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Fire behavior in masticated fuels: A review

Jesse K. Kreye [a,1], Nolan W. Brewer [b,c,1], Penelope Morgan [b,*], J. Morgan Varner [a], Alistair M.S. Smith [b], Chad M. Hoffman [d], Roger D. Ottmar [e]

[a] Department of Forestry, Forest & Wildlife Research Center, Mississippi State University, Box 9681, Mississippi State, MS 39762, USA
[b] Department of Forest, Rangeland, and Fire Sciences, University of Idaho, Moscow, ID 83844, USA
[c] Washington State Department of Natural Resources, 225 South Silke Road, Colville, WA 99114, USA
[d] Department of Forest and Rangeland Stewardship, Colorado State University, Fort Collins, CO 80523, USA
[e] US Forest Service, Pacific Northwest Research Station, Pacific Wildland Fire Sciences Laboratory, 400 North 34th St., Suite 201, Seattle, WA 98103, USA

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ABSTRACT

Mastication is an increasingly common fuels treatment that redistributes "ladder" fuels to the forest floor to reduce vertical fuel continuity, crown fire potential, and fireline intensity, but fuel models do not exist for predicting fire behavior in these fuel types. Recent fires burning in masticated fuels have behaved in unexpected and contradictory ways, likely because the shredded, compact fuel created when trees and shrubs are masticated contains irregularly shaped pieces in mixtures quite different from other woody fuels. We review fuels characteristics and fire behavior in masticated fuels across the United States. With insights from the few laboratory and field burning experiments conducted, we highlight the variation likely to occur across different ecosystems in which these treatments are being widely implemented. Masticated debris has a propensity to flame and smolder for long durations. Fuel variability and vegetation response will likely influence whether or not treatments reduce long-term fire hazard. We identify key science needs that will better elucidate fire behavior and effects in these treatments. With mastication widely applied in an expanding wildland–urban interface it is crucial to understand how such fuels burn. What we learn about combustion in these fuels will inform effective fuels management in these and other mixed fuels.

1. Introduction

Managing landscapes dependent on fire as an ecological process, while also mitigating the negative impacts of wildfire to people and property is challenging. In many fire-prone forest and shrubland ecosystems, vegetation structure and composition have changed, often increasing the threat of catastrophic wildfires (Agee and Skinner, 2005). Changing climate exacerbates vegetation change (Chapin et al., 2004; Linder et al., 2010; Chmura et al., 2011), potentially leading to increases in severity, frequency, intensity, and size of fires (Westerling et al., 2006; Goetz et al., 2007; IPCC, 2007; Lannom et al., in press). To protect people and property within the expanding wildland–urban interface (Stewart et al., 2007) from wildfire, fuel treatments are widely used to reduce crown fire hazard and extreme fire behavior (Agee and Skinner, 2005; McIver et al., 2008).

Mastication is an increasingly common fuel treatment primarily used in forest or shrub ecosystems. Understory trees and shrubs are "mulched", "chipped", "shredded", or "mowed" creating irregularly shaped fuel particles that effectively relocates vertical "ladder" fuels onto the ground to reduce fire hazard and improve resilience to future fires (Fig. 1a) (Kane et al., 2009; Vitorelo et al., 2009). Mastication can be used as a stand-alone treatment (Battaglia et al., 2010; Reiner et al., 2009), but may also be applied following understory thinning (Kane et al., 2009; Stephens and Moghaddas, 2005), or prior to prescribed burning (Kane et al., 2010; Knapp et al., 2011; Kreye et al., 2013a). Mastication and other fire surrogate treatments for fuels are commonly used where prescribed or wildfires would damage residual trees or other ecosystem attributes, and where prescribed burning is difficult, lacks community support, and carries high risk of exposing public to excessive smoke (Stephens and Moghaddas, 2005). Tightening restrictions as part of smoke management regulations, the expanding wildland–urban interface (WUI), and continued need for fuels management to promote healthy ecosystems all point to increased use of mastication and similar fuel treatments designed to alter fire behavior.

Unfortunately, probability of ignition, fire behavior, and duration of long-term smoldering in masticated fuels and the resultant

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* Corresponding author. Tel.: +1 208 885 7507; fax: +1 208 885 6226.

E-mail addresses: jkreye@cfr.msstate.edu (J.K. Kreye), Nolan.brewer@dnr.wa.gov (N.W. Brewer), pmorgan@uidaho.edu (P. Morgan), mvarner@cfr.msstate.edu (J.M. Varner), alistair@uidaho.edu (A.M.S. Smith), c.hoffman@colostate.edu (C.M. Hoffman), rottmar@fs.fed.us (R.D. Ottmar).

[1] These authors contribution equally to this work.

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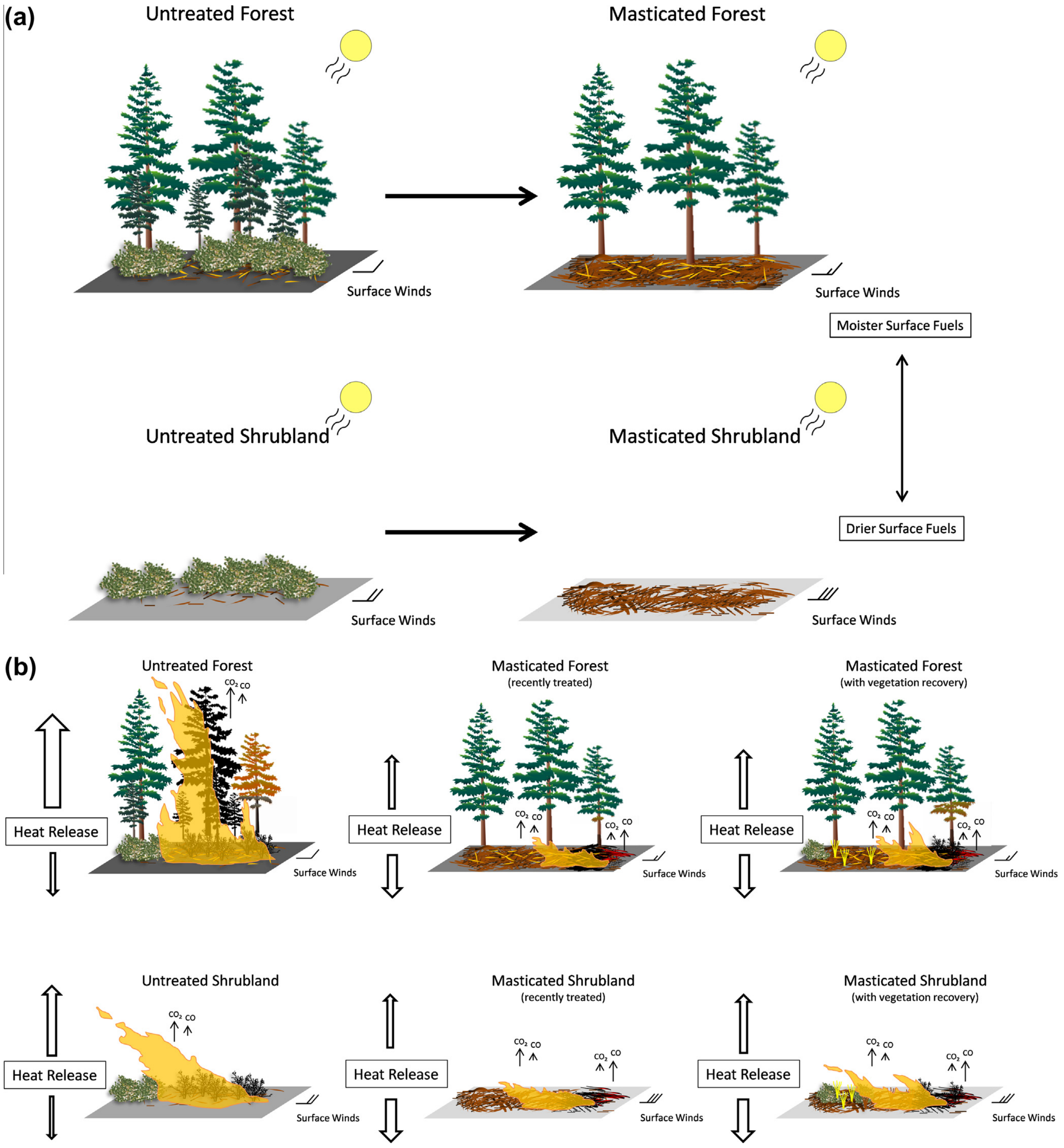

Fig. 1. Conceptual diagram of the changes in fuel conditions (a), and expected fire behavior soon after treatment and following some vegetation recovery after mastication of forests and shrublands (b). Vertical fuels (shrubs/small trees) are masticated and converted into compact surface fuels. Changes to fire behavior may be immediately dramatic, however long-term effectiveness will depend on the ability of treated vegetation to recover. The proportion of smoldering combustion relative to flaming combustion changes with mastication, as does the related heat release. The size of the heat release arrows refer to the relative proportion of heat release above and below; these are equal in all figures except for the untreated forest to indicate that a greater total heat release occurs due to crown ignition. In untreated shrublands, it is likely that only the surface fuels, and live foliage (and some live woody) are contributing to total heat release, while in the masticated shrubland, if most of the surface debris is consumed, there should be a greater total heat release because the masticated woody (now dead) will also contribute to energy output. The relative amounts of shading, surface winds, and CO and CO_2 emissions are also indicated.

