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Novel fuelbed characteristics associated with mechanical mastication treatments in northern California and south-western Oregon, USA

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Abstract. Mechanically masticated fuelbeds are distinct from natural or logging slash fuelbeds, with different particle size distributions, bulk density, and particle shapes, leading to challenges in predicting fire behavior and effects. Our study quantified some physical properties of fuel particles (e.g. squared quadratic mean diameter, proportion of non-cylindrical particles) and surface fuel loading with planar intercept and plot-based methods in 10 mechanically masticated sites in northern California and south-western Oregon. Total woody fuel load differed among masticated sites, ranging from 15.3 to 63.4 Mg ha^{-1}, with the majority of the load concentrated in the 10-h (53.7%) and 1-h (29.2%) time-lag classes. Masticated fuels were densely packed, with total depths ranging from 4.6 to 8.0 cm and fuelbed bulk densities ranging from 45.9 to 115.3 kg m^{-3}. To accurately quantify loading in masticated fuelbeds, we recommend using a hybrid methodology, where 1-h and 10-h fuel loadings are estimated using a plot-based method and 100-h and 1000-h fuel loadings are estimated using the standard planar intercept method. Most masticated fuelbeds differed in loading by fuel class and fuelbed depth, when compared with existing natural and slash-based fuelbeds, suggesting new fire behavior fuel models specific to masticated fuelbeds may be warranted.

Additional keywords: *Arctostaphylos*, *Ceanothus*, fuel loading, fuels management, mechanical fuels treatment.

Introduction

In many fire-prone ecosystems of the western United States, uncharacteristically heavy surface fuel accumulations and overly dense stands have prompted the need for wildland fuels treatments (Agee *et al*. 2000; Covington 2000; Agee and Skinner 2005). Although the reintroduction of fire to these ecosystems through prescribed fire or wildland fire use may be advantageous, many restrictions and concerns limit widespread use of fire by land managers. As a result, mechanical methods are increasingly being used as an initial or solitary fuels management strategy (Agee and Skinner 2005). Mechanical fuels treatments typically utilize traditional timber harvesting techniques to meet fuel treatment objectives; however, areas with non-commercial trees and shrubs often require a different strategy.

Mechanical mastication is a fuels management method that shreds or chops live and dead fuels including small trees, shrubs, down woody debris and other material with a rotary blade or rotary drum with flailing knives (Ottmar *et al*. 2001), depositing the accumulated debris onto the ground (Fig. 1). Mechanical fuel treatments, including mastication, are commonly used within fuelbreaks and at the wildland–urban interface, often in lieu of prescribed burning, because it avoids the air quality constraints, liability concerns, potential property and resource damage, and public perception issues associated with treatments including fire (Agee and Skinner 2005; Busse *et al*. 2005). Restrictions on the use of fire in combination with pressure on managers to treat more area have likely fostered the increased use of mechanical mastication on Forest Service land in California (Busse *et al*. 2005), a trend that may be common throughout much of the western United States. Mastication actively treats surface and ladder fuels, allowing improved firefighter access for suppression activities. In some situations, treatment of ladder fuels through mastication may make subsequent prescribed fire treatments easier to implement (Stephens and Moghaddas 2005). Furthermore, mastication may reduce soil impacts in comparison with other mechanical treatments used because the equipment operates on top of the generated mulch layer, minimizing soil compaction (Moghaddas and Stephens 2008). Mineral soil is often incorporated in the treated fuelbed (Hood and Wu 2006), which could also contribute to a dampening of fire behavior.

Despite its advantages, mastication is not without potential drawbacks. Mechanical mastication reduces vertical continuity, but increases dead surface woody fuel loading, retaining all generated fuels on site. Increases in surface fuelbed bulk density through compaction, via mastication or other methods, may reduce potential fire behavior (Jerman *et al*. 2004; Glitzenstein *et al*. 2006). Additionally, mastication can also alter the physical properties of fuel particles by breaking them up into pieces with smaller diameters and different particle shapes, both of which can increase surface area-to-volume ratios. Increases in the surface area-to-volume ratios have been shown to increase the rate of moisture adsorption and desorption with atmospheric or

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Fig. 1. Mechanically masticated site on the Six Rivers National Forest near Mad River, California, USA.

weather changes (Lancaster 1970), which, in turn, may directly impact ignitability, sustainability, combustibility and consumability of particles (Anderson 1970; Deeming and Brown 1975; Martin *et al*. 1993). Particles with greater surface area-to-volume ratios and potentially faster desorption rates may contribute to faster rates of spread, higher flame lengths, and increased fireline intensities compared with larger-diameter particles with lower surface area-to-volume ratios (Rothermel 1972, 1983). Unexpected fire behavior in masticated fuelbeds has been documented (Bradley *et al*. 2006) and may be partially explained by the woody particle alterations produced by mastication equipment.

Because of potential fire behavior concerns, managers and scientists are interested in determining the appropriate sampling method to estimate fuel loading in masticated areas. The same alterations to particle properties that potentially change fire behavior may also make estimating fuel loading using the traditional planar intercept method problematic (Brown 1974). The planar intercept estimation method relies on the assumptions that fuel particles are round and the diameter values in particle time-lag classes (e.g. 1-h, 10-h) are normally distributed (Van Wagner 1968). As mastication alters the particle size distribution (from larger to smaller particles) and particle shape (from near cylindrical to hemicylindrical or more rectangular in cross-section), evaluation of the appropriateness and accuracy of the planar intercept method for estimating fuel loading in this fuel type is needed.

