every replicate.

Three response variables were analysed in the study. Two variables were taken directly from the empirical data – the 24-h relative weight (24HR) and 96-h relative weight (96HR) – and one variable was taken from each regression equation: the b coefficient (BCOEFF). The 24HR and 96HR variables correspond to timelines used in many prescribed burning plans (decision to burn within 1–4 days), while the BCOEFF indirectly represents how fast the replicates dried (the smaller the BCOEFF, the faster the drying).

We compared these statistics across DEs (chamber, outdoors), sites (13), treatment ages (AGE: old *v.* young) and mastication method (VS1, VS2, CHIP, HS) based on a mixed-model analysis with an unbalanced design with each replicate as an observation. The model was unbalanced because there were unequal numbers of observations at each of the level combinations (i.e. SITE, MM and AGE). We classified age into two classes where young = 0–6 years and old = 7+ years (time since treatment) because there were an equal number of sites in each category. We considered including geographic location as an explanatory variable but location was closely correlated with mastication method (Keane *et al.* 2018). We explored various linear mixed models (using lme4 package in *R*), considering two- and three-way interactions

Table 2. Summary of the physical characteristics, and standard error (s.e.), of masticated fuelbeds by study site (see Table 1 for code definitions and site information) and fuelbed layer (litter, duff and masticated fuels) computed from microplot samples per site

Sites are listed in order of time since treatment (age). This information was used to recreate the masticated fuelbed replicates for each site (taken from Keane *et al.* 2018)

Site code	Mastication age (years)	Number of microplots	Fresh litter Load (kg m^{-2})	s.e. (kg m^{-2})	Depth (cm)	s.e. (cm)	Bulk density (kg m^{-3})	s.e. (kg m^{-3})	Duff Load (kg m^{-2})	s.e. (kg m^{-2})	Depth (cm)	s.e. (cm)	Bulk density (kg m^{-3})	s.e. (kg m^{-3})
							Old							
Amber	10	10	1.29	0.17	3.1	0.3	42.77	4.81	0.72	0.20	2.8	0.7	29.12	6.94
MEFChip	10	14	1.10	0.26	2.2	0.3	58.84	15.88	1.64	0.36	2.2	0.3	75.70	13.31
MEFWS	9	15	0.73	0.15	1.7	0.2	39.84	6.72	0.73	0.19	0.4	0.2	83.53	34.91
LG	8	9	0.72	0.13	2.2	0.2	32.91	6.10	4.56	0.72	4.5	0.5	106.70	17.54
PRCC1[A]	6	10	0.28	0.07	0.1	0.1	0.69	0.69	0.61	0.17	2.9	0.7	26.51	8.75
VC1	6	10	0.65	0.08	2.3	0.3	31.11	5.99	4.21	0.92	4.6	1.0	162.56	54.72
AmberNew	4	10	1.24	0.25	3.2	0.4	41.29	7.94	0.82	0.23	2.3	0.5	33.54	8.97
Skelton	3	10	1.63	0.27	2.0	0.3	95.12	20.83	0.76	0.35	1.5	0.3	45.09	23.94
PR3	2	10	0.60	0.11	2.5	0.9	33.87	8.55	3.71	0.87	5.6	1.3	55.39	16.13
BHMIX	2	10	1.72	0.19	1.8	0.3	28.81	38.82	1.25	0.19	3.1	0.3	43.30	6.08
BHMOW	2	10	1.07	0.18	1.6	0.2	86.22	20.36	0.68	0.16	2.2	0.4	36.58	8.63
PAL	2	10	0.68	0.16	1.2	0.3	20.30	54.53	3.28	0.31	3.6	0.6	129.86	33.03
VC2	2	10	0.97	0.21	2.5	0.6	48.07	14.53	1.62	0.29	2.3	0.5	128.67	44.68