effects on ecosystems are not well understood (Knapp et al., 2011; Kreye, 2012; Brewer et al., 2013; Kreye et al., 2013a). Mastication may not always reduce fire intensity and severity as is commonly assumed. Understanding the fuel characteristics of masticated sites and evaluating their effects on actual fire behavior will be important for fire prediction and evaluating treatment effectiveness. We have some understanding of how large downed woody fuels burn (Smith and Hudak, 2005; Hyde et al., 2011, 2012), but masticated fuel beds are likely a unique, compact mix of small and large fractured woody pieces (Fig. 1a, Fig. 2). Mastication is generally

Fig. 2. Masticated fuel beds typically include a mixture of size classes with many irregularly shaped pieces. Here, masticated fuel particles taken from a mixed-conifer stand in northern Idaho are sorted into 1-h, 10-h, and 100-h size classes (left to right respectively). Fuels were removed from the field 2 weeks following mastication. Note the irregular particle shapes and abundance of small diameter particles relative to logging slash.

expected to reduce the intensity and rate of spread of fire (Fig. 1b), however live fuel recovery and changes to microenvironments (e.g. increased solar radiation and surface winds; and unknown changes to fuel moisture) may complicate the long-term effects of these treatments on fire behavior (Agee and Skinner, 2005; Keyes and Varner, 2006). In addition, heat energy may be redirected to the soil surface, and as these compact fuels burn, underlying soils and adjacent plant structures (e.g. roots or basal cambia) are subjected to long duration heating. How exactly these fuel properties influence fire behavior in masticated fuels, either independently or recursively, is unknown. In this paper, we examine evidence from the few laboratory and field burning experiments conducted to elucidate anticipated effects, both in regard to masticated fuel properties and the resultant fire behavior when these fuels burn.

Our primary objectives in this review are to examine and synthesize existing knowledge of both fuel characteristics and fire behavior in masticated fuels, and to identify key science needs for better understanding and prediction of fire behavior in masticated fuels. Ecosystem researchers, fire scientists, and land managers need to understand fire behavior in masticated fuels, especially given unexpected fire behavior observed in recent fires within masticated fuel beds (Bass et al., 2012). Although the ecosystem implications of mastication and the subsequent post-fire effects have been recently highlighted (Rhoades et al., 2012) and are beyond the scope of our review, we highlight some related science and management needs in these areas. Given the likely increase in mastication treatments to reduce fire intensity in the expanding WUI and to treat fuel in wildlands, the need for science to understand and predict fire behavior, fire effects and emissions specific to when masticated fuels ignite is critical. With a wide range of treatment costs (e.g. 247–3446 US$ ha^{-1}, Vitorelo et al., 2009), such knowledge will be vital for national fiscal planning efforts both in advance of fire seasons and in effectively targeting fire suppression resources as fires burn, especially under increased wildfire and high suppression costs (Stephens and Ruth, 2005).

2. Characteristics of masticated fuels

Fire behavior is influenced directly by fuel properties that occur both at the particle and fuel bed scale (Rothermel, 1972; Frandsen, 1987). Understanding these properties in masticated fuels and evaluating how they contribute to their burning behavior is critical to predicting fire behavior in these treatments (Anderson, 1982). Masticated fuels are different than other woody fuels that result from thinning and logging in that masticated particles tend to be small, irregularly shaped and fractured, and densely compacted into shallow fuel beds. All of these factors likely contribute to differences in ignition probabilities, fire spread rates, and combustion durations from other activity fuels or natural fuel beds. For example, small fractured particles with high surface area:volume ratios may be expected to dry quickly (Anderson, 1990) and burn readily (Rothermel, 1972), however, when these particles are compacted, fuel bed properties may slow drying times (Nelson and Hiers, 2008; Kreye et al., 2012) and retard combustion (Kreye et al., 2011). Moreover, the great variability in fuel characteristics that exists across sites, ecosystems, and regions in which mastication treatments are being employed likely exacerbates these differences. Unfortunately, most of the downed woody debris fuel models used operationally for fire behavior prediction do not accurately represent the mixture of size classes, fractured particles, and arrangements commonly found within masticated fuel beds (Kane et al., 2009). Methods for quantifying mastication fuel loads vary; no clear consensus as to their relative accuracy has yet emerged. Not only do particles vary in their level of fracturing and fuel beds vary in their composition, but the spatial heterogeneity within and across masticated sites is largely unknown. In addition, temporal changes to fuels following mastication treatments may complicate generalization.

2.1. Quantifying masticated fuels

Two primary sampling methods for estimating loading in masticated fuel beds have been used: (1) modifications of the planar intercept method (Brown, 1974), and (2) versions of a destructive fixed area plot-based approach used by others (Hood and Wu, 2006; Kane et al., 2006) (Table 1). Hood and Wu (2006) found that woody fuel load estimates tended to be higher for planar intercept than for fixed area methods in mixed conifer and ponderosa pine (*Pinus ponderosa*) stands subjected to mastication. In contrast, Kane et al. (2009) found total woody fuel load estimates did not differ with sampling method. However, 1-h fuel particles were significantly greater using plot-based methods, whereas 10-h size particles were greatest using planar intercept methods (Kane et al., 2009). They attributed these biases to the assumption of cylindrical shapes for calculating fuel loads from piece counts with the line intercept method for fuels <7.6 cm diameter (Brown, 1974). Hybrid fuel load techniques combine both fixed area and planar intercept methods: 1, 10, and 100-h fuels are collected in small fixed-area frames, and 1000-h fuels are sampled by either belt transect or line intercept (Kane et al., 2009; see Table 1). Linear regression equations of masticated fuel loads based on fuel bed depth have been useful; within-site comparisons show promise, but this approach

Table 1
Masticated surface fuel loadings (Mg ha^{-1}) by fuel bed component for vegetation types studied. Sample techniques include destructive fixed-area and line-intercept (LIS) methods. Data are reported or inferred (indicated by*) from previous research.

Masticated vegetation type (State)	1-h	10-h	100-h	1000-h	Total woody	Litter	Duff	Herbaceous	Total fuel bed	Fuel depth	Woody sample methods
Lodgepole Pine (CO)[a]	16.9	19.3	5.2	5.3	46.7	10.2	11.5	0.2	68.6*	0.6–7.3	1 × 1 m plots for 1, 10, and 100-h.
Mixed Conifer (CO)[a]	23.0	24.5	10.8	5.0	63.4	27.7	19.2	0.1	110.4*		4 × 50 belt transect for 1000-h.
Ponderosa Pine (CO)[a]	8.0	18.0	7.4	5.3	38.7	13.6	10.5	0.2	63.0*		
Pinyon Pine/Juniper (CO)[a]	7.8	12.0	4.2	3.2	27.2	8.6	4.9	0.4	41.1*		
Loblolly Pine (SC)[b]	2.8	24.1	35.2	127.3	189.4*	5.3	*na*	0.2	194.9*	5.0–15.0	LIS sampling
Shrub-dominated (OR)[c]	12.3	24.6	8.6	5.3	50.7	10.3	6.7	0.0	67.8*	2.9–6.9	0.5 × 0.5 cm plot sampling
Shrub-dominated (CA)[c]	7.6	21.4	8.1	2.2	39.3	8.6	12.4	0.4	60.7*		
Shrub-dominated (CA)[c]	6.2	13.8	3.6	0.0	23.6	2.6	7.5	0.4	34.1*		
Shrub-dominated (CA)[c]	23.5	34.8	5.1	0.0	63.4	0.6	19.6	0.0	83.6*		
Shrub-dominated (CA)[c]	4.7	8.2	1.3	3.1	17.3	2.9	15.0	0.6	35.8*		
Shrub-dominated (CA)[c]	5.2	11.1	6.6	0.0	22.9	5.4	5.7	6.1	40.1*		
Shrub-dominated (CA)[c]	15.7	25.0	4.8	1.3	46.8	9.9	25.9	1.2	83.8*		
Shrub-dominated (CA)[c]	13.2	21.7	2.1	0.0	37.0	5.6	27.9	0.6	71.1*		
Shrub-dominated (CA)[c]	4.4	9.4	1.6	0.0	15.4	4.8	5.9	0.4	26.5*		
Shrub-dominated (CA)[c]	11.8	16.4	3.5	0.0	31.7	3.3	7.0	0.1	42.1*		
Mixed Conifer (ID)[d]	14.9	12.3	11.6	na	na	19.6	na	na	58.4	na	0.37 × 0.37 m plots
Pinyon Pine/Juniper (CO)[e]	na	na	na	na	na	na	na	na	95.9	3.0	Compared 1 × 1 m plot-based methods to LIS methods.
Ponderosa Pine/Gambel Oak (CO)[e]	na	na	na	na	na	na	na	na	82.0		
Jeffery Pine/White Fir (CA)[e]	na	na	na	na	na	na	na	na	73.0		
Ponderosa Pine, 25 yrs old (CA)[f]	0.2	1.4	0.0	57.4	59.0*	2.1	20.4	0.1	81.6*	3.8	1 × 1 m plots
Ponderosa/Jeffrey Pine (CA)[g]	2.9	12.3	12.0	17.9	45.1*	26.1	43.2	na	114.4*	na	LIS sampling
Ponderosa/Jeffery Pine (CA)[g]	1.3	8.3	7.4	32.0	49.0*	19.0	29.1	na	97.1*		
Mixed Conifer (CA)[h]	1.0	4.8	9.0	23.2	38.0*	17.1	32.0	na	87.1*	14.7	LIS sampling
Mixed Conifer (CA)[h]	1.1	4.6	8.7	30.5	44.9*	17.2	31.7	na	93.8*	14.6	
Longleaf Pine/Palmetto-Gallberry Mature 10 + yr rough (FL)[i]	3.1	2.1	0.4	na	5.6*	12.6	41.9	na	60.1*	8.1	1 × 1 m plots; 0.25 × 0.25 m (duff).
Longleaf Pine/Palmetto-Gallberry Mature 10 + yr rough (FL)[i]	3.2	5.3	2.8	1.9	13.2*	9.5	56.5	na	79.2*	5.2	LIS sampling
Longleaf Pine/Palmetto-Gallberry Mature 5 yr rough (FL)[i]	2.3	2.6	0.4	0.6	5.9*	11.8	37.9	na	55.6*	3.5	
Longleaf Pine/Palmetto-Gallberry 18 yr old plantation (FL)[i]	2.7	5.4	1.3	5.1	14.5*	13.6	67.3	na	95.4*	7.3	

