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# Behaviour and effects of prescribed fire in masticated fuelbeds

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**Abstract.** Mechanical mastication converts shrub and small tree fuels into surface fuels, and this method is being widely used as a treatment to reduce fire hazard. The compactness of these fuelbeds is thought to moderate fire behaviour, but whether standard fuel models can accurately predict fire behaviour and effects is poorly understood. Prescribed burns were conducted in young ponderosa pine (*Pinus ponderosa* Laws.) forests at two sites in northern California where the midstorey layer dominated by shrubs had been masticated. Surface fuels were raked from the base of a subset of trees before burning. Rate of spread and flame length were estimated for both backing and heading fires, soil heating measured with thermocouples and tree fire injury recorded. Standard fuel models often over-predicted rate of spread or under-predicted flame length. Custom models generally provided a better balance between the slow rates of spread and moderate flame lengths observed in prescribed burns. Post-fire tree mortality was most strongly associated with crown scorch and tree size; raking fuels from the base of trees did not improve survival. Under severe fire weather conditions, fire behaviour and effect models as well as observations from wildfires suggest that mastication may be more effective for moderating fire behaviour than reducing residual tree mortality. Treating masticated fuels with prescribed burns could potentially improve the resilience of stands to wildfire.

**Additional keywords:** crown scorch, fuel treatment, *Pinus ponderosa*, post-fire tree mortality.

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## Introduction

Shrubs and small trees that have proliferated following timber harvest, wildfire, or other disturbances present a fuel management challenge in many areas in western USA. Historically, these 'ladder' fuels were thinned or restricted to discrete patches by frequent fire. Mechanical mastication (also known as mulching, shredding or chipping) is a relatively new tool for treating shrub and small tree fuels, and is being widely used to reduce fire hazard (Glitzenstein *et al*. 2006; Harrod *et al*. 2009; Kane *et al*. 2009). By chopping ladder fuels into small pieces, standing live and dead fuels are converted to more compact dead surface fuels, which are usually left on the forest floor (Kane *et al*. 2009). Fuel loading is, therefore, not reduced, but fuels are rearranged. Mastication is one alternative for dealing with ladder fuels in areas where application of prescribed fire is impractical due to proximity to homes, smoke management or liability issues. In other situations, mastication may be a useful treatment before prescribed burning: both the reduced ladder fuels and elevated average height to crown base can make fire easier to reintroduce (Stephens and Moghaddas 2005).

Although a surface mulch of masticated material can protect the soil from erosion and retain nutrients, masticated fuels are still combustible. Masticated pieces are often highly fractured and fragmented, with a high surface area to volume ratio, and the total amount of biomass can be considerable (Kane *et al*. 2009; Reiner *et al*. 2009, Battaglia *et al*. 2010). A higher surface area to volume ratio would be expected to increase the rate of combustion and alter fire behaviour (Rothermel 1972). However, Kreye and Varner (2007) and Kreye *et al*. (2011) found no effect of particle fracturing from mastication on either the drying rates of shrub wood or on flame lengths when the wood was burned. In addition, another aspect of masticated fuelbeds – compaction – may suppress fire behaviour (Kreye *et al*. 2011). Glitzenstein *et al*. (2006) noted slower rates of spread and lower flame lengths in chipped *v.* unchipped plots, although interpretation was confounded by changing weather conditions during burning.

The high fuelbed bulk density resulting from mastication can also moderate some fire effects. Glitzenstein *et al*. (2006) reported that less of the area burned in mechanically masticated or chipped plots than in adjacent untreated plots in South Carolina. Compacting logging slash to increase bulk density has been shown to reduce crown scorch and overstorey tree mortality (Jerman *et al*. 2004). However, the considerable surface fuel remaining post-mastication has still led to concerns about tree mortality from cambial or root injury, as well as concerns about soil damage (Busse *et al*. 2005). The degree of cambial injury is related to the amount of fuel consumed adjacent to the bole as well as the thickness and thermal conductivity of the tree bark, and is controlled more by the duration of heating than fire-line intensity (Ryan and Frandsen 1991). Heat may also kill fine roots away from the bole, which has been hypothesised as a mechanism of tree mortality (Swezy and Agee 1991; Varner *et al*. 2009). Burning heavy loads of masticated fuels can potentially heat the soil well above lethal thresholds for roots at depths as great as 10 cm (Busse *et al*. 2005). However, the potential for lethal heating is reduced by burning when the soils are moist (Busse *et al*. 2010).

Mastication has only recently been widely adopted as a fuel treatment, so much of the science of predicting fire behaviour and effects in these fuelbeds has yet to be fully developed. The objectives of our research were to (1) evaluate fire behaviour and effects in units that were masticated and subsequently burned under prescription conditions; (2) compare fire behaviour and effects with outputs from commonly used models and develop custom model inputs where possible; and (3) evaluate the potential usefulness of mastication as a treatment for enhancing the resilience of the overstorey conifer component of masticated stands to fire under a range of hypothetical wildfire situations.

## Materials and methods

### *Field fire behaviour and effects*

Two sites in northern California were used to evaluate the behaviour and effects of fire in masticated fuelbeds. The 'Challenge' site was located on the Challenge Experimental Forest, Plumas National Forest (elevation 850 m) in the northern Sierra Nevada. The 'Whitmore' site was located on private timberland near the town of Whitmore in Shasta County (elevation 760 m) in the southern Cascades. Vegetation at both sites consisted of dense woody shrubs (primarily deer brush (*Ceanothus integerrimus* Hook. & Arn.), tanoak (*Lithocarpus densiflorus* (Hook. & Arn.) Rehder), and Pacific madrone (*Arbutus menziesii* Pursh) at Challenge and whiteleaf manzanita (*Arctostaphylos viscida* C. Parry ssp. *viscida*), common manzanita (*A. manzanita* C. Parry ssp. *manzanita*) and California black oak (*Quercus kelloggii* Newb.) at Whitmore) intermixed with and beneath a stand of predominantly ~40-year-old ponderosa pine (*Pinus ponderosa* Laws.) trees that regenerated naturally following logging (Challenge) or were planted after a wildfire (Whitmore).

Four 0.4-ha units at each site were masticated in the winter and spring of 2003, using a Rayco (Wooster, OH, USA) forestry mower attached to a bulldozer. Mastication primarily targeted the shrubs and hardwoods. Although small or suppressed conifers were sometimes also masticated, most of the larger conifers were retained. Following mastication, respective loadings of downed woody fuels and fuelbed depth averaged 39.3 Mg ha$^{-1}$ and 12.9 cm at Challenge and 15.3 Mg ha$^{-1}$ and 5.4 cm at Whitmore (Kane *et al*. 2009). The majority of woody surface fuel at both sites was in the 10-h size category (average particle diameter in the range 0.64–2.54 cm).

Prior to the burns, the basal area of residual conifers averaged 30 m$^2$ ha$^{-1}$ at Challenge and 15 m$^2$ ha$^{-1}$ at Whitmore. A total of 244 trees at Challenge and 305 trees at Whitmore (all ponderosa pine) were tagged, and diameter at breast height (DBH, 1.37 m), height to base of live crown and total tree height measured: DBH averaged 23.9 cm at Challenge and 19.8 cm at Whitmore. Respective tree height and height to base of live crown averaged 14.6 and 4.9 m at Challenge, and 9.5 and 2.2 m at Whitmore. At Challenge, a subset of 130 trees of average size were selected and half were randomly assigned to a raking treatment (fuels removed around the base of trees out to 0.5 m) in order to separate mortality as a result of bole injury from mortality caused by crown scorch or root injury.

Prescribed burns were conducted in May and June of 2005 at Challenge (~2.5 years post-mastication), and in June of 2006 at Whitmore (~3 years post-mastication) (Fig. 1). Weather conditions were similar for all burns, with RH ranging from 32 to 58% and light (<5 km h$^{-1}$) winds (Table 1). Fuel moisture immediately before ignition was determined by collecting samples of each fuel size category visible on the surface of the fuelbed, placing the fuels in airtight bottles, weighing in the laboratory to determine the wet weight then drying in an oven at 90°C for several days with periodic reweighing until equilibrium was reached.