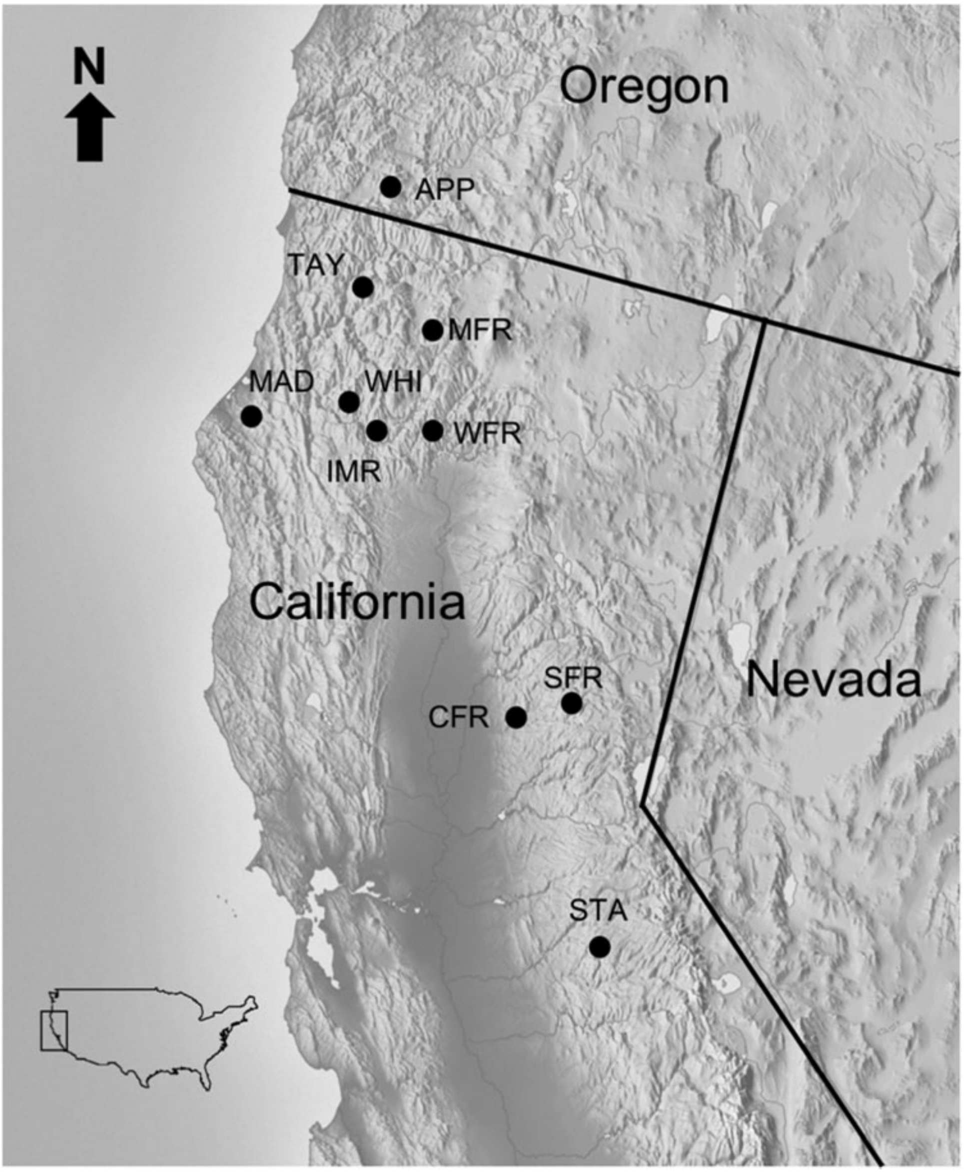

Fig. 2. Study site locations for mechanically masticated areas in northern California and south-western Oregon, USA. Site information abbreviations are provided in Table 1.

Few studies have estimated fuel loading in masticated fuelbeds of the United States (Stephens and Moghaddas 2005; Glitzenstein *et al*. 2006; Hood and Wu 2006). None of these studies have characterized the physical properties of masticated particles. Only one study (Glitzenstein *et al*. 2006) has compared methodologies for estimating fuel loading in masticated fuelbeds, and this was conducted in the south-eastern United States, where vegetation differs substantially to that found in the western United States.

In the present study, 10 mechanically masticated sites of northern California and south-western Oregon were evaluated with the following objectives: (1) to characterize the physical properties of masticated fuel particles; (2) to quantify variation in fuel loading among masticated sites; (3) to compare and contrast fuel loading estimates obtained by planar intercept and plot-based methods in masticated fuelbeds on multiple sites; (4) to determine the optimal sample size for estimating woody fuel loading in masticated fuelbeds; (5) to determine if fuelbed depth can be used to estimate fuel loading in masticated areas; and (6) to compare masticated fuelbed characteristics with existing natural and slash-dominated fuelbeds.

Methods

Study sites

Ten recently masticated sites in northern California and south-western Oregon, USA, were selected to collect fuel particles and estimate fuel loading (Fig. 2). Study sites (see Table 1 for explanation of abbreviations used in text) were located primarily on federal lands (USDA Forest Service, USDI Bureau of Land

Table 1. Site names, locations, treatment dates, and masticator types for 10 mechanically masticated study sites in northern California and south-western Oregon, USA
For Location: BLM, Bureau of Land Management; NPS, National Park Service; NRA, National Recreation Area; USFS, United States Department of Agriculture, Forest Service. For Masticator type: BM, boom-mounted; FE, front-end-mounted; RB, rotary blade; RD, rotary drum

Site code	Site name	Location	Treatment date	Sample date	Masticator type
APP	Applegate Valley	Applegate Valley, OR (BLM)	April–May 2005	October 2005	BM/RB Slashbuster brush cutter
CFR	Challenge fuel reduction	Plumas National Forest, CA (USFS)	December 2002	September 2004	FE/RD Rayco Forestry Mower
IMR	Iron Mountain Rd	Redding, CA (BLM)	November 2004	November 2005	FE/RD Masticating head on ASV Positrack
MAD	Mad River	Six Rivers National Forest, CA (USFS)	December 2004	January 2006	FE/RD Takeuchi, TL150 with FECON Bull Hog shredder head
MFR	Mt Shasta fuel reduction	Shasta–Trinity National Forest, CA (USFS)	May 2003	December 2005	FE/RD Rayco forestry mower (small) on a bulldozer
SFR	Sierraville fuel reduction	Tahoe National Forest, CA (USFS)	May–June 2003	September 2005	FE/RD Rayco forestry mower (small) on a bulldozer
STA	Sampson fuel reduction	Stanislaus National Forest, CA (USFS)	Fall 2003	June 2006	BM/RD Environmental Forestry head on excavator
TAY	Taylor Ridge	Klamath National Forest, CA (USFS)	April–May 2005	September 2005	BM/RB Brontasaurus head on excavator
WFR	Whitmore fuel reduction	Whitmore, CA (Private)	May 2003	October 2005	FE/RD Rayco forestry mower (small) on a bulldozer
WHI	Whiskeytown	Whiskeytown NRA, CA (NPS)	November 2002	December 2005	FE/RB Slashbuster on an ASV Positrack

Management, and USDI National Park Service) with one additional site on a private forest (Whitmore, California, USA). Four of the sites were part of an existing fuel reduction study involving mastication treatments (CFR, MFR, SFR, WFR), while the remainder were identified by local managers as representative areas. All mastication treatments used a front-end or boom-mounted masticator with either a rotating drum or blade-style head. Treatments were conducted between November 2002 and May 2005 (Table 1). The masticated vegetation within each of the study sites varied but was dominated by either shrubs (principally *Arctostaphylos* spp. and *Ceanothus* spp.) or small hardwood trees (e.g. *Lithocarpus densiflorus*, *Arbutus menziesii*), with some sites containing both.