[a] Battaglia et al. (2010).
[b] Glitzenstein et al. (2006).
[c] Kane et al. (2009).
[d] Brewer et al. (2013).
[e] Hood and Wu (2006).
[f] Reiner et al. (2009).
[g] Kobziar et al. (2009).
[h] Stephens and Moghaddas (2005).
[i] Kreye (2012).

has yet to be widely tested across many ecosystems (e.g., Hood and Wu, 2006; Kane et al., 2009; Battaglia et al., 2010; Kreye et al., in press).

2.2. Variability of masticated fuels across sites

Compounding the variability that can arise between sampling method choices is the wide variety in the composition of masticated fuel beds (Table 1). Some fuel beds were found to be dominated by small diameter woody particles (Kane et al., 2009; Battaglia et al., 2010; Brewer et al., 2013) while others were characterized by high proportions of foliar litter (Stephens and Moghaddas, 2005; Kobziar et al., 2009; Kreye et al., in press). Conifer needles contributed heavily in some sites (Stephens and Moghaddas, 2005; Kobziar et al., 2009; Reiner et al., 2009) whereas palm-type “shrubs” were a primary target for mastication in the southeast (Kreye et al., in press). Coarse woody (1000-h) fuels were rare or absent in many of the studies we examined, though they were observed to compose 65% of total surface fuel mass in loblolly pine (*Pinus taeda*) stands in South Carolina (Glitzenstein et al., 2006) and 94% in ponderosa pine plantations in California (Reiner et al., 2009). Duff loads varied greatly, ranging from 4.9 to 67.3 Mg ha^{-1} (Table 1). Variation in fuel bed composition complicates our ability to categorize masticated fuels and to predict the behavior and effects of fire in these treated sites. Regardless of fuel composition, however, masticated sites tended to include fine (small-diameter) surface fuel material compacted into shallow fuel beds.

Fuel particle shapes and sizes also vary, according to the masticated species and their pre-treatment stature (Kane et al., 2009; Kreye et al., in press), and likely from differences in machinery and operators. Small masticated woody particles (<0.64 cm) are typically hemi-cylindrical or rectangular, while larger particles (>0.64 cm) are more rounded (Kane et al., 2009). The size of branch material of vegetation being masticated influences the resulting fuel particles following treatments. Larger diameter branch material may be fractured into smaller diameter particles with a high degree of shape irregularity, whereas small diameter branch material may be severed into shorter, but still relatively cylindrical particles (Kreye et al., in press). Few particle surface area:volume (SAV) measurements (important for fire behavior calculations) are available for masticated fuels (Porterie et al., 2007). SAV likely differs from slash or other fuels from the same material because a high degree of particle fracturing occurs in mastication (Kreye and Varner, 2007; Battaglia et al., 2010).

As in many non-masticated sites, fuel loads in masticated stands can be highly variable (see Table 1) depending on vegetation type, pretreatment site conditions, type of machinery, machinery operator, and conditions desired for the post-treatment stand (Stephens and Moghaddas, 2005; Hood and Wu, 2006; Battaglia et al., 2010; Kane et al., 2009; Kreye et al., in press). Across the US, surface fuel loads (litter, fine and coarse woody, and duff) ranged from 27 to almost 200 Mg ha^{-1}, a level of variation not unlike other non-masticated fuels (Sackett, 1979; Wright and Eagle, 2013). The drivers of variability in masticated fuel loads, however, are indeterminate. As expected, fuel loads have been shown to differ when treatments occur in different forest ecosystems (Battaglia et al., 2010). In western shrub-dominated studies, pre-mastication site characteristics drove variability in fuel loads (Kane et al., 2009), and in Florida pine forests differing stand histories seemed to account for differences in post-treatment fuel loads (Kreye et al., in press). Among these different ecosystems and regions of the US, however, masticated fuel beds were all shallow, ranging from only 0.6 to 15.0 cm (Table 1), highlighting the general propensity for high fuel bed bulk densities to result from these treatments.

Where spatial variability of masticated fuel loads and other characteristics are high (Keane et al., 2012), fire intensity, soil heating, and fuel consumption will doubtless be influenced by microsite variability in fuel beds (Busse et al., 2005; Bradley et al., 2006; Keane et al., 2012). This variability will likely result from spatial variation in pre-treatment vegetation, and also from spatial restrictions on treatment operations (even within sites) by local factors (e.g., wetlands, riparian areas, exposed rock, topography restrictions). To fully grasp the implications of mastication on subsequent fire behavior, understanding of spatial heterogeneity of fuels at the fuel bed, stand, and landscape scale will be required.

2.3. Variability of masticated fuels over time

Masticated fuels change over time and the long-term efficacy of treatments to reduce fire intensity, increase resilience to future fires, and mitigate the hazards of fire to life and property likely depend on these changes. The mechanisms for temporal fuel dynamics, however, are complex: different decomposition rates of the masticated debris; varied additional inputs from litter fall and other woody debris; dissimilar responses of vegetation (Knapp et al., 2011; Hyde et al., 2012; Kreye et al., in press); and surface mixing effects, such as soil incorporation and hydrological/weathering processes. In the southeastern US, for instance, Kreye (2012) reported a mass loss rate of 26% in masticated litter and 19% mass losses in 1-h woody fuels after 1 yr, and 18%mass loss in 10-h woody fuels after 10 months. Needle cast, however, may have accounted for no difference or actual increases in litter loads >1 yr following treatment (Kreye et al., in press), an observation also made in western sites (Reiner et al., 2009; Knapp et al., 2011; Stephens et al., 2012). Reductions in fine woody fuels have been observed in sites as quickly as 8 months following mastication in southeastern US (Kreye et al., in press). Woody fuels were also reduced between 1 and 7 years post-treatment in a California site, but these changes were no different than those observed in nearby controls (Stephens et al., 2012). Understanding the implications of local fuel load changes over time will require longer term studies in masticated sites across relevant ecosystems.

In addition to the changes to surface fuels, the effectiveness and longevity of mastication treatments depend, in part, on the response of herbs, tree seedlings, and shrubs. As with other fuels treatments (Dodson et al., 2007; Schwilk et al., 2009), vegetation recovery from mastication can be complex and variable—dependent on site productivity, characteristics of the species treated (i.e. sprouters vs. non-sprouters), the “mulching effect” of the masticated debris, and the severity of the treatment or combinations of treatments (Potts and Stephens, 2009; Kane et al., 2010; Potts et al., 2010). Where vegetation recovery is rapid, it can reduce the duration of treatment efficacy (Lanini and Radosevich, 1986; Kane et al., 2010; Kreye et al., in press) and perhaps exacerbate fire hazard via the combination of residual masticated woody fuels beneath dense recovering shrub fuels. In other places, a so-called “mulching effect” has been observed, whereby deep masticated residuum stalls shrub recovery. In a productive Florida pine flatwoods site, for example, total fuel loads increased over time following a mastication treatment as shrub density reached pretreatment levels within 16 months and shrub biomass reached 24–56% of pretreatment levels after only 2 years (Kreye et al., in press). Because the sprouting ability of shrubs and trees following mastication will likely be a major determinant of the long-term efficacy of treatments to reduce fire hazard, vegetation characteristics must be taken into consideration when designing treatments. A simple “cookbook” approach will not suffice across the variety of ecosystems in which mastication may be employed.