Site code	Mastication age (years)	Number of microplots	Masticated (0–8-cm diameter) Load (kg m^{-2})	s.e. (kg m^{-2})	Depth (cm)	s.e. (cm)	Bulk density (kg m^{-3})	s.e. (kg m^{-3})	Total fuelbed Load (kg m^{-2})	s.e. (kg m^{-2})	Depth (cm)	s.e. (cm)	Bulk density (kg m^{-3})	s.e. (kg m^{-3})
Amber	10	10	1.93	0.41	1.7	0.4	157.50	69.50	3.94	0.75	7.6	1.0	52.96	6.98
MEFChip	10	14	2.23	0.38	1.8	0.4	171.41	49.21	4.97	0.82	6.2	0.7	77.30	6.00
MEFWS	9	15	1.52	0.43	1.4	0.5	86.66	17.27	2.98	0.64	3.6	0.6	90.95	12.70
LG	8	9	3.39	0.67	2.0	0.4	239.29	67.15	8.67	1.17	8.7	0.7	102.60	13.16
PRCC1[A]	6	10	4.29	0.99	7.4	2.1	102.25	37.52	5.18	1.13	10.5	2.5	72.49	24.12
VC1	6	10	4.85	0.77	3.3	0.6	214.50	73.90	9.71	1.42	10.2	1.1	93.85	6.93
AmberNew	4	10	2.63	0.61	3.1	0.7	89.50	9.08	4.69	0.84	8.5	1.0	52.30	5.49
Skelton	3	10	2.06	0.45	2.6	0.8	137.30	53.02	4.45	0.71	6.0	0.9	79.39	13.95
PR3	2	10	3.27	0.82	3.6	1.5	140.39	70.32	7.58	1.23	11.7	1.6	70.53	12.81
BHMIX	2	10	1.17	0.24	0.7	0.2	147.10	41.95	4.13	0.48	5.6	0.5	75.34	7.32
BHMOW	2	10	0.82	0.18	1.0	0.3	123.38	38.10	2.57	0.19	4.7	0.7	65.70	8.49
PAL	2	10	3.55	0.80	2.7	0.9	177.93	44.19	7.51	1.07	7.5	0.9	101.55	10.72
VC2	2	10	3.85	0.90	2.9	0.9	155.06	46.32	6.44	0.98	7.6	0.5	90.40	10.26

[A]Depths of fresh litter in 9 of the 10 microplots for PRCC1 are zero, which results in zero values for the bulk densities in those microplots.

among variables and found that the best model (with lowest AIC – Akaike information criterion) included age, mastication method and DEs as fixed factors and site as a random factor, without any interactions. To test the significance of fixed effects, we calculated type-III analysis of variance with F-tests (using car package in R) and we tested the significance of the random effect term (i.e. site) based on likelihood ratio tests (lmerTest package in R). All statistical tests used $\alpha = 0.05$ to determine significance. Finally, we conducted pairwise comparisons among least-square-mean estimates ($\pm$s.e.) for two of the fixed effects, DE and mastication method, to determine if groups were significantly different from each other (based on 0.05 Tukey-adjusted significance level). All analyses were done in the R statistical package (Team RC 2014).

Results

Relative weights (RWs) of the masticated fuelbeds ranged from 5.3 to 92.9% (values of 0.053 to 0.929 for 24HR) of saturation after 24 h of drying in the chamber and 11.6 to 102.0% (0.116 to 1.0017 for 24HR) in the outdoors DEs (Table 3; Table S.1). These ranges were much smaller and the values much lower after 96 h of drying (from 0.0 to 4.0% in both chamber and outdoors DEs). Most masticated fuelbeds lost 50% of their weight in less than 30 h and 63.2% of their weight (timelag constant used by Fosberg *et al.* (1970)) after 35 to 55 h. The VC1 site dried the most slowly, while the BHmow site dried the quickest (Table 3). In general, actual fuelbed moisture contents at zero RW ranged from 3 to 6% across all fuelbeds.

Results of the regression analysis for the 39 replicates across both DEs revealed high coefficients of determination (R^2) for nearly every replicate (R^2 ranged from 0.65 to 0.99; $n = 78$) using our equation form (Eqn 1) (Table S.1). Two examples of regression results across each of the three replicates for one site (LG) are shown for the chamber (Fig. 5*a*) and outdoors (Fig. 5*b*) DEs. We found few differences across replicates for nearly all

Fig. 3. (*a*) The synthetic wire cage used to build the masticated fuelbed using loadings for each of the 13 study sites; and (*b*) a recreated fuelbed for LG site (Table 1).

Fig. 4. An entire set of 39 fuelbeds was placed under a set of water sprinklers for 25 h to bring the woody fuels to saturation. Sprinklers were placed at each level.

the sites (see Table S.1) with the BCOEFF values ranging from −0.059 to −0.043 for both DEs and standard errors less than 0.005 (Table 3). In general, it appears that most fuelbeds reached equilibrium with their DE at ~100 h after saturation (Fig. 5; Table 3).