Physical properties of masticated particles

To characterize the physical properties of masticated woody particles, we measured: (1) the proportion of fuels with altered surfaces due to mastication; (2) particle diameter; (3) deviation of particle diameters from a cylinder; and (4) the distributional properties of particle diameters within each time-lag class following Brown (1974): 1-h (<0.64 cm diameter), 10-h (0.64–2.54 cm), 100-h (2.54–7.62 cm), 1000-h (>7.62 cm). Each of physical properties measured directly or indirectly quantifies particle properties important for potential fire behavior and estimating fuel loading using the planar intercept method. Particle measurements were made based on three sample collections per site. Irregular particles were defined as pieces having greater than 50% surface area altered by the mastication process. In addition, average squared quadratic mean diameters of particles in the 1-, 10-, and 100-h time-lag classes were obtained by visually dividing each particle into thirds and then measuring the minimum and maximum diameters at the midpoint of one of the thirds. For example, the first particle was measured at the midpoint of the first third, the second particle at the midpoint of the middle third, and the third particle measured at the midpoint of the last third, until all particles were measured. To approximate the degree of deviation from a cylinder or cube, the average difference between the measured minimum and maximum diameters was calculated for each time-lag class and site. A perfect cylinder would be represented by equal values of minimum and maximum diameters, whereas particles hemicylindrical in shape or rectangular in cross-section would differ substantially between the minimum and maximum diameters. Lastly, distributional curves for average squared quadratic mean diameters were examined for each time-lag class and site, to investigate deviations from the assumptions of normality assumed in naturally generated fuelbeds (Brown 1974; Brown *et al*. 1982).

Fuel loading estimation

All data collection occurred between the summers of 2004 and 2006, which was between 5 and 37 months after mastication, depending on the site (Table 1). Dead woody fuel loadings were estimated using two methods: the planar intercept method (Brown 1974) and a destructive plot-based sampling method. For each method, 15 samples were taken at each site with the exception of two sites (CFR and WFR, which were later prescribed burned) where 40 samples were collected.

For the planar intercept method, baseline transects were set up at random azimuths, traversing the treated area within each study site. Planar transects were established at a random azimuth every 25 m along the baseline transects to reduce the potential for bias due to non-random particle orientation. Planar transect length was 20 m, modified only when the location ended up near the edge of a treated area. All 1-h and 10-h time-lag particles that intercepted the sampling plane (1 m tall) were tallied along the first 2 m, while the 100-h fuel particles were tallied along the first 4 to 6 m, depending on the observed frequency of 100-h fuels in the area. The entire transect length was surveyed for 1000-h fuel particles and their diameters were measured, species recorded, and decomposition category (sound or rotten) assigned. Size-class determination of each of the fine fuel particles (1- to 100-h) was made along the narrowest diameter that intersected the plane. The narrowest diameter was measured because fire behavior and fuel moisture dynamics are partially a function of fuel particle size (Rothermel 1972, 1983), and we assumed that the narrowest diameter of a masticated fuel particle would better represent the particle's response to moisture loss and gain, and subsequent ignitability, than the widest diameter.

For the plot-based method, a 50 × 50-cm metal frame was placed on the ground at the 7-m mark of each planar intercept transect, and all fuels inside the frame collected. In the event that a woody fuel particle intersected the frame, the piece was cut along the boundary and the interior portion retained. In addition to the dead surface fuels, all living vegetation (both herbaceous and woody plants) rooted within the sampling frame was cut within 1 cm of the surface and placed in a separate bag. After the live fuel was removed, fuelbed depth was determined (for all sites except CFR) by pounding four 25-cm large-gauged nails into the soil, 10 cm diagonally from each of the plot frame corners, until the nail head was flush with the top of the litter and wood layer. Afterwards, the litter and wood layer was removed from the entire plot and the average distance from the top of the nail to the bottom of the litter and wood layer was measured. Next, the duff was removed and the distance between the top of the nail to the bare mineral soil was measured. Duff depth was calculated as the average difference between the total depth of organic debris and the litter and wood depth. Total fuelbed depth was the sum of the litter and wood depth, as well as the duff depth. All woody fuels occurring in the litter were separated by time-lag class in the laboratory. Mastication often results in some mixing of mineral soil throughout the fuelbed; any soil encountered was brushed off or removed from the litter and wood layer during sorting. Duff samples were placed in a bucket of water for several minutes and stirred to allow the mineral soil to sink to the bottom. Floating organic debris was then removed and allowed to air-dry for 1–2 days. All fuel categories were oven-dried for at least 72 h at 85°C in a mechanical convection oven and then weighed on an analytical balance. Fuelbed bulk density ($kg\,m^{-3}$) values were calculated by dividing the total fuel load estimates (wood, litter, and duff) in $kg\,m^{-2}$ by the total fuelbed depth (m).

Calculations for woody fuel loading using the planar intercept method were based on the formula provided by Van Wagner (1968) and Brown (1974):

$$\text{Fuel loading } (\text{Mg ha}^{-1}) = \frac{1.234 \times n \times d^2 \times s \times a \times c}{L}$$

where n is the number of particles intercepting the sampling plane, d^2 is the squared quadratic mean diameter (cm^2), s is the specific gravity (dimensionless), a is the secant of the non-horizontal particle angle, c is the slope correction factor, and L is the length of transect (m). Squared quadratic mean diameter (d^2) was calculated as the sum of all measured diameters (d) squared, divided by the number of samples measured (n):

$$d^2 = \frac{\sum d^2}{n}$$

Site-specific input values used to calculate planar intercept fuel loading estimates included specific gravity, particle angle, and squared quadratic mean diameter. Average specific gravity values were measured for each time-lag class (1-, 10-, and 100-h) at all 10 sites using the mass of displaced water method in accordance with ASTM D2395–02 Method B (ASTM 2002). Particle angle measurements were made along four 20-m transects at each site, measuring the first 10 particles encountered in each of the time-lag classes. Particle angle values were measured with a protractor as the angle of the woody fuel particle in reference to the ground surface to the nearest 5 degrees and then converted to secant for entry into the planar intercept formula (van Wagtendonk *et al.* 1996).

Statistical analyses

Means and standard errors were calculated for site-level estimates of total woody fuel loading and loading by different time-lag classes for both the planar intercept method and the plot-based method. Separate one-way analysis of variance (ANOVA) tests were used to determine if total woody fuel loading and loading for each time-lag class differed among sites and between fuel loading estimation methods. If differences were detected, a post-hoc Bonferroni means comparison test was used to determine which site locations and estimation methods differed from each other (Sokal and Rohlf 1995). If any of the data did not meet the assumptions of normality or equal variance, a square-root transformation of the data was made (Sokal and Rohlf 1995). Furthermore, if transforming the dataset still failed to meet the assumptions of an ANOVA, a non-parametric Kruskal–Wallis test on ranks and corrected for ties (test value = χ^2) was used, followed by a post-hoc Kruskal–Wallis Z-test using the Bonferroni test value. A Shapiro–Wilk W-test for normality was performed to determine whether particle diameters within each time-lag class were normally distributed (Sokal and Rohlf 1995), thus testing whether the normality assumption of the planar intercept method was violated.