Ignition of the units was primarily though strip-head fires, with strips ~2–3 m apart. When fire became too intense given the small size of the trees, time between strips was increased and more backing fire was used. Soil temperatures 5 and 10 cm beneath the mineral soil surface were measured every 2 min at the drip line of 6–12 trees in each unit using Omega 30-gauge, type K thermocouples with glass braid insulation (Omega Engineering Inc., Stamford, CT, USA). Omega 24-gauge, type K thermocouples with ceramic insulation were placed on the mineral soil surface and on top of the fuelbed, where higher temperatures were anticipated. During the burns, flame length and rate of spread were estimated for both heading and backing fires. Average flame length was estimated using metal poles marked in 30-cm increments placed near the flames as visual guides (Rothermel and Deeming 1980). Spread rate was quantified as the time necessary for fire to traverse a known distance between sticks or metal poles inserted into the forest floor.

Fuel loading was estimated before and after the burns using a plot-based method of Kane *et al.* (2009), with consumption being the difference between values obtained in the two sampling intervals. All organic material within a square (50 × 50-cm) metal frame was collected, sorted by fuel size category, dried in an oven for at least 72 h at 90°C then weighed. Forty systematically placed samples (10 per burn unit) were taken during each sampling interval. The exception was at Challenge were double the number of samples were collected before the burn. At Challenge, pre-burn sample dates were September 2004 and April 2005, whereas post-burn samples were collected in September 2005. Pre-burn samples at

**Fig. 1.** Prescribed burn in masticated fuels beneath a residual ponderosa pine overstorey on 4 June 2006, near Whitmore, California, USA.

Whitmore were collected in October 2005 and post-burn samples were collected in July and August 2006.

Tree injury was evaluated within 8 weeks of burning at both sites. Crown injury was quantified by visually estimating the percentage of crown volume scorched and measuring the height of maximum crown scorch on the uphill and downhill sides of each tagged tree. Stem injury was estimated by measuring the height of bole char on both the uphill and downhill sides of the tree and by estimating the percentage of the bole circumference at the tree base that was charred. At both sites, tree mortality was censused annually for 3 years following the burns.

### *Predicted fire behaviour and effects*

Estimates of flame length and rate of spread from field observations at Challenge and Whitmore were compared to predictions of fire behaviour from BehavePlus5.0 (Andrews *et al*. 2008), using standard fuel models (Anderson 1982; Scott and Burgan 2005) that were most similar to the characteristics of these masticated fuelbeds. Custom fuel models for three different levels of loading were also developed by replacing the parameter values for fuel loading in the SB2 model with field collected values from Challenge and Whitmore as well as altering the 1-h surface area to volume ratio and fuelbed depth (Table 2). The Mast-L model utilised data from the two units with the lowest fuel loading (Whitmore 1 and 2), the Mast-M model was based on four units with moderate fuel loading (Challenge 1 and 4; Whitmore 3 and 4), and the Mast-H model utilised values for the two sites with the highest fuel loading (Challenge 2 and 3). All custom models used the 1-h surface area to volume ratio published for fuel model sh5 (high load, dry climate shrub) (Scott and Burgan 2005). Model outputs for rate of spread and flame length were adjusted to approximate observed fire behaviour by varying fuelbed depth (Fig. 2). The fuelbed depth for Mast-L (0.11 m) and Mast-M (0.16 m) were slightly greater than field masticated fuelbed depth measurements (0.06–0.08 m and 0.06–0.14 m respectively). The fuelbed depth for Mast-H (0.27 m) was substantially greater than measured values (0.10–0.12 m), but an adjustment was necessary to obtain predicted fire behaviour values approximating observed values.

In order to evaluate the accuracy of fuel models for predicting tree mortality and to provide an approximate idea of the potential effectiveness of mastication as a tool for increasing stand resilience under wildfire conditions, tree and weather data from 10 masticated sites surveyed by Kane *et al*. (2009), including Challenge and Whitmore, were used for fire behaviour and effects simulations. Additional information about the sites, including machinery used and fuel loading is provided in Kane *et al*. (2009). Although midstorey shrubs were the primary focus of mastication at all sites, species composition, size and density of trees in the residual stand varied substantially. Data on species and DBH of residual trees were collected within eight circular 8-m radius plots (two in each of four units) established on systematically selected grid points at the Challenge and Whitmore sites. These were the only trees sampled in plots of known size at these two sites, and represent a subset of the trees used in the tree fire injury and mortality models. At one site near Mad River (Six Rivers National Forest, CA), all trees within the masticated unit were measured and tree density calculated by estimating the size of the treated area. Trees at the remaining sites were evaluated within 15 circular plots arranged systematically along linear transects traversing the masticated area. Radius of the plots ranged from 5 to 10 m, depending on the

**Table 1. Burn date, unit topography, weather, fuel moisture and fire behaviour for prescribed burns in masticated units at two sites in northern California**

For variables with >3 observations, values in parentheses represent ranges

| Site | Challenge | | | | Whitmore | | | |
|---|---|---|---|---|---|---|---|---|
| Unit | 1 | 2 | 3 | 4 | 1 | 2 | 3 | 4 |
| Burn date | 3-Jun-2005 | 28-May-2005 | 28-May-2005 | 28-Jun-2005 | 5-Jun-2006 | 5-Jun-2006 | 4-Jun-2006 | 4-Jun-2006 |
| Aspect | WSW | SW | SW | E | SW | S | W | SW |
| Slope (degrees) | 8 | 5 | 12 | 11 | 2 | 1 | 5 | 7 |
| Air temperature (°C) | 22 (19–24) | 23 (22–23) | 22 (20–24) | 22 (21–23) | 27 (26–29) | 22 (20–23) | 26 (26–27) | 22 (19–25) |
| RH (%) | 33 (27–38) | 55 (54–55) | 58 (49–62) | 50 (48–52) | 32 (26–38) | 47 (44–49) | 34 (32–35) | 48 (37–55) |
| Wind speed (km $h^{-1}$) | 2.2 (0–5) | 2.6 (2–3) | 2.4 (1–5) | 2.8 (0–4) | 2.7 (1–5) | 0.8 (0–2) | 2.6 (2–3) | 2.2 (1–3) |
| Wind direction | E–SW | E–W | SW–NW | W–NW | SW–W | SE–SW | SW–W | S–NW |
| 1-h fuel moisture (%) | 10.8 | 13.9 | 12.8 | 14.8 | 5.4 | 12.1 | 8.4 | 13.9 |
| 10-h fuel moisture (%) | 10.6 | 14.8 | 12.7 | 14.5 | 8.8 | 12.6 | 10.8 | 17.6 |
| 100-h fuel moisture (%) | 15.4 | 15.5 | 14.3 | 19.8 | 11.3 | 15.2 | 13.7 | 14.2 |
| 1000-h fuel moisture (%) | 23.1 | 39.0 | 116.6 | 74.1 | – | – | – | – |
| Fuel moisture of litter (%) | 11.2 | 14.9 | 13.0 | 15.0 | 6.0 | 14.7 | 7.9 | 15.7 |
| Fuel moisture of duff (%) | 80.7 | 136.7 | 58.9 | 55.5 | 14.4 | 24.7 | 34.9 | 45.2 |
| Soil moisture (%) | 34.0 | 40.1 | 37.0 | 35.2 | 19.0 | – | 26.0 | 24.0 |
| Rate of spread of backing fire (m $h^{-1}$) | 3.8 (1.4–6.3) | 4.1 (3.1–4.8) | 3.8 (1.2–7.2) | 5.5 (2.9–9.6) | 4.9 (2.8–7.2) | 4.9 (2.1–12.0) | 4.1 (2.1–6.5) | 4.0 (2.2–12.0) |
| Flame length of backing fire (m) | 0.28 (0.10 – 0.45) | 0.28 (0.15–0.40) | 0.34 (0.15–0.60) | 0.50 (0.15–0.40) | 0.26 (0.15–0.40) | 0.29 (0.15–0.40) | 0.36 (0.15–0.60) | 0.27 (0.15–0.50) |
| Rate of spread of heading fire (m $h^{-1}$) | 62.4 | 66.1 (23.4–144.0) | 43.4 (9.0–72.0) | – | 40.8 (24.0–72.0) | – | 26.3 (5.6–72.0) | 33.4 (14.0–56.5) |
| Flame length of heading fire (m) | 0.55 | 0.82 (0.60–1.00) | 0.79 (0.25–1.50) | – | 0.77 (0.70–0.80) | – | 0.55 (0.30–0.80) | 0.86 (0.50–1.50) |