In the linear mixed-model analyses, we found that after 24 h (24HR), there were no statistically significant differences in fixed effects across the 78 replicates for AGE ($P = 0.43$) but there were significant differences in MM ($P = 0.008$) and DE ($P = 0.005$) (Table 4). After 96 h of drying (96HR), we found significant effects for only DE ($P = 0.015$). Looking at model results using the β regression coefficient (BCOEFF), we found that there were significant differences in only DE (chamber v outdoors) ($P = 0.013$). SITE was a significant random effect ($P < 0.05$) in both the 24-h and 96-h mixed models, but not in the β regression coefficient model. Pairwise comparisons of the differences across MM and DE categories at 24 h (Fig. 6) showed that: (1) the HS MM under the outdoor DE was significantly different from VS2 MM under either DE; and (2) HS MM under the chamber environment significantly differed from VS1 and VS2 under the chamber environment. However, by 96 h of drying, there were no significant differences across any of the MMs and DEs (Fig. 6; Table 4).

Discussion

General findings

Nearly all of our masticated fuelbeds, regardless of mastication method or time since mastication, dried to equilibrium after ~80–100 h or ~3 days. If the relative equilibrium moisture content is ~3–6% based on initial measurements of each

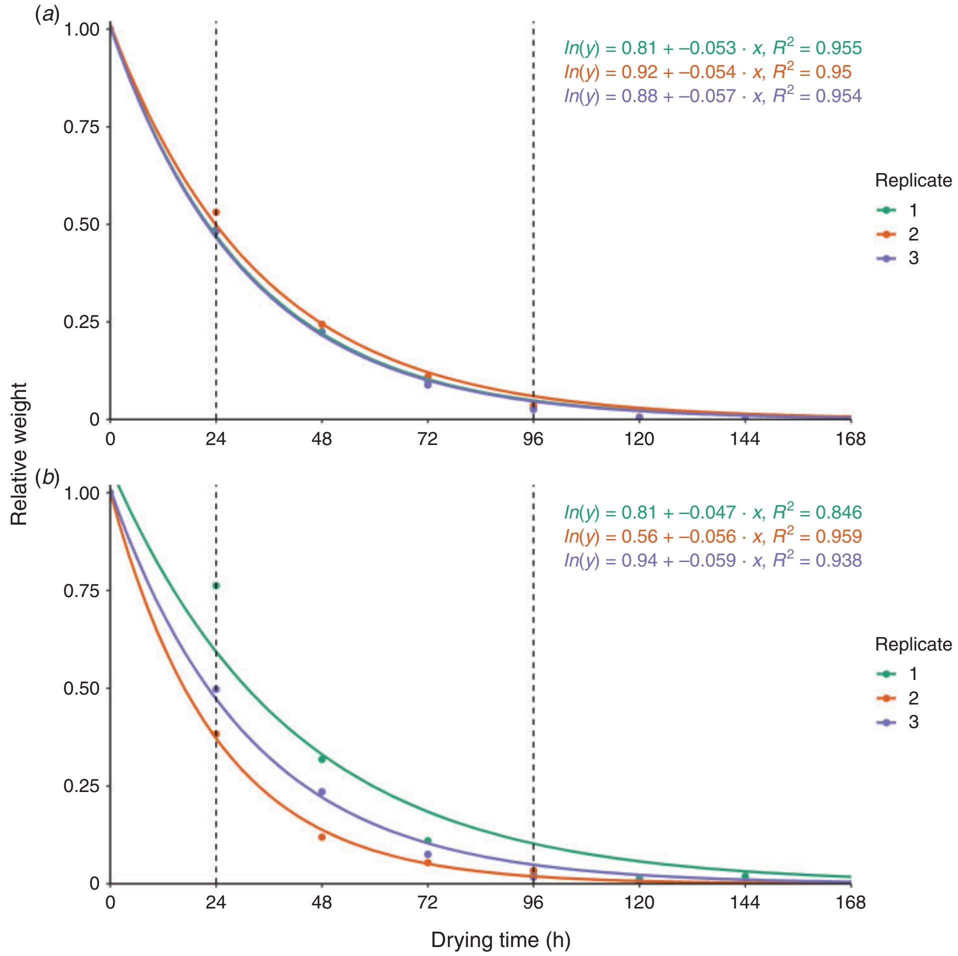

Fig. 5. The drying curves of the three masticated fuelbed replicates for the LG sample site (Table 1) when they were dried in the (*a*) chamber, and (*b*) outdoors. The two vertical dotted lines indicate the two times that were used to detect differences across age and mastication technique in the statistical analysis. Note that a regression analysis was done on each replicate and the equation and coefficient of determination (R^2) are presented for each replicate (Table S.1). The β coefficient or slope was also used as a response variable in the statistical analysis. Note: the second and third replication in (*a*) are nearly the same and right on top of each other.