Sampling efficiency was estimated for each method (plot-based and planar intercept) and woody fuel type (1-, 10-, 100-, 1000-h) based on bootstrap variances generated using the *S-Plus* statistical package (Insightful Corporation 2007), with data collected at two intensively sampled sites: a low-woody-fuel-loading site (WFR) and a high-woody-fuel-loading site (CFR). Bootstrap analysis statistically increases sample size by randomly sampling points (with replacement) from the original dataset. For this study, we generated 2000 bootstrap iterations across a sample size gradient for both methodologies. Recommended sample size was determined as the approximate inflection point of the generated curves for each method and fuel type (Sikkink and Keane 2008).

We performed linear regression analyses to determine the relationship between surface fuel loading and fuelbed depth using the plot-based estimates. Each linear regression equation was calculated with the y-intercept (b_0) set to zero, where no depth corresponded to no loading (Sokal and Rohlf 1995). The coefficient of determination (r^2) for each regression analysis is not reported owing to inaccuracies when the y-intercept is forced through the origin (Zar 1999). The CFR site was excluded from the analysis because a different methodology was used to estimate fuelbed depth. All statistical tests were performed using *NCSS* software (Hintze 2006), with the level of statistical significance assumed to be $\alpha = 0.05$.

To determine whether masticated fuelbeds investigated in the present study were similar to or distinct from existing fuelbeds, a k-means cluster analysis was performed in *NCSS* (Hintze 2006). Fuelbed data included in the analysis were taken from published photoseries (Maxwell and Ward 1979, 1980; Blonski and Schramel 1981) representing timber, slash, and shrub fuel types in close proximity to our study sites. We used data from the plot-based estimates of our study sites with the exception of the CFR site. Input data used in the cluster analysis included mean 1-, 10-, 100-, and 1000-h fuel loading, as well as mean litter and duff depth. These variables were included because of their direct influence on surface fire behavior (Rothermel 1972, 1983). Live fuel loading is also a desired fuelbed characteristic, but was unavailable from the photoseries data.

Results

Physical properties of masticated particles

Mastication changed the shape, size, and size distribution of fuel particles. For instance, the majority (58.7 ± 3.7%) of 1-h fuel particles (by weight) had irregular shapes due to being masticated. Larger fuel classes had lower proportions of irregular particles by weight (10-h = 51.0 ± 4.1%, 100-h = 35.1 ± 7.7%). Many of the particle shapes were described as hemicylindrical or rectangular in cross-section rather than round. The magnitude of these shape irregularities (i.e. deviation from round) is illustrated by percentage difference between the minimum and maximum diameter of masticated particles, which were 42.2 ± 1.5%, 34.9 ± 1.2%, and 29.0 ± 3.0% for 1-, 10-, and 100-h fuels respectively.

Squared average quadratic mean diameters varied significantly among sites for both 1-h ($\chi^2 = 404.5$, d.f. = 9, $P < 0.001$) and 10-h time-lag classes ($\chi^2 = 58.8$, d.f. = 9, $P < 0.001$) (Table 2). In addition, squared average quadratic mean diameters for the 1-h and 10-h time-lag classes were not normally distributed at all 10 sites. Shapiro–Wilk W-test values ranged from 0.58 to 0.81 (Table 2) with positively skewed ($g_1 > 0$) and leptokurtic ($g_2 > 0$) distributions (Sokal and Rohlf 1995). Conversely, 100-h fuels were normally distributed for all sites except three (CFR, SFR, and WHI; Table 2), although this size class also had much smaller sample sizes (range 2 to 17 across all sites).

Fuel loading estimation and methods comparison

Dead woody fuel loading estimates in the 1-h and 10-h time-lag classes differed significantly among sites ($P < 0.001$; Table 3), but loading of 100-h ($\chi^2 = 15.1$, d.f. = 9, $P = 0.089$) and 1000-h

Table 2. Fuel particle squared average quadratic mean diameters (d^2) and distribution statistics of 1-, 10-, and 100-h time-lag classes for 10 mastication study sites (see Table 1) in northern California and south-western Oregon, USA

Squared quadratic mean diameters (mean ± s.e.) among sites were compared using an ANOVA with a post-hoc Kruskal–Wallis multiple-comparison Z-value test and denoted with superscripted letters. Values that share the same letter within each column are not significantly different. The Shapiro–Wilk test statistic (W) ranges from 0 to 1, where 1 represents a perfect normal distribution. Probability (*P*) values in bold denote significant diameter difference (<0.05) among sites or a non-normal distribution by site

Site	1-h time-lag class				10-h time-lag class				100-h time-lag class			
			Normality				Normality				Normality	
	n	d^2 (cm^2)	W	*P*	*n*	d^2 (cm^2)	W	*P*	*n*	d^2 (cm^2)	W	*P*
APP	405	0.12 (0.01)^{bc}	0.80	**<0.001**	150	1.53 (0.13)^{bc}	0.62	**<0.001**	9	13.5 (2.3)	0.85	0.073
CFR	364	0.17 (0.01)^{a}	0.75	**<0.001**	294	1.70 (0.08)^{ab}	0.80	**<0.001**	15	12.5 (1.6)	0.76	***0.001***
IMR	561	0.15 (0.01)^{ab}	0.81	**<0.001**	164	1.39 (0.10)^{bc}	0.67	**<0.001**	7	11.4 (1.0)	0.86	0.143
MAD	1210	0.09 (0.00)^{d}	0.60	**<0.001**	147	1.36 (0.10)^{bc}	0.72	**<0.001**	4	11.9 (1.5)	0.95	0.734
MFR	604	0.13 (0.01)^{bc}	0.70	**<0.001**	262	1.41 (0.08)^{bc}	0.70	**<0.001**	4	13.3 (1.6)	0.89	0.404
SFR	444	0.13 (0.01)^{bc}	0.67	**<0.001**	231	2.21 (0.15)^{a}	0.69	**<0.001**	17	19.7 (3.6)	0.78	**0.001**
STA	728	0.14 (0.01)^{abc}	0.58	**<0.001**	266	1.51 (0.08)^{bc}	0.71	**<0.001**	7	13.6 (1.7)	0.96	0.832
TAY	855	0.13 (0.01)^{bc}	0.74	**<0.001**	252	1.19 (0.06)^{c}	0.71	**<0.001**	6	13.8 (1.8)	0.96	0.845
WFR	666	0.15 (0.01)^{abc}	0.75	**<0.001**	157	1.41 (0.13)^{bc}	0.53	**<0.001**	5	16.6 (1.4)	0.98	0.920
WHI	660	0.12 (0.01)^{c}	0.73	**<0.001**	167	1.59 (0.12)^{bc}	0.70	**<0.001**	2	16.6 (10.0)	0.75	**<0.001**
P		**<0.001**				**<0.001**				0.598		
All sites	10	0.13 (0.007)			10	1.53 (0.09)			10	14.3 (0.8)		