**Table 2. Custom fuel models for masticated fuels based on fuel loadings and observations of fire behaviour in prescribed burns at two sites (Challenge, Whitmore)**

The 1-h numbers included the litter. Custom models were created starting with the parameter values of the moderate load activity fuel model (sb2) of Scott and Burgan (2005), with the following modifications

| Model parameter | Mast-L (low loading) | Mast-M (moderate loading) | Mast-H (high loading) |
|---|---|---|---|
| 1-h fuel load (Mg $ha^{-1}$) | 7.8 | 12.7 | 17.6 |
| 10-h fuel load (Mg $ha^{-1}$) | 5.5 | 13.3 | 29.4 |
| 100-h fuel load (Mg $ha^{-1}$) | 0.7 | 2.8 | 13.1 |
| 1-h surface area to volume ratio ($m^2$ $m^{-3}$) | 2461 | 2461 | 2461 |
| Fuelbed depth (m) | 0.11 | 0.16 | 0.27 |

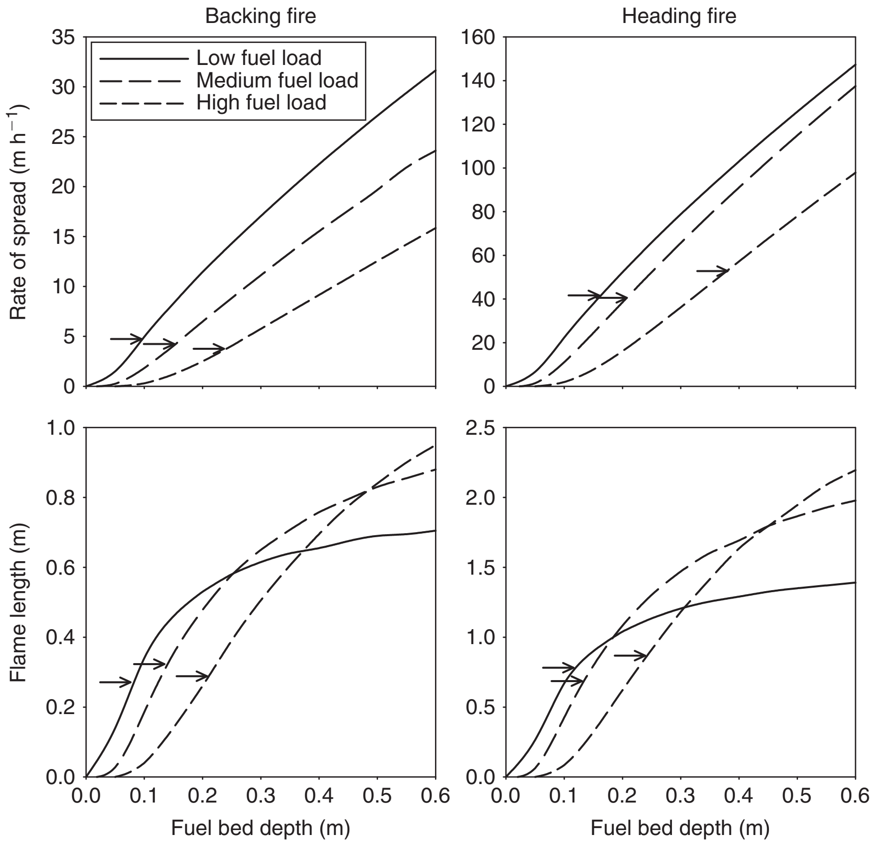


**Fig. 2.** Predicted rates of spread and flame lengths for backing fire and heading fire when depth of the fuelbed is varied. Fire behaviour outputs were modelled with BehavePlus5.0, using custom fuel model inputs (with the exception of fuelbed depth) given in Table 2. Arrows show the actual rates of spread and flame lengths for prescribed burns at Challenge and Whitmore.

abundance of trees. Density of different size classes of trees was calculated by species at each site. Average slope and aspect of each site was also estimated. Shrub fuel models 5 (Anderson 1982) and sh5 (Scott and Burgan 2005) were used to approximate pre-mastication conditions at all sites, whereas custom fuel models Mast-L, Mast-M and Mast-H (this paper) were used to approximate post-mastication conditions with the choice dictated by fuel loading values reported by Kane *et al*. (2009). Fuel model 5 has been used for montane chaparral vegetation by others (van Wagtendonk and Botti 1984). Outputs from both fuel models 5 and sh5 provide a range of potential outcomes for modelling shrub fuels, with the former likely more representative of higher elevation sites and the latter more representative of lower elevation sites with higher volatility.

Percentile fire weather was estimated for all sites with FireFamilyPlus4.0 (USDA Forest Service Rocky Mountain Research Station, Missoula, MT), using data from the nearest weather station or weather station located at similar elevation and slope position. Most stations had weather data for between 36 and 48 years. Only the Applegate (13 years) and Whitmore (15 years) sites had a shorter weather record. The fire season was assumed to be 1 June to 30 September for low elevation sites (<500 m), 15 June to 15 September for mid-elevation sites (500–1600 m), and 1 July to 1 September for higher elevation sites (>1600 m). Percentile weather was based on the energy release component of the burning index, considered wind from all directions, and was calculated for 37.5, 80, 90 and 97.5% conditions.

Average scorch height was estimated under the four percentile weather conditions at all 10 sites, using BehavePlus5.0. The wind speed outputs from FireFamilyPlus are assumed to be 6 m above the canopy, and were therefore adjusted to midflame windspeeds in BehavePlus5.0, using canopy cover as an input value. Canopy cover was estimated using the First Order Fire Effects Model (FOFEM 5.7, USDA Forest Service, Rocky Mountain Research Station), given the density of different tree size classes at each site. Canopy height was considered the average height for trees with a DBH > 10 cm. Crown ratio was determined as the average of all tree size classes. The sum of fine fuel loads (1-, 10-, 100-h and litter) at each site, reported by Kane *et al*. (2009), determined the custom fuel model used to predict scorch heights. FOFEM 5.7 was then used to estimate the expected mortality of residual trees.

### *Data analysis*

Significance of factors contributing to tree mortality at Challenge and Whitmore, and significance of the raking

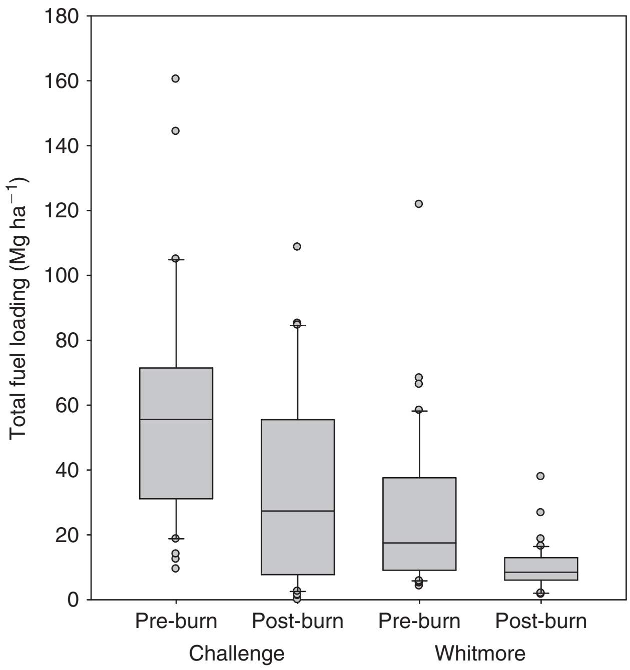


**Fig. 3.** Fuel loading values before and after prescribed burns at two masticated sites (Challenge and Whitmore) in northern California. Lines within box plots (25th to 75th percentile) show the median, with whiskers indicating the 10th and 90th percentiles. Outliers are shown as circles.