3. Fire behavior in masticated fuels

Observations of fire behavior in masticated sites during wildfires have suggested that due to low fire intensity and slow rate of spread, treatments may enhance suppression efficacy (Hudak et al., 2011). However, long-duration combustion of masticated particles has been implicated in difficulty containing, holding, mop-up, and increase in smoldering smoke during prescribed fires (Bass et al., 2012). Research assessing the overall efficacy of these treatments to reduce fire hazard is as yet insufficient. Fire behavior will likely differ in masticated fuels from those from natural or other activity (thinned or harvested stands) given their high concentrations of 1-h and 10-h fuels and their highly compacted fuel layer (Battaglia et al., 2010; Knapp et al., 2011; Kreye et al., 2011). Moreover, though the implications of masticated particles' highly variable shapes on fire behavior are also poorly understood, it is plausible that the unique combination of high fuel loads of those variably sized fuels, shallow fuel depth (i.e. high bulk density), and high proportions of small-diameter woody material (i.e. high fuel particle SAV) may very likely complicate our ability to predict fire behavior in masticated fuels. This is especially true since this combination is unusual in currently used fuel models (Kane et al., 2009). A critical factor in accurate fire behavior prediction is the rate of drying of masticated fuel beds (Jin and Chen, 2012), which is slowed by their compactness (Kreye et al., 2012). This compact nature likely makes both fuel depth and bulk density important variables in the prediction of fire behavior in these treatments. Few empirical data are available for generally describing fire behavior in masticated fuels.

3.1. Flame length and rate of spread

3.1.1. Small-scale (laboratory) studies

Reported flame lengths in masticated fuel beds burned in laboratory experiments have ranged from 0.12–1.70 m across a wide variety of vegetation types from which masticated debris was collected (Table 2, Fig. 4). As expected (Rothermel, 1972), longer flame lengths were associated with lower fuel moisture and greater fuel loads, which ranged from 2.5% to 16.0% and 10 to 169 Mg ha^{-1}, respectively, across studies (Busse et al., 2005; Brewer et al., 2013; Kreye et al., 2011, 2013a). Although we do not perform a formal meta-analysis in this review, average flame length increases with average fuel depth across studies (Fig. 4). Relationships

Table 2

Fuel bed characteristics and fire behavior results from laboratory fires in masticated fuels. Fuel bed loadings were calculated based on the burn platform size and mass of masticated fuels on the platform, then scaled up to corresponding Mg ha^{-1}. Variables explicitly tested within studies are in bold. The parent material (i.e. overstory or understory) of the bulk masticated particles used in the experiments are indicated by *.

Overstory vegetation (State)	Dominant understory species	Fuel bed loading (Mg ha^{-1})	Depth (cm)	Bulk density (kg m^{-3})	Fuel moisture (%)	Flame length (m)	Flame residence time (min)	Consumption (Mg ha^{-1})	Consumption (%)
*Mixed Conifer (ID)[a]	_S. albus, V. cespitosum_	56.7	5.5	105.5	**3–8**	0.30	7	52.1	90.3
*Mixed Conifer (ID)[a]	_S. albus, V. cespitosum_	57.6	5.9	96.5	**10–12**	0.23	10	51.7	91.3
*Mixed Conifer (ID)[a]	_S. albus, V. cespitosum_	59.3	5.8	104.3	**13–16**	0.12	14.8	54.1	89.7
18 yr old Ponderosa Pine[b]	*_A. viscida, A. manzanita_	**34.0**	**2.5**	133.0	16	0.3–0.4	20.0–26.0	26.0–27.0	76.0–79.0
18 yr old Ponderosa Pine[b]	*_A. viscida, A. manzanita_	**101.0**	**7.5**	133.0	16	1.0–1.1	23.0–26.0	90.0–93.0	89.0–91.0
18 yr old Ponderosa Pine[b]	*_A. viscida, A. manzanita_	**169.0**	**12.5**	133.0	16	1.3–1.7	27.0–28.0	154.0–159.0	91.0–94.0
Mixed Conifer (CA)[c]	***_Fractured A. manzanita_**	73.8	7.0	105.4	**5**	0.70	17.4	69.6	94.3
Mixed Conifer (CA)[c]	***_Intact A. manzanita_**	73.8	7.0	105.4	**5**	0.91	13.8	71.7	97.2
Mixed Conifer (CA)[c]	***_Fractured A. manzanita_**	73.8	7.0	105.4	**13**	0.53	23.3	70.5	95.5
Mixed Conifer (CA)[c]	***_Intact A. manzanita_**	73.8	7.0	105.4	**13**	0.75	18.8	72.8	98.6
Mixed Conifer (CA)[c]	***_Fractured C. velutinus_**	73.8	7.0	105.4	**5**	0.63	16.2	69.7	94.5
Mixed Conifer (CA)[c]	***_Intact C. velutinus_**	73.8	7.0	105.4	**5**	0.65	18.1	70.9	96.1
Mixed Conifer (CA)[c]	***_Intact C. velutinus_**	73.8	7.0	105.4	**13**	0.58	22.6	68.0	92.2
Mixed Conifer (CA)[c]	***_Fractured C. velutinus_**	73.8	7.0	105.4	**13**	0.61	21.5	70.8	95.9
Mixed Conifer (CA)[c]	*_A. manzanita_	73.8	7.0	105.4	**2.5**	0.95	13.2	69.5	94.2
Mixed Conifer (CA)[c]	*_A. manzanita_	73.8	7.0	105.4	**7**	0.79	17.3	69.5	94.2
Mixed Conifer (CA)[c]	*_A. manzanita_	73.8	7.0	105.4	**9**	0.77	17.4	69.9	94.7
Mixed Conifer (CA)[c]	*_A. manzanita_	73.8	7.0	105.4	**11**	0.69	22.3	68.9	93.3
Longleaf Pine (FL)[d]	*_S. repens, I. glabra_	10.0	6.0	16.7	**9**	0.69	na	9.1	90.7
Longleaf Pine (FL)[d]	*_S. repens, I. glabra_	20.0	9.0	22.2	**9**	1.06	na	18.4	92.0
Longleaf Pine (FL)[d]	*_S. repens, I. glabra_	30.0	12.0	25.0	**9**	1.59	na	29.4	98.0
Longleaf Pine (FL)[d]	*_S. repens, I. glabra_	10.0	6.0	16.7	**13**	0.29	na	9.8	97.7
Longleaf Pine (FL)[d]	*_S. repens, I. glabra_	20.0	9.0	22.2	**13**	0.76	na	19.3	96.3
Longleaf Pine (FL)[d]	*_S. repens, I. glabra_	30.0	12.0	25.0	**13**	1.14	na	29.1	97.0

[a] Brewer et al. (2013) used a 0.37 m^2 platform.

[b] Busse et al. (2005) used a 0.9 m^2 platform.

[c] Kreye et al. (2011) used a 0.26 m × 0.38 m platform.

[d] Kreye et al. (2013a) used a 4.0 m diameter circular platform.

between fuel depth and flame length are similar in both the Busse et al. (2005) and Kreye et al. (2013a) experiments, even though fuel composition differed substantially between these two studies. When fuel depths were controlled, however, fuel moisture was a consistent driver of variation in flame lengths (Busse et al., 2005; Kreye et al., 2011, 2013a). Little is known about the effects particle shape may have on fire behavior in masticated fuels; however Kreye et al. (2011) observed reduced flame lengths in dense fuelbeds composed exclusively of fractured particles compared to intact particles, with particle diameters controlled, of *Arctostaphylos manzanita*, contrary to the hypothesis that fracturing would increase fire intensity. These differences were not observed, however, when conducted with *Ceanothus velutinus*, another common shrub targeted for mastication in California. While particle-level characteristics are important drivers of fire behavior in wildland fuels (Rothermel, 1972), the influence of properties within fuel beds (e.g. load, depth, and bulk density) may be more critical for understanding fire behavior in the densely compacted fuels created by mastication.

Small-scale laboratory studies evaluating rates of fire spread are rare, because steady state rates of spread are difficult to achieve in small fuel beds. In one study, however, rates of spread were reported for burning of masticated palmetto/gallberry from southeastern US pine forests in 4 m diameter circular fuel beds (Kreye et al., 2013a). Rate of fire spread in this study was influenced by fuel moisture (9 versus 13%), but not by fuel load (10–30 Mg ha^{-1}, 17–25 kg m^{-3}), with the drier fuels burning faster. In other laboratory studies where masticated fuels were burned, total flaming time was reported instead of rate of spread. Comparing flame residence times between studies is difficult because fuel bed sizes vary (Table 2). Fuel moisture, a significant influence on flame length, has also consistently contributed to flaming duration (Table 2). Under higher moisture contents, fuel beds burned with shorter flames, but flaming times were prolonged (Brewer et al., 2013; Kreye et al., 2011), whereas the longer flames that occurred in drier fuels were sustained for shorter periods. The influence of moisture on flame length and flaming duration is not surprising (Rothermel, 1972), where drier fuels are likely to burn with greater intensity and faster consumption rates (see *Fire intensity* section below). Masticated fuels, with their compact nature and often heavy loading of small-diameter woody material, flame for longer durations than leaf litter (e.g., Engber and Varner, 2012), but for shorter times than heavier fuels, such as logs (Hyde et al., 2011). Since post-mastication residues can be spread across the forest floor and are often left on site, it will be important to understand the potential implications of long-duration heating when these residues burn (Busse et al., 2005; Kreye et al., 2013b). Laboratory studies provide substantial control over experimental conditions and allow researchers to determine specific roles of fuel bed properties on subsequent fire behavior, but the relative importance of these variables may diminish at operational scales. Fire behavior may be less sensitive to specific fuel bed properties when extraneous or unexpected factors become influential or where other variables (e.g. wind) dominate fire behavior.