Table 3. Comparisons of mean surface and ground fuel loading (standard error) for mechanically masticated areas from the plot-based sampling method (50 × 50 cm) by time-lag class and study site (see Table 1)

Live fuels consisted of both herbaceous and woody components. Post-hoc tests were completed with a Kruskal–Wallis multiple-comparison Z-value test and denoted with superscripted letters. Values that share the same letter within each column are not significantly different

Site	*n*	1-h	10-h	100-h	1000-h	Total woody	Live	Litter	Duff
						(Mg ha^{-1})			
APP	15	12.3 (2.8)^{ab}	24.6 (4.9)^{abc}	8.6 (4.9)	5.3 (5.3)	50.7 (10.0)^{ab}	0.0 (0.0)^{c}	10.3 (2.8)^{abc}	6.7 (3.1)^{bc}
CFR	40	7.6 (0.9)^{bc}	21.4 (2.7)^{abc}	8.1 (2.3)	2.2 (1.6)	39.3 (6.1)^{abc}	0.4 (0.3)^{bc}	8.6 (1.1)^{ab}	12.4 (1.8)^{abc}
IMR	15	6.2 (1.7)^{bc}	13.8 (4.0)^{bcd}	3.6 (1.7)	0.0 (0.0)	23.6 (6.9)^{bcd}	0.5 (0.4)^{abc}	2.6 (0.6)^{cd}	7.5 (3.1)^{bc}
MAD	15	23.5 (2.6)^{a}	34.8 (4.3)^{a}	5.1 (2.5)	0.0 (0.0)	63.4 (7.8)^{a}	0.0 (0.0)^{bc}	0.6 (0.3)^{d}	19.6 (4.3)^{ab}
MFR	15	4.7 (1.1)^{bc}	8.2 (2.2)^{cd}	1.3 (0.6)	3.1 (2.2)	17.4 (4.0)^{bd}	0.6 (0.3)^{abc}	2.9 (0.5)^{cd}	15.0 (3.7)^{abc}
SFR	15	5.2 (1.0)^{bc}	11.1 (2.3)^{bcd}	6.6 (2.9)	0.0 (0.0)	22.9 (5.4)^{bcd}	6.1 (2.0)^{a}	5.4 (1.5)^{abc}	5.7 (2.1)^{bc}
STA	15	15.7 (1.7)^{a}	25.0 (3.3)^{ab}	4.8 (1.6)	1.3 (1.3)	46.9 (6.1)^{ac}	1.2 (0.5)^{ab}	9.9 (1.0)^{a}	25.9 (4.0)^{a}
TAY	15	13.2 (2.9)^{ab}	21.7 (4.4)^{abcd}	2.1 (0.8)	0.0 (0.0)	37.0 (6.4)^{abc}	0.6 (0.3)^{abc}	5.6 (1.4)^{abc}	27.9 (5.0)^{a}
WFR	40	4.4 (0.8)^{c}	9.4 (1.7)^{d}	1.6 (0.6)	0.0 (0.0)	15.3 (2.8)^{d}	0.4 (0.2)^{bc}	4.8 (0.5)^{abc}	5.9 (1.2)^{c}
WHI	15	11.8 (2.4)^{ab}	16.4 (2.9)^{abcd}	3.5 (1.5)	0.0 (0.0)	31.8 (5.3)^{abcd}	0.1 (0.1)^{abc}	3.3 (0.7)^{bcd}	7.0 (1.5)^{abc}
P		<0.001	<0.001	0.089	0.264	<0.001	<0.001	<0.001	<0.001
All sites		10.5 (1.9)	18.6 (2.7)	4.5 (0.8)	1.2 (0.6)	34.8 (4.9)	1.0 (0.6)	5.4 (1.0)	13.4 (2.7)

($\chi^2 = 11.2$, d.f. = 9, $P = 0.264$) time-lag classes did not (Table 3). The greatest total woody fuel loading (63.4 Mg ha^{-1}) was observed at the MAD site and was more than 400% greater than the lowest fuel loading site (WFR), where the estimated woody fuel load was 15.3 Mg ha^{-1} (Table 3). Pooled across all sites, fuel loading estimates were largely concentrated in the 10-h and 1-h time-lag classes, comprising $53.7 \pm 1.5\%$ and $29.2 \pm 1.9\%$ of the total woody fuel loading respectively. Mean live fuel loading among sites was 1.0 ± 0.6 Mg ha^{-1}, representing less than 2% of the total fuel loading. Fuelbed depth varied significantly among sites ($\chi^2 = 20.6$, d.f. = 8, $P = 0.008$), ranging from 4.6 to 8.0 cm (Table 3). Fuelbed bulk density also differed significantly among sites ($\chi^2 = 69.4$, d.f. = 8, $P < 0.001$) with the average ranging from 45.9 to 115.3 kg m^{-3}.

Estimations of fuel loading using the planar intercept method also varied significantly among sites for all time-lag classes ($P < 0.001$; Table 4). Total woody fuel loading estimates ranged from 13.4 to 41.6 Mg ha^{-1} (Table 4) with the highest estimate observed at the MAD site, which was 300% greater than the lowest woody fuel loading site (IMR). Across all sites, most of the woody load was concentrated in the 10-h time-lag class ($50.6 \pm 4.6\%$), while the 100-h fuels comprised the second largest contribution ($25.4 \pm 2.7\%$).

Bootstrap analysis suggested that the optimal sample intensity using the plot-based method is between 10 and 15 samples or 2.50 to 3.75 m^2 in sample area (Fig. 3). The planar intercept method captured sufficient bootstrap variance with between 5 and 10 transects or 10 to 20 m of transect length for 1-h fuels and 10-h fuels and 20 to 40 m of transect length for 100-h fuels (Fig. 3). In general, the plot-based method resulted in higher bootstrap variances than the planar intercept method, with the exception of 100-h planar intercept variance from the high-fuel-load site (CFR) and 1000-h planar intercept variance from the low-fuel-load site (WFR).

Comparative analysis showed that the two sampling methods did not result in different estimates of total woody fuel loading ($F = 1.08$, d.f. = 1, $P = 0.311$), but the distribution of loading among the particle sizes appeared to differ. For 1-h fuel loading, the average plot-based estimate (10.5 Mg ha^{-1}) was nearly four times the average planar intercept estimate (3.5 Mg ha^{-1}; $F = 14.7$, d.f. = 1, $P = 0.001$; Tables 3 and 4). Conversely, 10-h fuel-loading estimates for 10-h fuels obtained using the plot-based method (18.6 Mg ha^{-1}), were 25% more than estimates obtained using the planar intercept method (14.0 Mg ha^{-1}) although this latter difference was not statistically significant ($P = 0.300$). The opposite trend was seen for the larger fuel categories, with planar intercept estimates for 100-h (7.1 Mg ha^{-1}) and 1000-h (3.8 Mg ha^{-1}) time-lag classes 60 to 70% greater than the estimates from the plot-based method (4.5 and 1.2 Mg ha^{-1} respectively; Table 3). Neither of these latter two differences were significant ($P = 0.076$ for 100-h, $P = 0.162$ for 1000-h respectively).