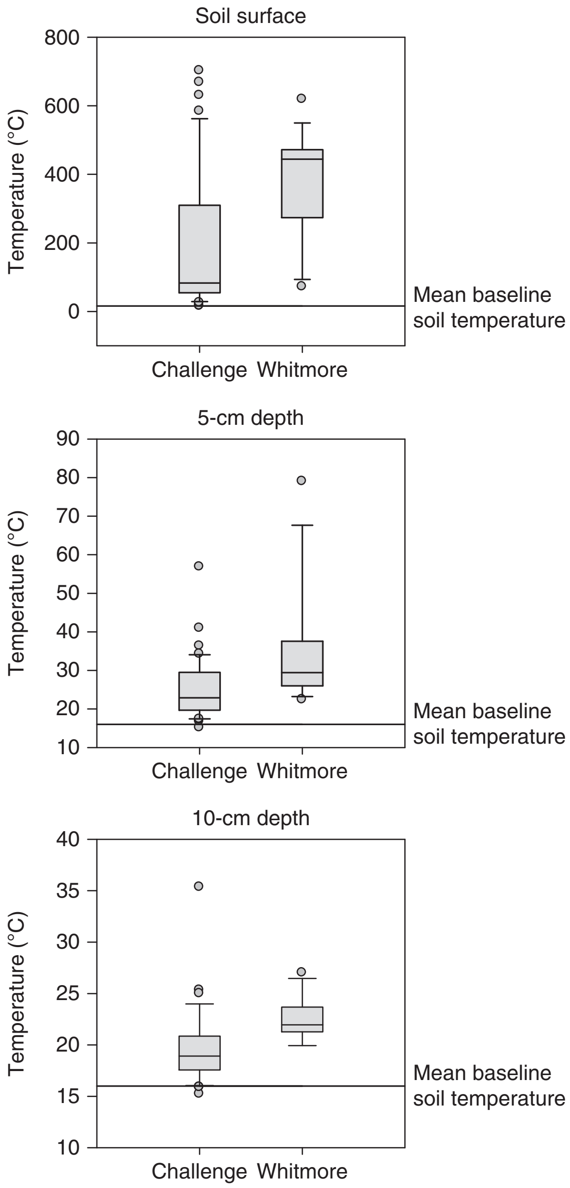


**Fig. 4.** Maximum temperature reached at the duff–mineral soil boundary, 5 and 10-cm soil depths at Challenge and Whitmore, measured using 12 thermocouples deployed per layer per site. Lines within box plots (25th to 75th percentile) show the median, with whiskers indicating the 10th and 90th percentiles. Outliers are shown as circles.

treatment for a subset of trees at Challenge was determined using PROC GLIMMIX in SAS (SAS Institute, Cary, NC), with mortality status of individual trees as the dependent variable, fire injury measurements as independent variables (fixed effects) and unit as a random effect. Parameters of the generalised linear model were estimated with the Gauss–Hermite Quadrature method (Pinheiro and Bates 1995). All possible combinations of explanatory variables were also examined with a model selection approach using $AIC_c$ (Burnham and Anderson 2002). The importance value of the different variables contributing to mortality was estimated as the sum of the $AIC_c$ weights. Model fit was evaluated with a 10-fold cross-validation estimate of the correct classification rate and statistical significance of the independent variables was determined with the associated *P*-value from the full model.

## Results

Consumption of all dead and down fuels (woody, plus litter and duff) in the prescribed fires averaged 37.5 Mg ha$^{-1}$ at Challenge, and 16.4 Mg ha$^{-1}$ at Whitmore (Fig. 3). Litter and 1-h woody fuels, which were the driest at both sites (Table 1), were most readily consumed (98 and 70%), whereas larger wood and duff contained considerable moisture (Table 1), and were generally less completely consumed (30 and 41%). Consumption of 10-h fuels was intermediate (mean = 52%). Rate of spread for heading fires was approximately two times faster at Challenge than at Whitmore (mean = 57.3 and 26.8 m h$^{-1}$ at Challenge and Whitmore), but rate of spread for backing fires was similar (mean = 4.3 and 4.4 m h$^{-1}$ at Challenge and Whitmore) (Table 1). Whitmore not only contained less masticated fuel (Kane *et al*. 2009) but slopes were not as steep (Table 1). Flame lengths were approximately twice as long for heading than backing fires (mean = 0.72 and 0.32 m for heading and backing fire), but both were similar for the two sites (Table 1).

Temperature at the duff–mineral soil boundary during burning ranged from ambient (background) to 702°C at Challenge and ambient to 619°C at Whitmore (Fig. 4), dependent largely on whether the duff was completely consumed. Little heat from the burning masticated fuels appeared to penetrate deeply into the mineral soil, with only two out of

72 thermocouples (both at Whitmore) registering greater than 60°C at a depth of 5 cm (Fig. 4). The maximum temperature registered at a depth of 10 cm was 35°C at Challenge and 27°C at Whitmore (Fig. 4). For comparison, the ambient pre-fire 10-cm soil temperatures were 14 and 18°C at the two sites.

### *Observed post-fire pine mortality*

Residual overstorey pine mortality 3 years after prescribed fires was 34.8% at Challenge and 7.0% at Whitmore (Table 3). At Challenge, five trees where fuels had not been raked from the base were completely scorched in the prescribed burns. A total of 67 trees containing some green leaves immediately after the burn had died by the following year. An additional nine trees died between 1 and 2 years post-fire. At Whitmore, only one tree suffered 100% scorch in the prescribed burns. Fifteen trees that contained some green needles immediately after the fires died within the first year, and an additional four trees died by the end of the second year. No additional mortality was noted at the end of year three at either site. All fire injury parameters were higher at Challenge than at Whitmore (Table 3), tracking the observed tree mortality results.

When the factors associated with tree mortality were analysed on the combined Challenge and Whitmore data, the DBH $\times$ site and the uphill char height $\times$ site interactions were significant ($P < 0.05$). Therefore, data for each site were analysed separately. The '% bole circumference charred' variable was not significant at either site, produced instability in the model due to the lack of variability in the dataset, and was therefore dropped from subsequent analyses. The ranking of mortality predictions from the full model and the model using the model-averaged coefficients were nearly identical and coefficient estimates of the most significant variables were similar and of the same sign (Table 4). As a measure of goodness-of-fit, the 10-fold cross-validation estimates of the overall correct classification rates using the full model were 89.9 and 95.7% for Challenge and Whitmore. At both sites, percentage of crown volume scorched (PCVS) and DBH were the best predictors of tree mortality (Table 4; Fig. 5), with smaller trees and trees with a greater percentage of crown volume scorched more likely to die. Trees tolerated a higher percentage of crown scorching at Whitmore than at Challenge. The point at which a 10-cm diameter tree was equally likely to live or die occurred at ~60% of crown volume scorched at Challenge and 80% of crown volume scorched at Whitmore (Fig. 5). Bole char height on the uphill side of the tree was significantly associated with mortality at Whitmore ($P = 0.031$), but not at Challenge ($P = 0.516$).

Raking fuels from the base of residual pines at Challenge did not affect tree survival ($P = 0.972$). After 3 years, 28% of the raked and 35% of the unraked trees had died. PCVS was similar between treatments, averaging 51% among raked trees and 55% among unraked trees. As with the results for unraked trees, residual ponderosa pine mortality appeared to be primarily due to crown scorch. When all variables (raking treatment, DBH, bark char height – high side, bark char height – low side and PCVS) were analysed together with status 3 years post-fire as the dependent variable, only the PCVS was significant ($P < 0.001$).