fuelbed, then it is safe to assume that our masticated fuelbeds are able to burn after only 3 days judging from the results of this study. This agrees with the findings of Kreye *et al.* (2012) who found 40 to 69 h response times in masticated *Arctostaphylos manzanita* and *Ceanothus velutinus* shrubs. Our masticated fuelbeds dried to near the moisture of extinction (assumed as 20%) after just 1 day (see Figs 5 and 7) and were probably dry enough to burn after only 2 days. These findings also indicate that our masticated fuelbeds are probably capable of carrying a wildfire during most of a dry fire season.

We found clear differences in drying rates among mastication methods employed (HS differed from the other three; Table 4). Whereas drying rates across mastication methods of VS1, VS2 and CHIP fuelbeds were statistically similar, material from sites treated with horizontal-mounted equipment (HS) consistently dried at slower rates (Fig. 6). These differences were probably a result of the size of masticated particles, which could be important to managers when trying to model fire behaviour and fire effects in masticated fuels.

Similarly to other MASTIDON findings, we found that drying rates were similar across all ages of fuelbeds, even when age was expressed as a simple two-category ordinal variable (Sikkink *et al.* 2017; Keane *et al.* 2018). After 10 years, we expected woody decomposition to alter important physical characteristics such as particle density, surface area and bulk density of masticated fuels (Edmonds 1991; Berg 2000; Keane 2015), but because Keane *et al.* (2018) found few significant physical or chemical changes after 10 years of decomposition, we assumed that the lack of changes in fuelbed physical and chemical properties was responsible for the lack of difference in drying times in the present study. Kreye *et al.* (2012) also found little difference in desorption rates of masticated *v.* intact woody fuel particles. Sikkink *et al.* (2017) found some differences in the chemical compositions and some structural properties as masticated fuelbeds age, but it appears these changes had little influence on drying times.

A lack of effect from fuelbed age on drying rates can also be related to study design. First, most of the sites in our study

Table 3. A summary of the mean relative weight (RW) and standard error (s.e.) estimated from the regression analysis across three replicates ($n = 3$) for each of 13 sites (see Table 1 for descriptions) by drying environment (chamber, dried in a controlled chamber; outdoors, dried outside in parking lot) for three response variables: 24HR (relative weight after 24 h), 96HR (relative weight after 96 h), and BCOEFF (β regression coefficient in Table S.1)

Age is the years since mastication treatment. RW is a number where 1.0 indicates fuelbed weight at saturation and 0.0 signifies that the fuelbed weight at equilibrium with environmental conditions ~3–6%

		Chamber						Outdoors					
		24HR		BCOEFF		96HR		24HR		BCOEFF		96HR	
Site code	Age (years)	RW	s.e.	Value	s.e.	RW	s.e.	RW	s.e.	Value	s.e.	RW	s.e.
Amber	10	0.127	0.024	−0.059	0.002	0.002	0.001	0.320	0.112	−0.051	0.004	0.010	0.005
MEF Chip	10	0.126	0.009	−0.055	0.003	0.002	0.000	0.248	0.085	−0.049	0.005	0.008	0.004
MEF-WS	9	0.138	0.013	−0.058	0.002	0.002	0.000	0.137	0.046	−0.045	0.006	0.005	0.001
LG	8	0.643	0.019	−0.055	0.001	0.013	0.001	0.596	0.080	−0.054	0.004	0.014	0.006
PRCC1	6	0.086	0.015	−0.050	0.002	0.002	0.001	0.193	0.038	−0.053	0.006	0.005	0.002
VC1	6	0.929	0.007	−0.043	0.000	0.043	0.001	1.017	0.136	−0.045	0.003	0.043	0.013
Amber New	4	0.431	0.093	−0.053	0.004	0.011	0.005	0.543	0.106	−0.049	0.003	0.017	0.005
Skelton	3	0.254	0.032	−0.058	0.004	0.004	0.001	0.270	0.082	−0.048	0.005	0.009	0.003
PR3	2	0.712	0.026	−0.053	0.002	0.017	0.003	0.694	0.090	−0.054	0.003	0.016	0.006
BH Mix	2	0.053	0.006	−0.052	0.001	0.001	0.000	0.246	0.075	−0.049	0.004	0.008	0.003
BH Mow	2	0.072	0.008	−0.051	0.000	0.002	0.000	0.116	0.032	−0.043	0.007	0.005	0.002
PAL	2	0.743	0.019	−0.048	0.001	0.024	0.003	0.857	0.149	−0.053	0.006	0.025	0.014
VC2	2	0.344	0.029	−0.059	0.002	0.005	0.001	0.474	0.073	−0.054	0.004	0.012	0.005