A significant difference in the coefficient of variation was detected in the 100-h ($F = 39.00$, d.f. = 1, $P < 0.001$) and 1000-h ($F = 6.13$, d.f. = 1, $P = 0.033$) time-lag classes. The difference between these two methods in the 100-h and 1000-h time-lag classes was substantial, with the plot-based method having 85 and 69% greater coefficient of variation values respectively.

Table 4. Mean woody fuel loading estimates by time-lag class based on the planar intercept sampling method for mechanically masticated sites (see Table 1)

Post-hoc tests were completed with a Kruskal–Wallis multiple-comparison Z-value test and denoted with superscripted letters. Values that share the same letter within each column are not significantly different

Site	*n*	1-h	10-h	100-h ($Mg\ ha^{-1}$)	1000-h	Total woody
APP	15	5.7 (0.9)^{b}	16.8 (2.9)^{abc}	9.2 (2.2)^{abc}	3.1 (1.0)^{b}	34.8 (4.4)^{ab}
CFR	34	1.0 (0.2)^{de}	14.3 (1.5)^{bc}	12.9 (1.3)^{a}	7.0 (1.4)^{ab}	35.3 (3.0)^{ab}
IMR	15	2.2 (0.5)^{cde}	6.1 (1.1)^{d}	4.8 (1.3)^{bcd}	0.3 (0.2)^{cd}	13.4 (2.3)^{c}
MAD	15	4.3 (0.5)^{bc}	30.1 (3.9)^{a}	7.2 (1.7)^{abc}	0.0 (0.0)^{d}	41.6 (4.6)^{a}
MFR	15	2.0 (0.3)^{de}	8.1 (1.5)^{cd}	3.1 (1.2)^{cd}	0.7 (0.4)^{cd}	14.0 (2.7)^{c}
SFR	15	1.0 (0.2)^{de}	8.1 (2.2)^{cd}	7.2 (1.6)^{abc}	16.8 (4.0)^{a}	33.1 (4.5)^{ab}
STA	15	9.8 (1.1)^{a}	21.2 (3.4)^{ab}	8.9 (1.7)^{ab}	1.1 (0.9)^{cd}	41.0 (6.0)^{a}
TAY	15	4.4 (0.5)^{bcd}	15.8 (2.0)^{bc}	8.3 (2.0)^{abc}	8.4 (5.7)^{bcd}	36.8 (6.8)^{ab}
WFR	40	1.6 (0.2)^{de}	10.0 (1.4)^{cd}	1.7 (0.4)^{d}	0.3 (0.2)^{d}	13.6 (1.6)^{c}
WHI	15	2.7 (0.4)^{cde}	10.0 (1.5)^{bcd}	7.6 (1.4)^{abc}	0.0 (0.0)^{d}	20.4 (2.8)^{bc}
P		<0.001	<0.001	<0.001	<0.001	<0.001
All sites		3.5 (0.8)	14.0 (2.3)	7.1 (1.0)	3.8 (1.7)	28.4 (3.5)

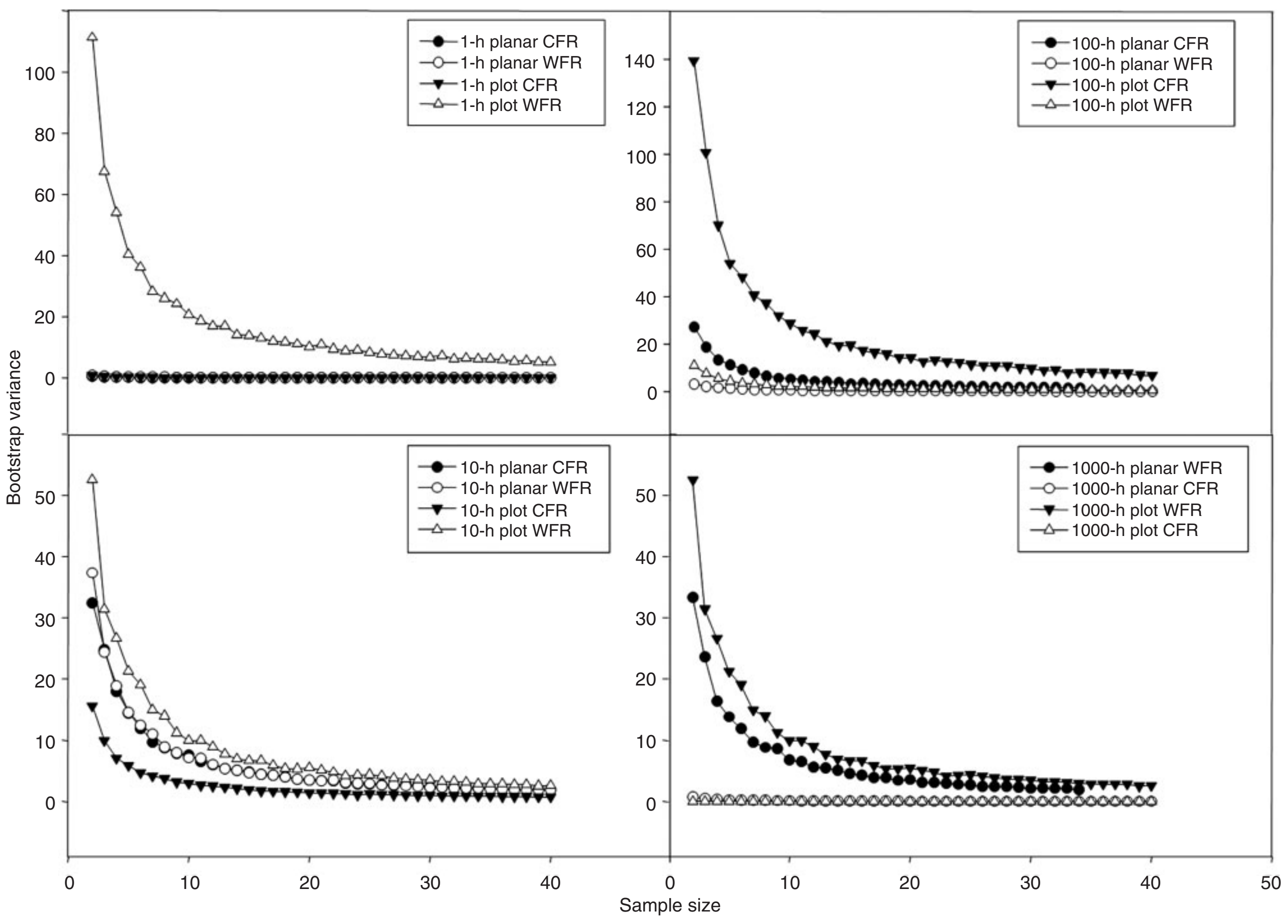

Fig. 3. Bootstrap variances (based on 2000 iterations) by sample size for 1-, 10-, 100-, and 1000-h masticated fuels from both the plot-based method (triangles) and the planar intercept method (circles). Sample size for the plot-based method represents 0.25 m^2 per sample for all fuel classes. Planar intercept method represents 2 m (1-h, 10-h), 4 m (100-h), and 20 m (1000-h) per sample. Data were collected from a high-load site (CFR; closed symbol) and a low-load site (WFR; open symbol).