3.1.2. Field studies

During field-scale burning in masticated sites, flame lengths ranging from 0.26 to 1.88 m have been reported across studies conducted in the western and southeastern US (Table 3). Flame lengths across these studies were similar to those observed in laboratory experiments, and fuel loads, fuel depths, and moisture contents were fairly well represented by the laboratory studies. A general pattern relating flame length to fuel depth, however, is not apparent across, or even within, these studies (Fig. 4). Fuels are rarely as uniform in the field as in laboratory studies and weather can rapidly change during burning. Knapp et al. (2011) reported that moisture content and burning pattern (heading vs. backing fire), and not fuel loads, were associated with average flame lengths. Kobziar et al. (2009) reported high variations in flame lengths were due to patches of herbaceous fuels within masticated sites. Also, when shrubs emerge over the dense surface fuels from mastication, fire behavior may be less driven by the surface fuels. In contrast to lab burning in masticated fuels in the southeastern US (Kreye et al., 2013a), recovering shrub fuels in field sites were more strongly related to flame lengths than the masticated surface fuels (Kreye, 2012). Changes in fuel beds and resulting fire behavior over time have received little attention to date, but these changes could significantly alter fire behavior (Fahnestock, 1962; Knapp et al., 2011; Kreye, 2012).

Measured rates of fire spread varied within and across masticated sites. In two studies, rates of spread ranged over two orders of magnitude, from 0.06 to 5.9 m·min^{-1}. Factors influencing rates of spread included whether fires were backing versus heading (Knapp et al., 2011), season of burn (Kreye, 2012), and within-site variability (Kobziar et al., 2009). Open wind speeds were generally light (<10 km hr^{-1}) across studies, with the exception of the 12.6–23.4 km hr^{-1} winds that occurred during prescribed burns in masticated *Pinus taeda* stands in South Carolina (Glitzenstein et al., 2006), where average rate of spread was only 0.52 m·min^{-1}, but the burn occurred under the highest fuel moistures recorded (12.7–33.2%) of all studies (Table 3). Knapp et al. (2011) suggested that fire spread rates (0.44–1.04 m min^{-1} for heading fires and 0.06–0.09 m min^{-1} for backing fires) in ponderosa pine sites in California were influenced by layers of pine needles that accumulated on the surface of the masticated fuels in the three intervening years since mastication. Kobziar et al. (2009) reported that patchiness (forest openings with herbaceous plants intermixed with patches of dense masticated fuels) resulted in faster spread rates, potentially as a result of more aggressive ignition tactics. Spread rates during winter and summer prescribed burns in masticated sites in Florida averaged 3.4 and 5.9 m min^{-1}, respectively. Summer burns had slightly wetter fuels, but higher wind speeds (Kreye, 2012). Masticated palm leaves dominated surface fuels in these sites, however, and substantial shrub recovery had occurred, even as early as 6 months following mastication. All of these field-scale studies highlight the variability in rate of spread that may occur during prescribed burns. However, it is still unknown how quickly masticated sites might burn under more extreme conditions likely to occur during a wildfire.

Studies aimed at comparing fire behavior between treated and untreated sites have been rare and differ greatly in their results, with some sites burning less intensely in the treated sites (Kreye, 2012), and in others mastication has exacerbated fire behavior (Bradley et al., 2006). Given that vegetation recovery, decomposition rates of masticated debris, and specific treatment objectives are likely to vary, the use of mastication to remove understory (shrubs and small trees) fuel strata is unlikely to yield the same desired effects on subsequent fire behavior under all circumstances.

3.2. Fireline intensity

Fireline intensity reflects the rate of energy output at the flaming front (Byram, 1959) and is important to understand in masticated fuels. Fireline intensity has rarely been measured in masticated fuels, though it could provide insight into their potential energy release. Once again, wide variability characterizes the methods of estimating fireline intensities. Small-scale experiments either rely on rates of fire spread and fuel consumption to calculate average intensity (Kreye et al., 2013a) or use short-interval mass loss rates to estimate 'instantaneous' energy output throughout the burns (Kreye et al., 2011). Field experiments estimate fireline intensities from observed flame lengths (Kobziar et al., 2009),

Table 3
Field observations of weather, fuel bed characteristics, fire behavior variables, and post-fire consumption in masticated fuels. Bold variables were tested within a particular study.

Dominant masticated material	Weather conditions			Fuel characteristics			Fire characteristics			Post-fire	
	Temperature (°C) month	Windspeed (km h^{-1})	Relative humidity (%)	Loading (Mg ha^{-1})	Depth (cm)	Fuel moisture (%)	Fire type	Rate of spread (m min^{-1})	Flame length (m)	Consumption (Mg ha^{-1})	Consumption (%)
Mixed Shrub Woodland, CA[a]	15–22 Apr/May	3.0	34–73	na	na	na	Backing	na	0.74–1.88	na	na
Loblolly Pine Coastal Flatwoods, SC[b]	NA February	12.6–23.4	na	200.4[g]	5.0–15.0	12.66–33.15	Strip Head	0.52	0.28–0.44	na	na
40 yr old Ponderosa Pine (CA)[c]	22 May/June	<5.0	33–58	60.3[h,i]	12.9	10.6–14.5	**Heading**	0.72–1.04	0.55–0.82	37.5	62.2
40 yr old Ponderosa Pine (CA)[c]	23 May/June	<5.1	33–59	60.3[h,i]	12.9	10.6–14.5	**Backing**	0.06–0.09	0.28–0.50	37.5	62.2
40 yr old Ponderosa Pine (CA)[c]	22–27 June	<5.0	32–48	26.0[h,i]	5.4	6.0–17.6	**Heading**	0.44–0.68	0.55–0.86	16.4	63.1
40 yr old Ponderosa Pine (CA)[c]	22–27 June	<5.1	32–49	26.0[h,i]	5.4	6.0–17.6	**Backing**	0.07–0.08	0.26–0.36	16.4	63.1
Ponderosa/Jeffrey Pine Plantation (CA)[d]	18.0 June	8	55	68.0[g]	na	10.0	Strip Head	0.8	0.7	32.3	47.5
Ponderosa/Jeffrey Pine Plantation (CA)[d]	19.0 June	8	54	68.0[g]	na	5.3	Strip Head	3.7	1.1	32.3	47.5
25 yr old Ponderosa Pine (CA)[e]	5–15 December	5–13	30–100	25.9[j]	2.1	4–12	Strip and Spot Ignition	na	0.97–1.06	20.6	79.5
25 yr old Ponderosa Pine (CA)[e]	5–15 December	5–13	30–100	35.0[j]	2.8	4–12	Strip and Spot Ignition	na	0.97–1.07	32.4	92.6
Longleaf Pine Flatwoods-10 + yr rough (FL)[f]	**23–24 February**	1.6–2.7	47–49	17.7[k]	6.0	12.1	Strip Head	3.4	1.1	12.6	71
Longleaf Pine Flatwoods-10 + yr rough (FL)[f]	**31–34 July**	1.6–7.2	61–76	24.1[k]	4.9	14.7	Strip Head	5.9	1.5	11.6	48

[a] Bradley et al. (2006).
[b] Glitzenstein et al. (2006).
[c] Knapp et al. (2011).
[d] Kobziar et al. (2009).
[e] Reiner et al. (2009).
[f] Kreye (2012).
[g] All woody surface fuels and litter.
[h] All woody surface fuels, litter, and duff.
[i] Kane et al. (2009).
[j] "Masticated" fuels only (differentiated from "natural" fuels, but is not clearly defined in the article).
[k] 1, 10, and 100-h woody surface fuels and litter.