Table 4. ANOVA *F* statistic and *P* value results from the three response variables: 24HR (relative weight after 24 h drying), 96HR (relative weight after 96 h) and BCOEFF (β coefficient of drying curve) for the two drying environments (DE) (chamber and outdoors), the mastication method (MM) (HS, VS1, VS2, CHIP; see Table 1), and age (AGE, time since treatment) (0–6, 6–10 years) (Table 1)

Fixed effects were DE, MM and AGE. SITE was considered a random effect and it was significant for 24HR and 96HR ($P < 0.05$); d.f. is the degrees of freedom, and the *P* value of significant response variables is in bold. We were unable to evaluate interactions because of the low number of replicates

		24HR		96HR		BCOEFF	
Covariate	Df	*F* statistic	*P* value	*F* statistic	*P* value	*F* statistic	*P* value
Intercept	1	8.217	**0.020**	0.010	0.921	816.667	**0.000**
DE	1	8.337	**0.005**	6.265	**0.015**	6.604	**0.013**
MM	3	8.371	**0.008**	1.869	0.213	0.616	0.622
AGE	1	0.688	0.431	0.604	0.459	0.657	0.522

(10 of the original 13) were warm, dry ponderosa pine sites with low precipitation and high temperatures resulting in slower decomposition rates (Keane 2008). Second, the deposition of post-treatment fuels, such as litter and woody debris from surviving trees, may have added newer fuel to aging fuelbeds, thereby influencing physical and chemical characteristics. Third, large differences in drying rates among mastication methods may have masked the effects of age (Fig. 6); we had to include a diversity of mastication methods in this study because it was logistically difficult to obtain enough sites of different ages. Finally, substantial differences in biophysical conditions across the different aged sites (Tables 1, 2) may have added uncertainty to our substitute-space-for-time chronological sampling approach (Fig. S.1). The dry, warm ponderosa pine sites were scattered over Idaho, Montana, South Dakota and New Mexico, while the mesic sites were from different stands in a small area of northern Idaho (Table 1). Combining these two site types increased variance and made it challenging to detect strong relationships with age.

Study limitations

Certainly, there were limitations in our study design that warrant cautious interpretation and direct application of our results. The most important limitation is that we used a space-for-time substitution to get different-aged fuelbeds, and, further increasing uncertainty, we found few sites in the same forest type and treated with the same mastication method. Because of the lack of suitable sites, we had to include sites that were treated by four different mastication methods and sites with two different forest types (ponderosa pine *v.* cedar and hemlock) (Table 1). This was unavoidable. As a result, additional uncertainty was introduced into the analysis that potentially masked