**Table 3. Effects of prescribed fire on residual ponderosa pines in masticated stands at two sites in northern California, with range among burn units in parentheses**

| Variable | Site | |
|---|---|---|
| | Challenge | Whitmore |
| Crown volume scorched (%) | 58.5 (15.0–78.0) | 46.4 (29.5–56.5) |
| Crown scorch height (m) | 10.0 (7.5–11.0) | 5.5 (4.8–5.9) |
| Bole char height uphill (m) | 2.94 (2.06–4.57) | 1.53 (1.29–1.83) |
| Bole char height downhill (m) | 0.61 (0.50–0.80) | 0.29 (0.23–0.38) |
| Bole circumference charred (%) | 98.5 (97.3–100) | 88.6 (78.7–95.1) |
| Tree mortality 3 years post-fire (%) | 34.8 (8.8–91.1) | 7.0 (0–10.5) |

### *Predicted fire behaviour and tree mortality*

Of the standard fuel models tested, models 9 (long needle litter), 10 (timber litter and understorey), and sb1 (low load activity fuel) most closely approximated observations of rates of spread for backing fire (Table 5). Flame lengths for backing fire were best predicted with fuel models 10 and sb2 (moderate load activity fuel) (Table 5). For heading fire, fuel model sb2 came closest to matching observations for rate of spread and flame length at Challenge (Table 6). At Whitmore, fuel model 9 came closest to matching rate of spread observations and fuel models 10 and sb2 came closest to matching flame length observations (Table 6). We also evaluated a high load activity fuel model

**Table 4. Significance of variables associated with tree mortality after prescribed fire in masticated fuels at the Challenge and Whitmore sites**
Only the trees with fuels remaining intact at the base (unraked) were used. Results for both the full model (including all variables), the importance values (sum of the AICc weights of the model in which the variable appeared), and the model averaged coefficients (weighted average of estimated coefficients in which the variable appeared) are shown

| Variable | Challenge ($n = 179$) | | | | Whitmore ($n = 305$) | | | |
|---|---|---|---|---|---|---|---|---|
| | Full model | | Importance value | Model averaged coefficients | Full model | | Importance value | Model averaged coefficients |
| | Estimate | $P$ | | | Estimate | $P$ | | |
| Intercept | −2.415 | 0.368 | 1.000 | −2.301 | −8.772 | 0.119 | 1.000 | −8.910 |
| Diameter at breast height | −0.180 | 0.006 | 0.967 | −0.172 | −0.435 | <0.001 | 1.000 | −0.418 |
| Crown volume scorched (%) | 0.074 | <0.001 | 1.000 | 0.077 | 0.138 | 0.002 | 1.000 | 0.140 |
| Char height (high uphill) | 0.152 | 0.520 | 0.309 | 0.165 | 0.875 | 0.035 | 0.854 | 0.969 |
| Char height (low downhill) | 0.757 | 0.293 | 0.401 | 0.809 | 1.048 | 0.220 | 0.497 | 1.220 |

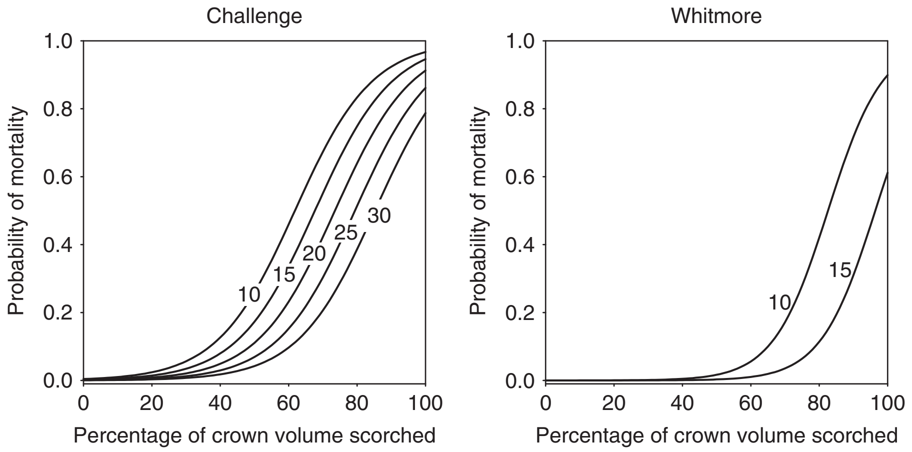


**Fig. 5.** Predicted mortality of size classes of residual ponderosa pine trees with different levels of crown scorch within masticated units at Challenge and Whitmore from logistic regression models. Predictions were made for diameter at breast height of 10–30 cm (in 5-cm increments) at Challenge, and 10 and 15 cm at Whitmore.

**Table 5. Comparison of average fire behaviour and effects observations for backing fire within prescribed burns with modelled outputs for backing fire from BehavePlus5.0**

Prescribed burns were a combination of backing and heading fire but the majority of the area in most units was likely burned in heading fires. Actual scorch height values are given in Table 6. Predictions were made for standard fuel models and three custom models for masticated fuels: s.e. are given for the actual values

| Fire behaviour | Challenge | | | Whitmore | | |
|---|---|---|---|---|---|---|
| | Rate of spread ($m\,h^{-1}$) | Flame length (m) | Scorch height (m) | Rate of spread ($m\,h^{-1}$) | Flame length (m) | Scorch height (m) |
| Actual | | | | | | |
| Low loading | – | – | – | $4.9 \pm 0.8$ | $0.28 \pm 0.03$ | – |
| Moderate loading | $4.6 \pm 0.3$ | $0.39 \pm 0.05$ | – | $4.5 \pm 0.4$ | $0.32 \pm 0.13$ | – |
| High loading | $4.0 \pm 0.2$ | $0.31 \pm 0.03$ | – | – | – | – |
| Predicted | | | | | | |
| Fuel model 9 | 5.0 | 0.16 | 0.2 | 5.8 | 0.18 | 0.3 |
| Fuel model 10 | 4.7 | 0.28 | 0.6 | 4.9 | 0.29 | 0.7 |
| Fuel model Sb1 | 4.6 | 0.19 | 0.3 | 5.4 | 0.21 | 0.4 |
| Fuel model Sb2 | 10.1 | 0.36 | 0.9 | 11.7 | 0.39 | 1.2 |
| Fuel model Sb3 | 17.5 | 0.52 | 1.8 | 20.0 | 0.58 | 2.3 |
| Fuel model Mast-L, low loading | 4.2 | 0.31 | 0.7 | 5.2 | 0.35 | 1.0 |
| Fuel model Mast-M, moderate loading | 4.3 | 0.36 | 1.0 | 5.3 | 0.41 | 1.3 |
| Fuel model Mast-H, high loading | 4.8 | 0.44 | 1.4 | 5.9 | 0.50 | 1.8 |

(sb3); however this model substantially over-predicted rate of spread and flame length for both backing and heading fire (Tables 5, 6). In general, fuel models with fuel loading inputs closest to what has been noted at many masticated sites in northern California and southern Oregon (Kane *et al.* 2009) often over-predicted rate of spread (sb2, sb3), and under predicted flame length (sb1). The custom models for masticated fuels generally provided a better balance, indicating fire with a slow rate of spread, yet higher flame lengths (Tables 5, 6).

Using the custom fuel models and assuming a heading fire, BehavePlus under-predicted crown scorch height by a factor of 2.1 at Challenge and 1.6 at Whitmore. With modelled scorch heights as inputs, FOFEM predicted that at Challenge, 8 and 11% of trees would die with a backing fire and a heading fire. At Whitmore, FOFEM predicted that 6 and 22% would die with a backing fire and a heading fire. Actual tree mortality at Challenge (34%) was greater than FOFEM model predictions whereas actual tree mortality at Whitmore (6.5%) was at the low end of the range of model predictions.