Table 5. Linear regression results between fuel depth (*x*) and litter and woody fuel load (*y*) across nine masticated sites (see Table 1) in northern California and south-western Oregon, USA

Linear regression equation form: $y = 0 + b_1(x)$; s.e., standard error; probability, $P > 0.05$

Site	*n*	b_1 (s.e.)	*P*
APP	15	8.9 (1.24)	<0.001
IMR	15	5.9 (0.78)	<0.001
MAD	15	14.1 (0.63)	<0.001
MFR	15	6.8 (1.14)	<0.001
SFR	15	9.7 (0.67)	<0.001
STA	15	10.7 (0.88)	<0.001
TAY	15	8.6 (0.85)	<0.001
WFR	40	4.6 (0.44)	<0.001
WHI	15	6.2 (0.58)	<0.001
All sites	9	8.3 (4.27)	<0.001

Fuelbed depth and loading relationships

Fuelbed depth was a strong predictor of total woody and litter fuel loading at each site ($P < 0.001$; Table 5). Slope values for within-site depth-to-load relationships ranged from 4.6 to 14.1 (Table 5). The slope of the depth-to-load relationships by site was positively correlated with litter and woody fuel loads ($r^2 = 0.95$, $P < 0.001$), with greater-fuel-load sites (e.g. APP, MAD, STA) having higher slope values.

Fuelbed comparisons

Masticated fuelbeds from our study were distinct from other common regional fuel types including timber, slash and shrub fuelbeds (Fig. 4). Based on a k-means cluster analysis, the dataset partitioned into two clusters and explained 73% of the variation. Cluster 1 was composed of five masticated fuelbeds (APP, MAD, STA, TAY, WHI), whereas cluster 2 included the remaining four masticated sites (IMR, MFR, SFR, WFR) and all of the timber slash and shrub fuelbeds. Three of the four mastication sites (MFR, SFR, WFR) that were in cluster 2 contained ponderosa pine as the predominant overstorey tree species. Significant differences between the two clusters were detected in 1-h ($F = 128.9$, $P < 0.001$) and 10-h ($F = 55.18$, $P < 0.001$) fuel loading. Cluster 1 had more than eight times the amount of 1-h fuel loading and almost four times more 10-h fuel loading compared with cluster 2.

Discussion

Physical properties of masticated particles

Mechanical mastication changes physical properties of woody fuel particles that can influence fire behavior (i.e. rate of spread, flame length, and fireline intensity) in treated areas. Our results suggest that mastication reduces particle size, changes particle shape from round to irregular, and increases particle fracturing. Changes in physical properties of particles include greater surface area-to-volume ratios, which can result in increased fire behavior (Rothermel 1972, 1983). Conversely, the compacted nature of masticated fuelbeds may reduce the rate of spread, flame length, and fireline intensity (Scarff and Westoby 2006),

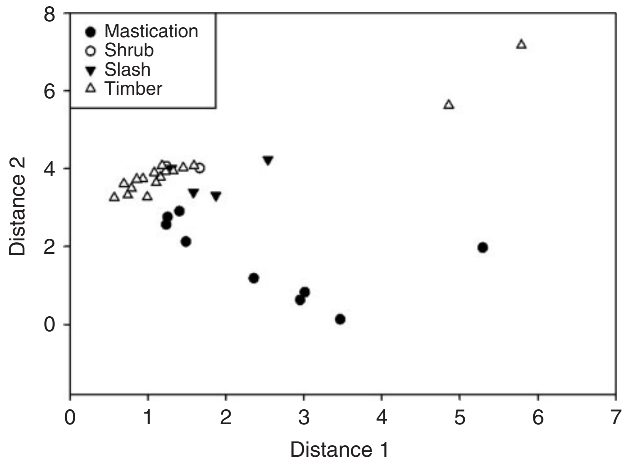

Fig. 4. Partitioning of compressed fuelbed characteristics (unitless) representing: 1-, 10-, 100-, 1000-h woody fuels, and litter and duff depth, by fuelbed type based on the results of a k-means cluster analysis. The five mechanically masticated fuelbeds residing in the lower right-hand corner formed a significantly distinct cluster compared with the remaining fuelbeds.

potentially ameliorating any increase in fire behavior related to particle alteration. Research has shown that compaction of a fuelbed composed of slash reduced scorch height and percentage mortality of residual pines (Jerman *et al.* 2004). Alternatively, greater fuelbed bulk density could lead to more smoldering combustion and greater heat duration (Busse *et al.* 2005). A densely packed fuelbed may also promote incomplete combustion, thus increasing smoke production. Elevated or prolonged temperatures may cause higher tree mortality due to root death or cambial girdling (Varner *et al.* 2007). Other consequences of prolonged exposure to high temperatures include seed bank depletion and non-native plant establishment.

Differences in squared quadratic mean diameter by site, deviations in particle shape from a cylinder, and non-normally distributed particle dimensions all violate assumptions necessary for estimating fuel loads using the planar intercept method (Van Wagner 1968; Brown 1974; Brown *et al.* 1982). Time-lag classes represent a range of diameter values and the planar intercept fuel loading equation assumes that accurate site-based squared quadratic mean diameters are known. Single 'standard' diameter inputs are used in many of the fire behavior and fire effects modeling programs (e.g. *FireFamilyPro*, *FMAplus*), and differences between those standard inputs and masticated particle diameters could result in under- or overestimates of fuel loading. Additionally, the planar intercept fuel loading calculation requires that woody particles be cylindrical and that diameters be normally distributed within each time-lag class to accurately convert count data to loading estimates. Deviations of the distributional characteristics or the particle shape may lead to inaccurate loading estimates and result in poor predictions of fire behavior and effects.