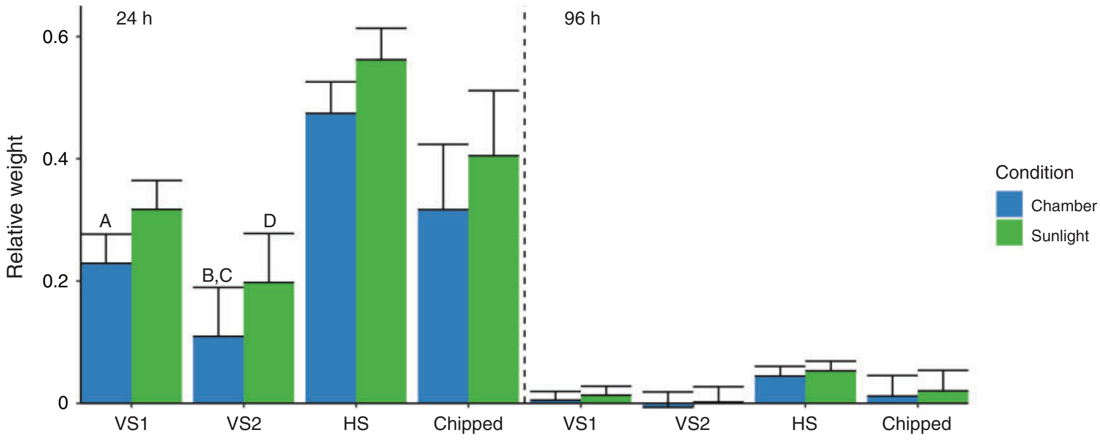

Fig. 6. Bar charts showing relative weights of the masticated fuelbed at 24 h (left) and 96 h (right) after saturation, as estimated from least square means for: the chamber (blue) and outdoors (green) drying environments and the four mastication methods, namely VS1, VS2, HS and Chipped (see Table 1). Error whiskers are one s.e., and letters indicate statistical differences ($\alpha = 0.05$) based on pairwise comparisons: (*a*) chamber, VS1 *v.* outdoor, HS; (*b*) chamber, VS2 *v.* chamber, HS; (*c*) chamber, VS2 *v.* sunlight, Hs; and (*d*) sunlight, VS2 *v.* outdoor, HS. Note that there are significant differences across techniques at 24 h but none after 96 h.

any detectable changes in drying over fuelbed age. There are many problems with the space-for-time substitution, as noted by Johnson and Miyanishi (2008), the most important being significant differences in biophysical settings across sites, but our study adds to those problems by representing different methods and forest types. However, given the great differences in conditions across our sites, it is interesting that most of our recreated fuelbeds had similar drying rates.

Another major shortcoming was that there was an uneven distribution of samples across the explanatory variables of mastication method and age. Only one site was masticated by the chipping (CHIP) method, while five were masticated with HS and VS1 methods and two with VS2. Five sites were sampled 2 years after treatment, two sites 10 years after treatment, and the remaining six sites represented 3, 4, 6, 8 and 9 years after treatments (Table 1).

Yet another source of uncertainty was that the fuelbeds were assembled by hand from the woody materials collected from each of the 13 sites (Tables 1, 2). Although it would have been more desirable to conduct our drying tests with the fuelbed *in situ* and keep local materials intact to retain compaction and material layering that occurred during mastication, this was unrealistic in terms of time, logistical and cost constraints; it would have been difficult to accurately weigh the fuelbed *in situ*. Moisture dynamics of the soil below the masticated fuels would also influence the application of our results in the field.

The design of the mesh fuelbeds, their placement on the shelf and ground, and the wetting method also influenced drying times. In nature, the masticated fuel rests on top of a soil profile without a sharp vertical edge (edge of cage), in contrast to the layering in our square wire mesh cages on top of muslin fabric. As such, our experiment represents perhaps faster drying rates than may be observed in nature because the fuelbed sides were exposed to the atmosphere and the cage was placed on a shelf or parking lot, and the procedure used to wet the fuelbeds to saturation may have resulted in a few of the larger particles never reaching saturation. Although these cages were evenly and heavily sprinkled throughout the 25 h (Fig. 4), there may have been an uneven distribution of water distribution within and across cages. Moreover, some cages had large woody chunks that may not have been fully saturated during the 25 h of sprinkling. However, we felt that the constant wetting period was more important to convey than a target moisture content of the fuel particles because it was easier and more directly understood by managers. There was such a wide diversity in size, shape and rot of each wood particle that attaining a target moisture content from particles was impractical if not impossible, and there was such large differences in the fuelbeds across sites that a target moisture content for the entire fuelbed would have been meaningless.

Management implications

The primary finding of this study is that masticated fuelbeds less than 10 years old generally took ~3 days to dry after a wetting rain regardless of how long it had been since treatment or what mastication method was used. However, hot and dry conditions will accelerate that drying time because this study was conducted using a more conservative 26.6°C and 30% relative humidity as a baseline in the chamber. We also replicated this experiment in the outdoors and found similar results. In fact, the small differences between chamber and outdoors DEs suggest that our results could be used directly in the field.