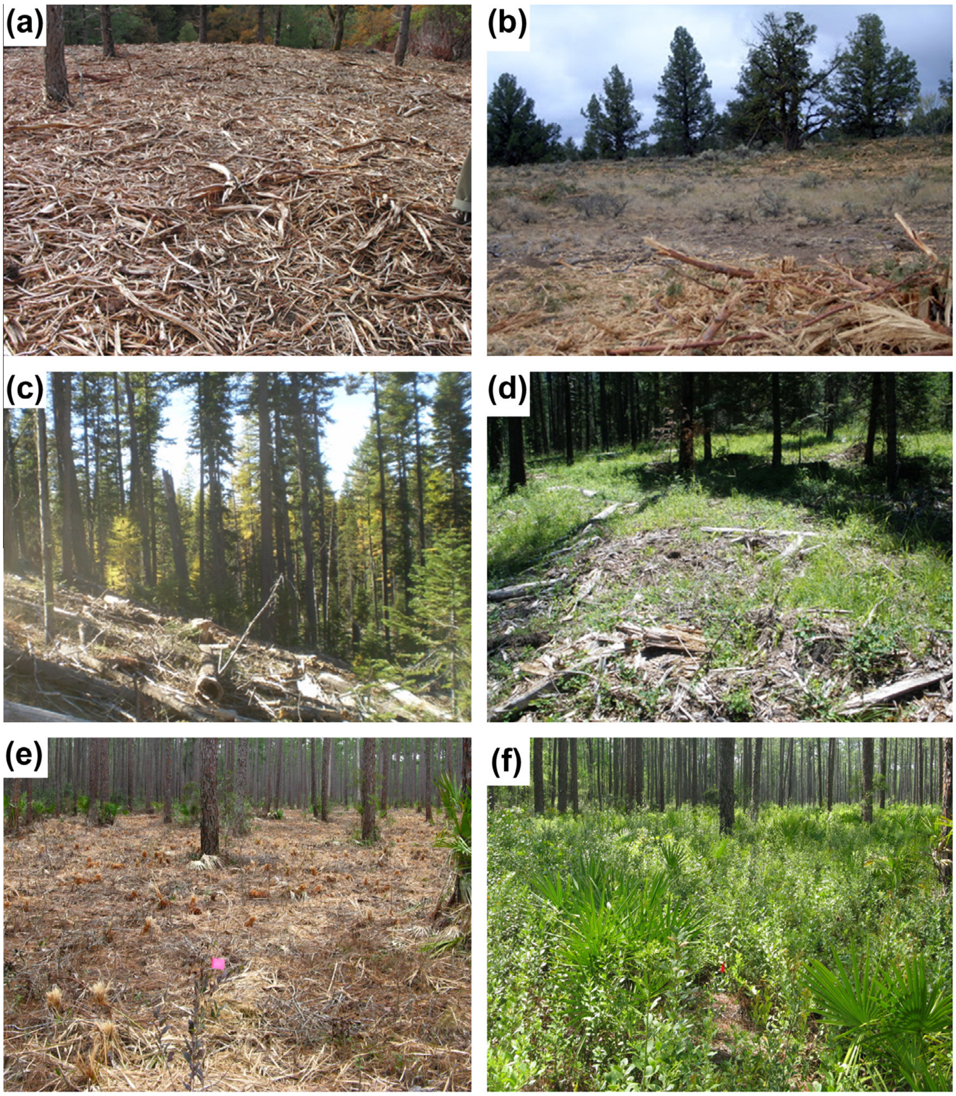

Fig. 3. Photographs showing different mastication treatments in: (a) manzanita shrub fuels, northern California (Photo by J. Kane), (b) western juniper and sagebrush vegetation in the Owyhee Mountains, Idaho (Photo by USFS), (c) mixed-conifer forest in eastern Oregon (Photo by S. McDonald, USFS), (d) mixed-conifer forest in northern Idaho (Photo by N. Brewer). Note the differences of the large woody debris present, horizontal continuity, and compaction of the fuel beds, and (e and f) pine flatwoods in Florida immediately (e) and 1 yr (f) following treatment (Photos by J. Camp; both taken at the same location).

however the relationship between flame length and fireline intensity is dependent on fuel bed structure (Alexander and Cruz, 2012) and may differ in masticated fuels (Kreye, 2012). Other metrics of fire intensity beyond fireline intensity are also widely used, as noted by Heward et al. (in press), including heat release per unit area that Rothermel (1972) termed the "fire reaction intensity", integrals of the measured temperature over time (Smith et al., 2005), and the fire radiative power (Wooster, 2002; Smith and Wooster, 2005; Kremens et al., 2010).

Fuel moisture (Kreye et al., 2011, 2013a) and fuel load (Kreye et al., 2013a) contributed to variation in fireline intensities in two laboratory experiments with masticated fuels, in which fireline intensity ranged from 40 to 118 kW m^{-1} in heavy (73.8 Mg ha^{-1}) woody-dominated fuels burned at 2.5–11.0% fuel moisture (Kreye et al., 2011). In lighter (10–30 Mg ha^{-1}) litter-dominated fuels fireline intensity ranged between 317 and 593 kW m^{-1} burned at 9% and 13% moisture (Kreye et al., 2013a). Kreye et al. (2011) reported that fireline intensity peaked quickly during burns in drier masticated fuels, but rapidly declined, reflecting rapid combustion, whereas in wetter fuels, maximum fireline intensities were lower, but were sustained for longer periods. Although total energy release across burns did not differ, the varying dynamics of the heat energy release during combustion highlights the importance of understanding potential fire effects from burning in these dense fuels (Kreye et al., 2013b). In addition, even though fuel loads did not differ across these treatments, particle fracturing decreased fireline intensity in masticated *A. manzanita* (but not in masticated *C. velutinus*) shrubs, adding little insight into how particle shape influences fire behavior in these fuels. In experiments where litter dominated the masticated fuels (Kreye et al., 2013a), both moisture and fuel load influenced fireline intensity, with dry, heavy fuel beds burning with the greatest intensity. Shredded palmetto foliage was dominant in these fuels and likely contributed to the higher intensities observed. In a field experiment in California, Kobziar et al. (2009) reported fireline intensities in two prescribed burns in masticated fuels of 116 and 313 kW m^{-1}, respectively. Further work evaluating fire intensity, and also the propensity for long-duration heating (i.e. residency time), during burning in these fuels will be critical to understanding the efficacy of treatments at meeting both fire hazard reduction and ecological objectives.

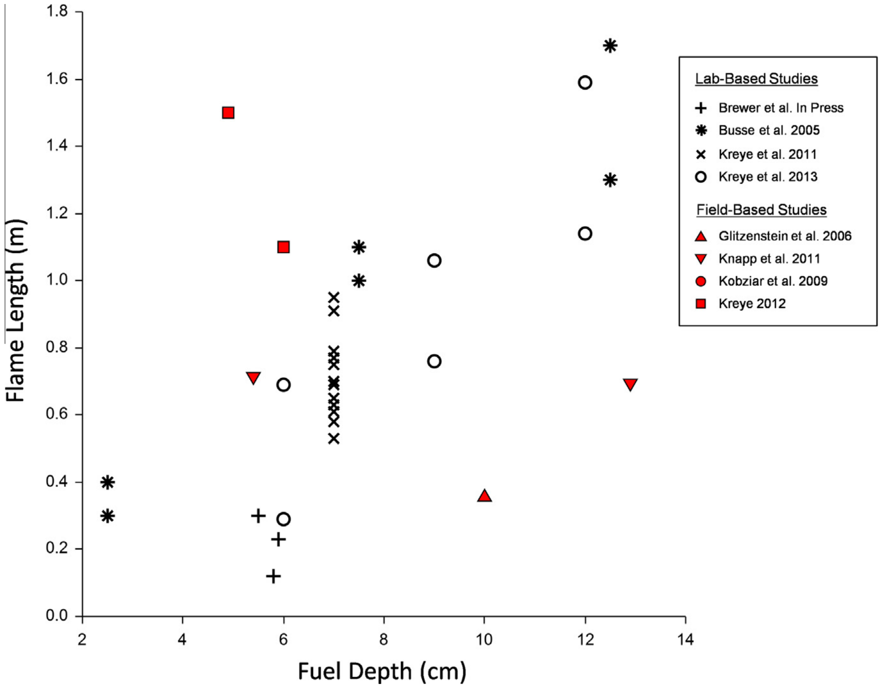

Fig. 4. Average flame lengths versus fuel depths across eight studies (4 lab-based, 4 field-based) quantifying fire behavior in masticated fuels.

3.3. Residual flaming and smoldering combustion

A frequent observation in masticated fuels is residual flaming once the initial flaming front passes. In laboratory (Brewer et al., 2013; Busse et al., 2005; Kreye et al., 2011) and field fires (Knapp et al., 2011), residual masticated woody fuels sustained flaming long after the initial front passed. Knapp et al. (2011) attributed higher than predicted crown scorch to the abundant residual flaming they observed in prescribed fires. The cause of residual flaming may be that whereas overlying pine litter is responsible for the rapid initial spread, the more coarse masticated woody fuels ignite and burn more slowly. Much of the work aimed at predicting fire behavior focuses exclusively on the fire front, but long-term residual flaming is important to ecological effects and residual smoke generation.