Fuel loading estimation and methods comparison

Total dead woody fuel loading estimates in this study ranged widely (15.8 to 65.5 Mg ha^{-1}), but were similar to reported estimates from the northern Rocky Mountains (39.0 to

56.0 Mg ha^{-1}; Hood and Wu 2006) and the central Sierra Nevada (38.0 Mg ha^{-1}; Stephens and Moghaddas 2005). A study quantifying fuel loading in a masticated, post-hurricane-impacted area had a total fuel loading estimate of 189.7 Mg ha^{-1}, consisting of mostly 1000-h fuels (Glitzenstein *et al.* 2006). Most sites in our study had the greatest proportion of load concentrated within the 1-h and 10-h time-lag classes. Stephens and Moghaddas (2005) found the greatest proportion of woody load in the 100-h time-lag class, likely attributed to slash generated from a preceding thinning treatment. Concentration of the woody fuels into fine fuel classes in our study is the direct result of chipping and shredding from the masticating head and will likely vary depending on type of masticator, rotational speed of the masticator head, style of the operator, and pretreatment vegetation composition and structure. We found no significant difference in proportion of fuel loading in the 10-h diameter size class among masticator types (J. M. Kane, unpubl. data), suggesting that other factors (i.e. vegetation) may be of greater importance in determining particle size, shape, and distribution. Future studies that quantify pretreatment surface and ground fuel loading, as well as standing biomass, may be better able to address these particular questions.

Violations in the assumptions of the planar intercept method may be responsible for inaccurate estimates of 1-h fuel loading (−67%) compared with the plot-based method in our study. This result is in contrast to that of Glitzenstein *et al.* (2006), who found that 1-h and 10-h fuel loading was 150 and 420% greater respectively for the planar intercept method compared with the plot-based method. This difference between studies was unexpected because both studies used the same plot size (0.25 m^2). However, substantially greater 1-h fuel loading was found in our study compared with the Glitzenstein *et al.* (2006) study, suggesting that the plot-based method is more accurate and efficient (requiring fewer samples) above some threshold of fuel loading.

Based on our results, the plot-based method may be most accurate for estimating loads of 1-h and 10-h fuels, while coarser fuels (100-h and 1000-h) may be better estimated using the planar intercept method. The larger time-lag classes were relatively uncommon at most of our sites and infrequently encountered with the plot-based method owing to a relatively small area sampled, causing a high degree of variability in loading estimates (Table 3). The planar intercept method samples a greater portion of the treated area, thus increasing the likelihood of encountering 100-h and 1000-h fuels compared with the plot-based method.

Use of bootstrapping permutations on data from both a high- and a low-fuel-loading site indicates that our chosen sample size of 15 was adequate for capturing within-site variation (Fig. 4). In general, for most woody fuel loading types, less variability was found among samples for the planar intercept method than the plot-based method. The planar intercept method may be more efficient in capturing variability because transects cover more area than the plot-based method. However, sampling efficiency is contingent on both accurate and precise measures. Although the planar intercept method may be precise, our study suggests that it may be less accurate in estimating fuel loading within the 1-h fuel loading class compared with the plot-based method, subsequently increasing error in fire behavior predictions in masticated fuelbeds. Lack of accuracy is likely due to the depth and compactness of the fuelbed, which make it difficult to see all fuel particles intercepted by the transects.

Fuel loading and depth relationships

The ability to estimate fuel loading by means of fuel depth-to-loading relationships would simplify the process and substantially reduce the resources necessary to acquire these important data. Surrogate measures such as fuel depth have been shown to accurately estimate fuel loading in some fuel types (Fulé and Covington 1994; van Wagtendonk *et al.* 1996; Knapp *et al.* 2005). Results from the present study suggest that fuelbed depth for both among-site (using site-level averages) and within-site values are strong predictors of fuel loading in masticated sites (Table 5). These results support similar findings from Hood and Wu (2006), who found significant relationships between fuelbed depth and load measured in different plant community types, *Pinus jeffreyi–Abies concolor* ($r^2 = 0.74$) and *Pinus ponderosa–Quercus gambelii* ($r^2 = 0.42$). Although our results and others suggest a strong relationship, other variables may influence the strength of the correlation between fuelbed depth and load, including the masticator head used and operator effort (time spent per unit area). Masticator heads that chopped fuels into smaller particles and higher operator effort appeared to produce greater homogeneity in fuelbed bulk density. Too few sites were evaluated in the present study to calculate a separate depth-to-loading relationship for each potentially important contributing factor, but this work is warranted.

Although the use of depth-to-load equations to estimate fuel loading at other locations may be reasonably accurate, managers may benefit from the future development of alternative fuel loading estimation methods for this fuel type. Options include photoseries that provide representative images of masticated sites across regional fuel loading gradients, or predictive equations of fuel loading by time-lag class based on pretreatment biomass estimates for different vegetation types.

Fuelbed comparisons

Most masticated fuelbeds differed from both natural (timber and shrub) and slash-based fuelbeds. The differences were primarily due to the concentration of woody fuel loading in the 1-h and 10-h fuel class with masticated fuelbeds. Fuelbed depth measurements were not significantly different compared with other fuel types, as masticated fuelbeds seem to have very compacted fuelbeds. Measures of bulk density or packing ratio may better distinguish masticated fuelbeds from other fuel types. Data on fuelbed bulk density and packing ratio were not available for the particular photoseries data used to make comparisons.

The distinction of masticated fuelbeds from existing fuel types suggests that the development of unique fire behavior fuel models maybe warranted. Differences in 1-h and 10-h woody fuel loading are likely to lead to differences in fire behavior. Empirical evidence based on observations of fire behavior in masticated fuelbeds is necessary to confirm the need for separate fuel models.

Management implications

Most mechanically masticated fuelbeds differed from natural and slash-based fuel types occurring in similar ecosystems. Differences included the high loading of fine fuels, large proportion of fuels in the smaller-diameter categories, high bulk density, and the greater surface area-to-volume ratio of the average particle due to fracturing during the mastication process. It has been noted that actual fire behavior in masticated fuelbeds differs substantially from outputs of fire behavior models, such as BehavePlus (Andrews *et al*. 2005) when measured fuelbed parameters are entered (Glitzenstein *et al*. 2006; E. E. Knapp, unpubl. data), and the above differences may help explain why. Novel characteristics of masticated fuelbeds highlight the need for accurate fuel loading estimates and new fuel models to predict fire behavior and effects. To optimize the accuracy of fuel loading estimates in masticated fuelbeds, we suggest a hybrid methodology using the plot-based method for smaller fuels (1-h and 10-h) and the planar intercept method for larger fuels (100-h and 1000-h). In addition to fuel loading accuracy, managers are often concerned with desired sample intensity to cost-effectively estimate fuel loading. Based on our results, it appears as if 10 to 15 samples should sufficiently encompass the variation within masticated fuelbeds such as those encountered within our study. Sample intensity may need to be increased in areas with greater heterogeneity. In situations where less accurate fuel loading is needed, use of fuel depth-to-load equations may be sufficient. Further work that develops other ways to estimate fuel loading in masticated fuelbeds, such as a photoseries, may also prove useful. As the use of mechanical mastication and other fuels treatments expand, the needs to develop methods to characterize these novel fuelbeds and their subsequent fire behavior and effects will increase.

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