Models predicted that at 10 sites (Challenge, Whitmore, plus eight additional sites listed by Kane *et al.* (2009) (Table 7), mastication would not appreciably improve residual tree survival with wildfire under a range of weather conditions. For example, under 80th percentile weather conditions, mortality across sites was predicted to average 70 and 87% with the two shrub fuel models, and 65% with the custom masticated fuel models to 82% with the custom masticated fuel models including a scorch height correction factor (1.8 = average ratio of

**Table 6. Comparison of average fire behaviour and effects observations for heading fire within prescribed burns with modelled outputs for heading fire from BehavePlus5.0**

Prescribed burns were a combination of backing and heading fire but the majority of the area in most units was likely burned in heading fires. Predictions were made for standard fuel models and three custom models for masticated fuels: s.e. are given for the actual values, when based on three or more observations

| Fire behaviour | Challenge | | | Whitmore | | |
|---|---|---|---|---|---|---|
| | Rate of spread ($m\,h^{-1}$) | Flame length (m) | Scorch height (m) | Rate of spread ($m\,h^{-1}$) | Flame length (m) | Scorch height (m) |
| Actual | | | | | | |
| Low loading | – | – | – | $40.8 \pm 15.6$ | $0.77 \pm 0.03$ | $5.4 \pm 0.3$ |
| Moderate loading | 62.4 | $0.55 \pm 0.15$ | $8.6 \pm 0.3$ | $29.8 \pm 12.1$ | $0.70 \pm 0.17$ | $5.6 \pm 0.2$ |
| High loading | $54.8 \pm 12.6$ | $0.80 \pm 0.11$ | $10.6 \pm 0.2$ | – | – | – |
| Predicted | | | | | | |
| Fuel model 9 | 31.5 | 0.38 | 1.0 | 29.6 | 0.38 | 1.2 |
| Fuel model 10 | 29.7 | 0.64 | 2.5 | 25.0 | 0.60 | 2.5 |
| Fuel model Sb1 | 29.2 | 0.45 | 1.4 | 27.3 | 0.44 | 1.5 |
| Fuel model Sb2 | 64.0 | 0.82 | 3.7 | 60.1 | 0.82 | 4.0 |
| Fuel model Sb3 | 110.8 | 1.23 | 6.7 | 103.3 | 1.20 | 7.1 |
| Fuel model Mast-L, low loading | 26.5 | 0.72 | 3.0 | 26.1 | 0.73 | 3.4 |
| Fuel model Mast-M, moderate loading | 27.0 | 0.85 | 3.9 | 26.6 | 0.86 | 4.3 |
| Fuel model Mast-H, high loading | 30.2 | 1.03 | 5.1 | 29.7 | 1.04 | 5.6 |

**Table 7. Residual stand at 10 masticated sites in California and southern Oregon and fuel model for estimating fire behaviour post-mastication**

Species are listed from highest to lowest percentage basal area (in parentheses). Canopy cover estimated using FOFEM 5.7. Species abbreviations are ABCO, white fir (*Abies concolor* (Gordon & Glend.) Lindley); ARME, *Arbutus menziesii*; CADE, incense cedar (*Calocedrus decurrens* (Torrey) Florin); PIAT, knobcone pine (*Pinus attenuata* Lemmon); PIJE, Jeffrey pine (*Pinus jeffreyi* Grev. & Balf.); PIPO, *Pinus Ponderosa*; PSME, Douglas fir (*Pseudotsuga menziesii* (Mirbel) Franco var. *menziesii*); QUCH, canyon live oak (*Quercus chrysolepis* Liebm.); QUGA, Oregon white oak (*Quercus garryana* Hook.); QUKE, *Quercus kelloggii*). DBH, diameter at breast height (1.37 m)

| Site | Name | Elevation (m) | Weather station | Fuel model (post) | Residual overstorey | | |
|---|---|---|---|---|---|---|---|
| | | | | | Average DBH (cm) (range) | Canopy cover (%) | Species (percentage of basal area) |
| APP | Applegate | 780 | Buckhorn Spring | Mast-H | 10.9 (1.0–38.5) | 32 | ARME (41), QUKE (36), PIPO (10), QUGA (9), PSME (4) |
| CFR | Challenge | 855 | Pike County Lookout | Mast-H | 23.9 (5.5–66.5) | 51 | PIPO (100) |
| IMR | Iron Mountain Road | 235 | Whiskey-town | Mast-M | 15.8 (0.5–59.6) | 7 | PIPO (96), PIAT (4) |
| MAD | Mad River | 935 | Mad River | Mast-H | 28.4 (16.8–70.5) | 17 | PIPO (51), PSME (44), QUGA (5) |
| MFR | Mount Shasta | 1335 | Mt Shasta | Mast-L | 17.9 (4.3–29.6) | 44 | PIPO (100) |
| SFR | Sierraville | 2010 | Stampede | Mast-M | 3.8 (1.1–7.0) | 4 | PIJE (65), PIPO (35) |
| STA | Stanislaus | 945 | Mt Elizabeth | Mast-H | 17.4 (1.7–45.3) | 12 | PIPO (84), QUCH (13), QUKE (3) |
| TAY | Taylor Ridge | 1815 | Blue Ridge | Mast-M | 32.3 (2.3–69.9) | 11 | PIPO (45), ABCO (34), PSME (13), CADE (5), PIJE (3) |
| WFR | Whitmore | 760 | Whitmore | Mast-L | 19.2 (6.8–40.3) | 33 | PIPO (100) |
| WHI | Whiskey-town | 385 | Whiskey-town | Mast-M | 17.7 (2.5–64.4) | 31 | PIAT (55), QUKE (43), PIPO (2) |

actual scorch height to predicted scorch height using the custom fuel models for burns at Challenge and Whitmore) (Table 8). Mortality predictions were 0–10% higher under the 97.5 percentile fire weather conditions.

## Discussion

The behaviour of fire in our prescribed burns was in line with behaviour noted in other recent studies of burning in approximately comparable loadings of masticated fuels. Average rates of spread for heading fires (57.3 and 33.5 $m\,h^{-1}$ at Challenge and Whitmore) were similar to those reported for prescribed fires in masticated fuelbeds in northern California (54.5 $m\,h^{-1}$; USFS Adaptive Management Services Enterprise Team, unpublished report about fire behaviour in masticated fuels, Moonunit prescribed fire, 2004, on file with the Tahoe National Forest). Kobziar *et al*. (2009) measured rates of spread ranging from 48 to 222 $m\,h^{-1}$ for two prescribed burns in masticated small tree and shrub fuels in central California. In 'chipped' plots in a different vegetation type in South Carolina, USA, the median

**Table 8. Predicted mortality of residual trees at 10 masticated sites with a head fire under percentile fire weather conditions modelled from nearby weather stations using FireFamilyPlus**