In addition to residual flaming, smoldering combustion complicates fire behavior in masticated fuels (Knapp et al., 2011). Smoldering combustion can lead to fire control problems if high winds reignite previously burned areas or blow embers across containment lines (Bass et al., 2012). In masticated fuels, smoldering combustion can also lead to increased duff consumption, mineral soil heating, root injury (Busse et al., 2005) and to certain emissions such as non-CO_2 aerosols and particulate matter (Hardy et al., 2001). Kreye et al. (2011) reported that an additional 40–64 min of smoldering combustion occurred beyond the 14–23 min of flaming combustion. Brewer et al. (2013) reported 160–183 min of smoldering beyond the 18–45 min of flaming. Smoldering combustion primarily occurs in compacted fuels, underlying duff, and coarse woody debris (CWD), especially decayed wood (Hyde et al., 2011). Smoldering can lead to holdover fires and control problems days later. The fire behavior mechanisms driving smoldering combustion in these types of fuels are still poorly understood (Ottmar, 2013). In addition to long-duration flaming, smoldering combustion in masticated fuels will need to be better understood to fully evaluate the potential effects from burning in these dense fuels.

3.4. Consumption and emissions

The consumption of fuels determines emissions generated during fires (Hardy et al., 2001; Ottmar et al., 2008). Consumption of masticated fuels during laboratory burns has been substantial (76–98%, Table 2), with the majority of fuel beds being >90% consumed. Not surprisingly, consumption during field studies has been more variable (47–93%; Table 3). Given that mastication creates heavy quantities of surface fuels from live shrubs and trees unlikely to have completely been consumed during fires (De Castro and Kauffman, 1998), emissions generated during burning in masticated fuels need to be understood. Fuel consumption is a two-stage process of (1) pyrolysis and (2) flaming and smoldering combustion that occur simultaneously and at different rates, depending on the characteristics and condition of the fuel, weather, topography, and in the case of prescribed fire, ignition rate and pattern (Ottmar, 2013). Flaming combustion is a relatively efficient process, producing CO_2, H_2O, and particulate matter (Fig. 1b). Because smoldering consumption is less efficient than flaming combustion, smoldering results in more non-CO_2 emissions and particulate matter. The smoldering phase also produces less intense heat energy, but more of that heat is transferred into underlying mineral soils where it influences ecosystem response. Further, smoldering combustion leads to a less buoyant smoke plume potentially impacting local air quality (Hardy et al., 2001). Dense fuel beds, including those created through mastication, often consume more during the smoldering phase than the flaming phase (Ohlemiller, 1985). There are several models widely used by scientists and land managers to predict fuel consumption and emissions, including the First Order Fire Effects Model (Reinhardt et al., 1997), CONSUME (Prichard et al., 2005), and CanFIRE (de Groot et al., 2007). Although these models account for flaming and smoldering consumption and emissions production, they do not account for masticated fuels (Reinhardt et al., 1997; de Groot et al., 2007; Prichard et al., 2005).

3.5. Ember generation and spot fire occurrence

Perhaps one of the most difficult and least understood fire behavior characteristics to quantify is firebrand generation, dispersal, and spot fire ignition in wildland fuels (Babrauskas, 2003; Potter, 2012a,b). Ember generation and spot fire ignitions can create substantial firefighter and public safety concerns. Given that masticated particles are small (light in mass), but may burn for long periods (Kreye et al., 2011), their propensity to become firebrands needs investigation. Anecdotal evidence from prescribed burning in Colorado (Bass et al., 2012) suggests both that burning embers may not only loft, but can blow across the surface into adjacent unburned fuels, and that the slow flaming and smoldering of masticated fuels poses issues for re-ignition. Fire behavior during prescribed fires, however, may not elucidate potential ember generation and spot fire ignition from masticated sites burning during wildfires, especially under more severe conditions and where large-scale convection is possible (Potter, 2012a,b). Despite the importance of fire brands, there is a paucity of research, across any fuel types, related to firebrand generation, their transport, and the ignition of material at their landing site (Albini, 1979; Manzello et al., 2006, 2009; Perryman et al., 2013). Given that mastication is so often used in fuel breaks to mitigate landscape-scale fire spread (Kane et al., 2009; Kreye et al., 2013a), understanding fire spread mechanisms in addition to just the flaming front will be critical to evaluate the effectiveness of these treatments (see Fig. 3).

3.6. Modeling fire behavior in masticated fuels

Fire behavior modeling may be used to inform fire suppression activities, develop prescribed burning or wildland fire use prescriptions, or to plan fuel management activities on the landscape. A few studies (Glitzenstein et al., 2006; Kobziar et al., 2009; Knapp et al., 2011; Kreye, 2012) provide comparisons between empirical fire behavior observed during prescribed burns in masticated fuels in the field to that predicted using software (BehavePlus, Andrews et al., 2008 or Fuels Management Analyst Plus, Carlton, 2004) relying on Rothermel's (1972) fire spread model to predict fire spread and intensity. Agreement between predictions and observations varied greatly, even within studies. Even though the same model (Rothermel, 1972) was used to predict fire behavior, the methods used to input fuels characteristics varied both within and across studies, highlighting difficulties in dealing with fuel bed properties (Keane, 2013) when modeling fire behavior in these unique fuels (Kane et al., 2009).

In masticated pine-shrub forests in South Carolina with some shrub recovery, observed flame lengths and rates of spreads were similar to those predicted when only the chipped surface fuels were modeled. When a southern rough shrub model was used, however, both flame lengths and spread rates were over-predicted by as much as 160% and 221%, respectively (Glitzenstein et al., 2006). Although fuel moisture was higher than the other studies during these burns (Table 3), results indicated that vertical fuel heterogeneity may be problematic for fire behavior prediction. Studies in masticated pine sites in California (Kobziar et al., 2009; Knapp et al., 2011) suggested that disparities between predicted and observed fire behavior were also likely due to fuel heterogeneity. Using a standard fuel model (Anderson, 1982), Kobziar et al. (2009) observed variable results. Predicted fire behavior (flame length, fireline intensity, and rate of spread) closely matched (<20% error) observations in one site, but suffered large (36–76% error) under predictions in another. Knapp et al. (2011) compared observed fire behavior (rate of spread and flame lengths) to predictions using several standard (Anderson, 1982; Scott and Burgan, 2005) and three customized (using actual fuel measurements) fuel models. Results of model performance varied, depending on the sites. They did find that for their custom models to match observations, they had to increase fuel depths beyond actual depths, especially in sites where fuel load was the greatest. Kreye (2012) created custom fuel models for several plots in masticated pine-palmetto forests and compared predicted to observed fire behavior (flame lengths and rates of spread). Error rates varied, but flame lengths and rates of spread were generally over-predicted. Recovering shrubs were incorporated into fuel inputs, which likely played a role in over-predicting fire behavior by drastically increasing fuel depth, as with Glitzenstein et al. (2006). Thus, fuel heterogeneity may prove problematic where dense surface fuels are overtopped by recovering vegetation.

Accuracy of fire behavior models depends on a variety of factors; error rates associated with their predictive ability are not uncommon across other fuels (Cruz and Alexander, 2013). The reported modeling issues regarding fuel bed heterogeneity, especially where shrubs recovered quickly, suggests that characterizing masticated fuels may not be as simple as developing a generalized masticated fuel model. Understanding fuel dynamics following treatments will be important for predicting fire behavior and evaluating treatment efficacy in mitigating fire hazard and ecological effects. Custom fuel models may be developed for specific sites, but 'fine-tuning' these models to fit observed fire behavior may mean that the commonly used Rothermel (1972) fire spread model poorly predicts resulting fire behavior. Because of their fuel heterogeneity, masticated fuels, along with many other fuel types, may require new physically based process modeling approaches (e.g., Linn et al., 2002; Mell et al., 2007) to understand and parameterize the mechanisms controlling fire behavior. Research quantifying the spatial variability of masticated fuels may also prove helpful in understanding the spatial scales at which model assumptions are being violated and what effect fuel heterogeneity has on model error.

4. Science and management needs

Many questions remain for understanding fire behavior in masticated fuels (Table 4). Well-designed laboratory experiments and instrumented prescribed fire experiments are needed that can inform model prediction systems. Advancing our understanding of the combustion processes in the dense, mixed fuel beds that result from mastication and burn with long-duration flaming and smoldering will inform fire science more broadly (Table 4). Understanding the underlying combustion process and the link between the conditions before, during, and after fires is key.

4.1. Characterizing masticated fuel beds and their dynamics

Existing fire behavior and prediction models require inputs on the quantity and variability of fuels; in the United States the two common tools used to rapidly provide such information without time-consuming measurements are fuel models and photographs of representative fuel loads (referred to as fuel photo series in the United States). Ottmar and Safford (2012) developed several masticated fuel beds for the Fuel Characteristic Classification System (Ottmar et al., 2007). It is unclear where these and existing fire behavior fuel models (Anderson, 1982; Scott and Burgan, 2005), developed for natural fuels and logging slash, are useful approximations for masticated fuels. In the instances where no analogous fuel models are adequate to represent masticated fuel beds, customized fuel models and new fuels inventory methods will be necessary to estimate fuel bed characteristics, fuel loads, particle size, fuel depth, as well as the potential fire behavior and effects. Development of fuel bed height and loading relationships should be established regionally and locally where mastication is commonly

Table 4
Potential science needs in masticated fire behavior research.