In general, most of the masticated fuelbeds in this study behaved more similarly to 10-h woody fuels than to 100-h woody fuels. We estimated a range of timelags across all replicates to be ~20–30 h as computed from saturation to 63.2% loss in weight averaging a 28-h timelag (Fosberg *et al.* 1970). This is primarily because most of the coarse woody material from tree crowns was chopped or crushed into finer pieces during mastication, and these pieces are amorphous in shape, having high surface area and exposed heartwood, all of which may facilitate rapid drying.

A set of curves was created from this study to aid fire managers in conducting prescribed burns in masticated fuels

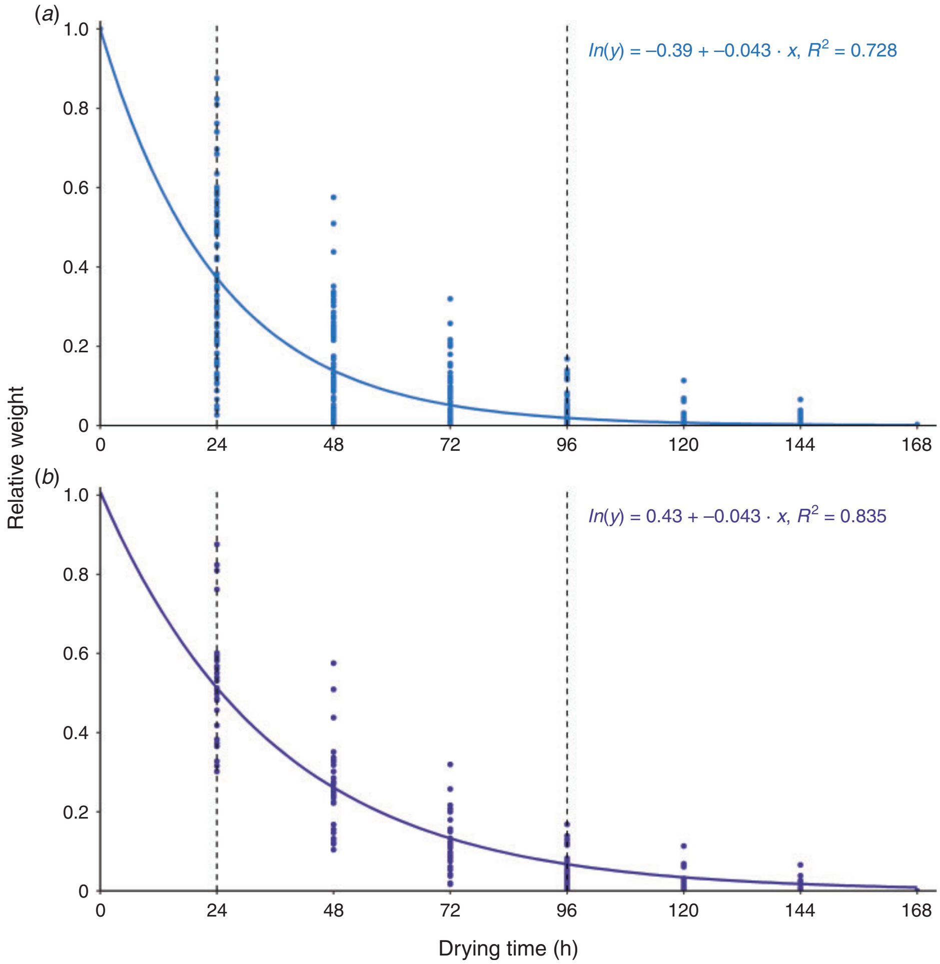

Fig. 7. Operational drying curves created for replicates across both drying environments (DE: chamber, outdoors) for four different situations: (*a*) across all sites and replicates ($n = 39$); (*b*) for only the horizontal shaft mastication method (HS). Drying environment (chamber, outdoors) observations were combined because statistical analysis found little significant differences between them for each site.

or planning for potential adverse effects of unplanned wildfires if they burn masticated fuelbeds (Fig. 7). These curves can be used to determine how long masticated fuelbeds will take to dry until they are at equilibrium with the atmosphere after a soaking rain. A generalised curve was developed using all of the data collected in the study (Fig. 7*a*) to use for all sites, even those that may not be represented in this study. A curve for data from the HS mastication treatments is provided (Fig. 7*b*) because these fuelbeds appear to dry more slowly than other three mastication methods. All other curves can be used for the other three mastication methods.

Conflict of interest

The authors declare no conflicts of interest.

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