Crown scorch was predicted using BehavePlus and tree mortality was predicted using FOFEM. The first of the pre-mastication outputs is for fuel model 5 and the second for fuel model sh5. For post-mastication, the predicted mortality in parentheses assumes a scorch correction factor of 1.8× the BehavePlus model output. Site abbreviations are as given in Table 7

| Site | Percentile weather | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | Pre-mastication | | | | Post-mastication | | | |
| | 37.5 | 80 | 90 | 97.5 | 37.5 | 80 | 90 | 97.5 |
| APP | 83–99 | 89–99 | 93–99 | 97–99 | 87 (96) | 94 (99) | 95 (99) | 98 (99) |
| CFR | 15–52 | 26–82 | 31–84 | 38–85 | 24 (40) | 32 (66) | 37 (76) | 45 (81) |
| IMR | 70–86 | 81–86 | 84–86 | 86–86 | 64 (80) | 76 (85) | 79 (86) | 83 (86) |
| MAD | 20–87 | 72–87 | 83–87 | 87–87 | 39 (77) | 70 (87) | 80 (87) | 85 (87) |
| MFR | 42–80 | 62–80 | 73–80 | 79–80 | 27 (61) | 45 (74) | 54 (79) | 62 (80) |
| SFR | 80–80 | 80–80 | 80–80 | 80–80 | 80 (80) | 80 (80) | 80 (80) | 80 (80) |
| STA | 79–87 | 86–87 | 87–87 | 87–87 | 72 (87) | 82 (87) | 85 (87) | 87 (87) |
| TAY | 55–91 | 64–91 | 76–91 | 87–91 | 40 (58) | 50 (75) | 53 (81) | 57 (88) |
| WFR | 29–80 | 51–80 | 61–80 | 70–80 | 20 (49) | 37 (74) | 43 (77) | 56 (79) |
| WHI | 69–93 | 84–98 | 88–99 | 92–99 | 72 (88) | 83 (92) | 88 (93) | 91 (95) |
| Average | 54–84 | 70–87 | 76–87 | 80–87 | 52 (72) | 65 (82) | 69 (84) | 74 (86) |

and average rates of spread for prescribed fires was found to be 31.2 and 81.6 m $h^{-1}$ (Glitzenstein *et al*. 2006). The average flame length we measured in heading fires (0.72 m) was similar to the 0.74-m average reported by Bradley *et al*. (2006), the 0.7–1.1 m noted by Kobziar *et al*. (2009) and within the range of values (0.3–1.2 m) measured by Vaillant *et al*. (2008), all in prescribed fires. Flame lengths in these studies of masticated fuels at western USA sites, including ours, were generally somewhat higher than those reported for 'chipped' plots in South Carolina, where Glitzenstein *et al*. (2006) observed flame lengths of only 0.35 m.

An overstorey dominated by ponderosa pine was maintained at both sites in our study and 2–3 years had transpired between the mastication treatment and the prescribed burns, so a layer of needle litter blanketed the masticated fuel in many areas. This would explain why rate of spread was well predicted by a long-needle conifer litter fuel model (fuel model 9 by Anderson (1982)). However, the total surface fuel loading of fuel model 9 is much less than found in many masticated sites including Challenge and Whitmore (Kane *et al*. 2009). Thus, flame length and fire effects are better predicted with higher loading models such as 10 (timber and understorey (Anderson 1982)), or sb2 (moderate load activity fuel (Scott and Burgan 2005)) or custom models. Without a layer of pine needles, rates of spread would likely have been slower than values reported here. In a study utilising small (1 × 1 m) experimental burns of heavy loads of masticated wood without pine needles (Busse *et al*. 2010), a spread rate of only 1.8 m $h^{-1}$ was noted for backing fires (M. D. Busse and E. E. Knapp, unpubl. data), less than half the rate for backing fires measured in the field in this study.

The high fuelbed bulk density is likely one reason for the relatively slow rate of spread observed in many other studies of masticated fuels. Another is the abundance of larger diameter (10-h) fuel pieces relative to the finer fuels. Kane *et al*. (2009) found that a high percentage of the woody fuel at these sites was composed of 10-h (0.64–2.54-cm diameter) pieces. With the finer 1-h (0–0.64-cm diameter) particles potentially settling more over time, a substantial portion of the fuelbed at the surface where combustion occurs was likely composed of this larger wood. Because of the lower surface area to volume ratio, more energy must be expended to preheat these larger pieces (Rothermel 1972). Addition of larger fuels to fuelbeds composed of fine fuels has been shown to greatly reduce rate of spread (Catchpole *et al*. 1993).

In developing custom fuel models, we started with a slash model (sb2 by Scott and Burgan (2005)) and altered the fuelbed depth as well as the surface area to volume ratio of the fuel component acting as the primary carrier of fire, in order to produce fire behaviour outputs approximating the combination of relatively slow spread rate and moderate flame lengths noted in the prescribed burns. For the average 1-h surface area to volume ratio, we used to lowest value found among comparable fuel models by Scott and Burgan (2005), namely 2461 $m^2 m^{-3}$ of the sh5 high load dry climate shrub model. Although we might have been able to estimate the average surface area to volume ratio from measurements of masticated pieces done by Kane *et al*. (2009), we thought that more information on the stratification of particle size vertically through the fuelbed and a better understanding of the relative importance of 1- and 10-h pieces in contributing to fire spread would be necessary to do so. Because of the abundance of 10-h pieces in these masticated fuelbeds, this size class of fuels may need to be included in the surface area to volume calculation, along with the 1-h fuels. The Rothermel fire spread equation (Rothermel 1972) is very sensitive to fuelbed depth, and this was our primary means of adjusting outputs to approximate field fire observations. For sites with the highest fuel loading, a custom model including the actual loading and fuelbed depth measured in the field produced outputs suggesting it would not burn or only burn very minimally. This limitation of the Rothermel (1972) equation for compact, moderate to high load fuelbeds, has been noted by others (Glitzenstein *et al*. 2006). Thus, adjusting the inputs for fuelbed depth upwards was necessary, especially for the high load custom model. It is possible that combustion with the initial flaming front occurs mostly on the surface layer of certain types of fuelbeds (Cruz and Fernandes 2008), including masticated fuelbeds, making the high bulk density less of an impediment to burning than fire behaviour models predict.

Although the custom masticated fuel models were not the best predictors for all outputs, they provide a balance between fire behaviour and effects predictions. For masticated fuelbeds covered in a layer of pine litter, another option would be to use fuel model 9 for estimating rate of spread and a fuel model with higher loading (e.g. fuel model sb2 or the masticated fuels custom models) to estimate flame length and fire effects. These custom fuel models should be considered preliminary and just a starting point for further adjustment. Custom fuel models have only been validated for a narrow range of mild weather conditions typical for prescribed burns, and not conditions likely to occur with wildfire. In addition, fire behaviour in prescribed burns can be strongly influenced by the ignition pattern (Rothermel and Rinehart 1983). However, igniting only one strip at a time across most of the burn area in this study meant that the influence of fire front interactions potentially caused by ignition pattern was reduced. More problematic was the narrowness of strips and small size of the burn units, which may not have allowed fires to become fully free-burning, as is assumed in fire behaviour simulations. We waited for fire to become well established after a strip was ignited in order to obtain the best possible flame length and rate of spread estimates, but the narrow width limited the number of opportunities to obtain head fire observations in some of the burn units. Fire behaviour estimates, especially for heading fires, should, therefore, be viewed with caution. Backing fires in these fuels appeared to become free-burning relatively rapidly.

Also at issue are deficiencies in the Rothermel (1972) fire spread model itself, which leads to errors when fire behaviour in complex fuelbeds is linked to fire effects. The Rothermel model is restricted to combustion at the immediate flaming front (Scott and Burgan 2005); thus fire effects in fuelbeds where considerable consumption continues to occur after the flaming front has passed (such as in masticated fuelbeds) are likely to be under predicted. The fuelbeds in this study consisted of several years' deposition of pine needles on top of masticated wood. Fire appeared to spread initially and more rapidly across the pine litter layer and uppermost masticated wood, burning downward into the layer of masticated wood over time. As a result, the flaming zone was likely wider than would have been expected with burning in either pure needle litter or pure masticated fuels. Both the wider flaming zone and residual combustion after the main flaming front may help explain the greater than expected crown scorch noted in our study and by others (Bradley *et al*. 2006).

### *Soil heating and tree mortality*

Despite the loading of masticated material, little of the surface heat upon burning appeared to penetrate deeply into the mineral soil. Relatively high duff moisture during these late spring–early summer burns led to incomplete consumption. Sandberg (1980) noted that a moisture level of less than 30% allowed duff to burn independently of surface fire; the average duff moisture in six out of the eight units exceeded this threshold. Retained duff likely prevented much of the surface heat from even reaching the underlying mineral soil. Busse *et al*. (2005, 2010) found that soil heating was substantially dampened when soil moisture was 20% or greater. Only with very dry soils (10% moisture) was heat sufficient to kill roots (>60°C) at a depth of 10 cm. This is consistent with our findings of few thermocouples reaching this heating threshold, even at 5-cm depth. The only thermocouples within the soil registering temperatures >60°C were at Whitmore. Even though the Whitmore site had lower average fuel loading, the underlying mineral soil was drier at the time of the burns (mean moisture = 23 *v.* 37% at Challenge). It should be noted that in the Mediterranean climate of California, where little rain falls in the summer, surface soils are often quite dry during the main wildfire season. Soil heating results reported here for prescribed burns may therefore be different than might be expected if masticated fuelbeds are consumed in a wildfire under typical dry, late summer conditions.