Science questions	Follow-up topics
Characterizing fuel beds	
What are the effects of mastication treatments on fuel beds?	Changes in fuel loading Changes in particle size Changes in fuel bed depth Characterizing the spatial and temporal variability in masticated fuel mixtures Characterizing the variability across fuel beds using different mastication machinery Validating fuel loading determination methods
How do masticated fuel beds change over time?	Comparisons to non-masticated fuel beds Changes in moisture content profiles Changes in decomposition rates (e.g., C/N ratios) Changes in species composition and biodiversity overstory growth and mortality Vegetation recovery rates and species trajectories
Characterizing fire behavior	
What are the effects of mastication on fire behavior?	Changes to fireline intensity Changes to the fire duration and rate of spread Drivers and patterns of post-frontal flaming Changes in the ratio of flaming and smoldering combustion Changes in the ratio of energy transfer methods (radiation, convection, and conduction) Changes in the generation of holdover embers Role of windspeed, moisture content, fuel bed depth, particle size, fuel mixtures, etc., in influencing fire behavior in masticated fuel beds
Characterizing fire effects	
What are differences in combustion products?	Changes in combustion completeness Changes in charcoal and black carbon production Changes in the apportionment of different gas species, aerosols, and particulate matter
What are longer-term impacts?	Impacts on vegetation mortality Impacts on soil properties Impacts on biogeochemical cycles Impacts on water infiltration and run off

employed. Other approaches to estimate fuel loads may also prove useful, such as regression models relating pre-treatment standing volume to be masticated to post-mastication surface fuel loads. These would need to be regionally validated, as well as periodically assessed through time, to evaluate the strength of the relationship as the masticated materials decompose and vegetation responses occur.

The complications of fuel dynamics in masticated fuel beds deserve substantial attention, given their relevance to fire behavior variation and duration of treatment efficacy. Woody particle and fuelbed decay, litter inputs from residual overstory trees, and vegetation recovery must be addressed. In simple woody masticated fuels lacking a residual overstory and without resprouting shrubs, fuels will undergo comparably simple decomposition and compaction over time. In sites with residual overstory trees and/or resprouting shrubs, the resulting fuel dynamics and fire behavior and effects will be more difficult to evaluate (Kane et al., 2010; Knapp et al., 2011), particularly over time after initial treatment. These same issues of treatment longevity and maintenance plague many other aspects of fuels management.

Detailed fuel characterizations within masticated fuels across the range of ecosystems where treatments are occurring are critical to enhance our understanding of the variability of fuels (Keane, 2013) and the consequent fire behavior and effects across ecosystems. Studies should not only focus on quantifying fuel loads, bulk density, surface area-to-volume ratio of masticated particles, and plot level variability, but should include estimates of the scale at which spatial variability occurs. Such analyses should incorporate the implications for both flaming and smoldering combustion, fuel consumption and soil heating, all of which influence both ecological effects and emissions. Moreover, understanding the long-term efficacy and ecological consequences of mastication and other fuel treatments is needed.

4.2. Moisture dynamics in masticated fuels

Characterizing fuel moisture dynamics is fundamental to our understanding of fire behavior in masticated fuels. Thus far few moisture studies have been conducted in masticated fuels (Kreye and Varner, 2007; Kreye et al., 2012; Kreye, 2012). Drying rates of dense fuel beds are likely to be slower than predicted from their constituent particles (Kreye and Varner, 2007; Kreye et al., 2012). Loss of shrub or tree cover from mastication, however, may enhance drying of surface fuels through increased solar radiation and beneath-canopy wind flow (Kreye, 2012). Additional studies across a range of environmental conditions and fuel bed types are needed. Information regarding both the horizontal spatial variability and vertical moisture profiles in masticated fuels is also needed. Due to the high bulk density of these fuels, it will also be important to evaluate the ignition thresholds and the moisture of extinction in these fuels, as they may differ from assumed moisture thresholds of litter, duff, or slash. Further laboratory and field experiments determining moisture dynamics in varying fuel types, loading, depths, and composition will aid in modeling efforts to predict moisture contents in these fuels.

4.3. Fuel consumption and emissions resulting from burning masticated fuels

To better understand and manage fires in masticated fuels, data are needed on fuel consumption during flaming and smoldering combustion and the resulting emissions generated. Measuring the relative apportionment of carbonaceous and nitrogenous gases and the relative quantity of $PM_{2.5}$ and PM_{10} emitted during the different combustion phases is of particular importance to the predictive assessment of air quality and smoke management. Additionally, assessment of volatile organic compounds (VOCs) and secondary VOCs that may arise from the combustion of chemically treated (e.g., fire retardant) masticated fuels will be of particular interest. Further research is needed on the potential transition from flaming to smoldering combustion in masticated fuels. Moreover, laboratory and field experiments in masticated fuels focused on quantifying not only emissions and combustion efficiency, but also the transition between smoldering and flaming combustion will not only advance our fundamental understanding of fire as a process but also inform management decisions regarding prescribed and wildfires in masticated fuel beds.

4.4. Combustion and fire behavior: novel fuels burning in novel conditions

Masticated fuels are novel (Kane et al., 2009), and they will likely be burning under novel conditions in the future (Westerling et al., 2006; Westerling and Bryant, 2008). The empirical approaches on which many of the fuel consumption models currently rely are poorly suited to describing the implications of burning masticated fuels in novel conditions that we might expect with climate change. This could include fire occurrence in locations and at times uncommon historically and under conditions where fuels and soils are especially dry.

Ultimately, managers and scientists need a better grasp of expected fire behavior during prescribed burns and in wildfires that ignite and spread in masticated fuels. Laboratory experiments will undoubtedly be useful, field observation (in prescribed and wildfires) and experimentation are necessary next steps. In addition to characterizing "real" fires, field experiments and retrospective studies can assess the degree to which laboratory observations "scale up" and identify the shortcomings and strengths of laboratory findings.

Laboratory and field experiments can be used to parameterize models of fire behavior in masticated fuels across different vegetation types and at different ages, similar to experiments conducted in large woody fuels by Fahnestock (1960, 1962), Brown (1972), and others. Experiments should evaluate principal fire behavior variables (fire intensity, rate of spread, mass loss, smoldering duration, and consumption). Given the substantial variation in moisture regimes of the regions where mastication is employed, thoughtful attention to fuel moisture dynamics will be important facets of these designs. Studies focusing on firebrand ignition and spread could be adapted after similar methods described by Manzello et al. (2006) and re-ignition potential (particularly resulting from residual smoldering) could be evaluated similarly. For each of these, studies that embrace mixtures of fuels (e.g., masticated debris beneath shrub fuels, fuel beds overlying or intermixed with duff and litter) in the development and testing of fire behavior predictions in lab and experimental fires should be prioritized.

5. Conclusions

The compact fuel beds created when trees and shrubs are masticated contain a mix of shredded irregularly shaped particles and resulting fire behavior differs from other woody fuels with important but largely unknown implications for ignition, fire spread, and combustion duration. Results from the few laboratory experiments reveal the influence of fuel load, fuel depth, and fuel moisture on fire behavior in the surface debris created from mastication, however fuel variability and recovering vegetation are important contributors to post-treatment fire behavior at the field-scale in which treatments are employed. Generally, masticated fuels burn with prolonged flaming and smoldering combustion, compared to other fine surface fuels (e.g. litter), and long-duration heating will need to be considered when developing treatments to meet management goals. As with slash and other downed woody fuels, smoldering fires in masticated fuel beds will likely be capable of flaring up under certain wind conditions, requiring special attention when sites are burned under prescribed or wildfire conditions.

Fuel models that capture the complexities of masticated fuel beds are needed, as are studies of the particle characteristics in these mixed fuel beds. Additionally, the role of emergent fuel bed-level properties such as depth, bulk density, and spatial heterogeneity on subsequent fire behavior will need to be better understood in these unique fuels. Comparisons of fire behavior between treated and untreated sites are rare and differ in their results and the efficacy of mastication to mitigate fire hazard will likely vary due to differences in treatment objectives, spatial and temporal variability in fuels, and the vegetation response following treatment. Clearly, more research is needed to fully understand fire behavior in masticated fuel beds and across treated sites in different ecosystems to ultimately evaluate the efficacy of these treatments at reducing fire behavior and ameliorating negative fire effects.

Given the demand for cost-effective fuels treatments and the use of mastication in conjunction with prescribed fire, managers need to have a comprehensive understanding of the fire behavior associated with burning in masticated fuels. With an expanding WUI and an increasing number of large fires, fuels management using mastication will expand, and some of those fuel treatments will burn. Our ability to predict the behavior and effects of these fires will help managers prioritize both treatments and maintenance of those sites already treated. For the broader science community, the widespread use of masticated treatments highlight research needs for understanding smoldering combustion, emissions, potential for extended burning, ember generation and transport, the complexities of mixed fuel beds, and the linkages between fire behavior, fuel consumption, and fire effects.

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