The lack of substantial soil heating suggests that above-ground fire effects were more likely to be the cause of mortality experienced by residual trees within the burn units. The dominant cause of mortality at both sites appeared to be crown scorching. All trees that were completely scorched died. The percentage of trees at the Challenge site experiencing delayed mortality at given levels of crown scorch (i.e. approximately equal numbers surviving and dying at 70% crown scorch) was similar to values reported by other studies (Stephens and Finney 2002; McHugh and Kolb 2003; Hood *et al*. 2007). The Whitmore site appeared to tolerate higher percentages of crown volume scorched, with the majority of trees surviving at 90% of crown volume scorched and below. The reason for this difference among sites is unclear, but the 2005 burns (Challenge) were conducted after a winter with slightly above average precipitation and the 2006 burns (Whitmore) were conducted after a winter that was considerably wetter than average. Following two straight wet winters, trees may have been less stressed at the time of the Whitmore burns. The difference in mortality between sites may also be partially related to fuel loading and the ignition pattern; burns at Whitmore consumed less than half the amount of fuel that was consumed at Challenge. Less variability in the firing pattern and uniformly flatter topography may also help to explain the reduced variability in scorch damage among units at Whitmore (Table 3).

Smaller diameter trees had a greater probability of dying because they are shorter and, thus, more likely to have experienced heavy crown scorch, but also because smaller trees tend to have thinner bark and may therefore be more susceptible to cambium injury (Ryan and Reinhardt 1988; van Mantgem and Schwartz 2003). The relatively even fire intensity in these prescribed burns meant that there was insufficient variation in PCVS in the larger tree diameter classes to adequately predict mortality, especially at Whitmore (Fig. 5). At Whitmore, char height was also significantly associated with mortality; however, the results of the raking study, which showed no effect of raking on mortality, indicates that the significance of this variable could also be because trees with high bole char tended to also have experienced heavier crown scorch ($R = 0.367$, $P < 0.001$). Given the relatively small size of the trees and the heavy fuels, we expected that bole charring would exert a stronger influence than it did. The boles of small trees contain more inner bark, which apparently also provides greater insulation than outer bark (van Mantgem and Schwartz 2003) and might help explain the relatively low mortality rates given the amount of char. All of the tree mortality occurred within the first 2 years after the burns, and most occurred within the first year. It is possible that mortality delayed by more than a few years post-fire is more of an issue with larger trees (Agee 2003; Kolb *et al*. 2007).

Although fire behaviour models have been shown to have an under-prediction bias (e.g. scorch height in this study; crown fire behaviour in general (Cruz and Alexander 2010)), fire effects models can still offer reasonably good predictions of tree mortality (Hood *et al*. 2007). The under-prediction of mortality at Challenge could be due to variability in the firing pattern and variation in slope – the greatest tree mortality occurred with the initial ignition on steeper slopes in the first unit to be burned. After witnessing greater than desired scorching, the duration between strips in the strip-headfire ignition pattern was increased. The fire behaviour and effects outputs from BehavePlus do not take this within-unit variation into account and are calculated based on the unit averages. It should also be noted that calibrating tree mortality results with fire behaviour in prescribed burns is a challenge because the ignition pattern of strips makes quantifying how much the of stand burned in a backing fire and how much burned in a head fire difficult.

Given that the custom fuel models have not been tested beyond the prescribed burning conditions in this study, outputs of the modelling exercise to predict tree mortality under wildfire conditions should be treated as preliminary. In modelled wildfires under 80th percentile and above conditions, substantial to nearly complete mortality of overstorey trees was predicted at all 10 sites, whether the stand was masticated or not. These predictions may be underestimates of actual mortality, especially at the higher percentile weather conditions and at sites dominated by ponderosa pine; the tree mortality models in FOFEM 5.7 project up to 20% survival of ponderosa pine trees with 100% of the crown volume scorched, whereas our data from Challenge and Whitmore showed that no trees with this level of scorch survived. Despite modelling uncertainties, the results are approximately in line with observations of wildfire effects in the field. As examples, during the 2007 Antelope Complex on the Plumas National Forest, CA, mixed outcomes, ranging from high-intensity fire and complete mortality of the residual stand in units with the heaviest masticated fuel to a low-intensity understorey burn (61-cm flame lengths) in masticated units that burned at night, have been noted (J. Fites, unpubl. data; http://www.fs.fed.us/adaptivemanagement/projects/FBAT/docs/Antelope_FINAL3_12_04_07.pdf, accessed 10 August 2011). In the Washoe Fire, which burned 4 ha in the Tahoe Basin in August 2007, abundant surface fuels in a masticated unit (pre-existing fuels plus fuels added by the mastication treatment) generated sufficient heat upon burning to completely scorch and kill residual trees averaging 29 m tall (E. E. Knapp and C. N. Skinner, pers. obs., September 2007). On the positive side, the owner of an adjacent home observed that the relatively slow spread and moderate flame lengths (1.2 m) within the masticated unit allowed firefighters to extinguish spot fires outside of the main fire perimeter and then return to attack the main fire. The masticated area also created conditions for effective retardant drops. This allowed the fire to be stopped at a small size (still burning five houses) after entering the masticated area, despite being driven by strong winds. In a wildfire in lodgepole pine forest in Idaho, Graham *et al.* (2009) reported high burn severity within a masticated unit, although more trees survived within the unit than in adjacent untreated stands.

### *Management implications*

Fire behaviour observations in prescribed burns in this study and in small-scale experimental burns (Busse *et al*. 2005, 2010; Kreye *et al*. 2011), as well as observations of effects post-wildfire suggest that the benefits of mastication for mitigating wildfire behaviour are perhaps clearer than the benefits for improving the survival of forest stands with wildfire. The conditions under which mastication alone provides the greatest benefit for fighting fire are not well understood but worthy of study. In areas where mastication targets woody shrubs, one concern might be if shrubs resprout after mastication (Kane *et al*. 2010) and grow to the point of presenting a fire hazard more rapidly than the masticated material decomposes. Without strong winds, shrubs may not readily burn at times of the year when live fuel moistures are high. For example, flame lengths in prescribed fires have been reported to be greater in masticated units than in adjacent unmasticated shrublands under high live fuel moisture and low wind conditions (Bradley *et al*. 2006). With higher surface fuel loading (masticated wood) beneath resprouting shrubs, it is possible that surface fire could more effectively preheat the live shrub fuels, even at times of the year when live fuel moistures are high, potentially contributing to an increased fire hazard. Clearly, more research is needed to document fire behaviour in masticated fuelbeds under a broader range of conditions.

One way to eliminate the uncertainties of fire behaviour or stand resilience with wildfire would be to reduce the masticated fuels with a prescribed burn. In California and southern Oregon, mastication is commonly used in young stands emerging from shrubs, including plantations, and results of this study show that it is possible to use prescribed burning in such situations to further reduce the masticated fuels, despite relatively heavy loading. At sites with low to moderate loads of masticated fuels or larger residual trees, few issues may be encountered. As suggested by Busse *et al.* (2010), underground damage to soils or roots may largely be avoided by burning when soils are moist. With higher fuel loads or smaller trees, mortality due to crown scorching may become an issue. However, crown scorching can be mitigated by adjusting burning prescriptions and firing techniques, such as burning when air temperature is low, or burning when wind speeds are sufficient to disperse the heat horizontally, thereby reducing the effect on the tree crowns.

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