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Prescribed burning and mastication effects on surface fuels in southern pine beetle-killed loblolly pine plantations

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ABSTRACT

Surface fuels were characterized in loblolly pine (*Pinus taeda* L.) plantations severely impacted by southern pine beetle (*Dendroctonus frontalis* Ehrh.) (SPB) outbreaks in the upper South Carolina Piedmont. Prescribed burning and mastication were then tested as fuel reduction treatments in these areas. Prescribed burning reduced fuelbed continuity by consuming litter (Oi layer), duff (Oe + Oa), and woody surface fuels (1-, 10-, and 100-h timelag size classes) immediately after the treatment. Total loading of 1- and 10-h fuels in burned stands (3.1 Mg ha^{-1}) remained significantly lower than that in the control (no treatment) (5.6 Mg ha^{-1}) in the 2nd year post-treatment. However, 100- and 1000-h fuels increased post-burn due to accelerated failure of remaining pine snags and totaled 14.5 Mg ha^{-1} in the 2nd year post-treatment which was not significantly different than the control (17.3 Mg ha^{-1}). Mineral soil exposure averaged 73% of burned stands after consumption of the duff layer in many areas. Custom low, moderate, and high load fuel models were developed for SPB-killed stands and produced simulated fire behavior (flame length and rate of spread) similar to two standard slash-blowdown fuel models (SB2 and SB3) when input to the BehavePlus fire modeling system. Mastication resulted in a compacted (bulk density = 131.3 kg m^{-3}) and continuous layer of woody debris that averaged 15.1 cm in depth. Equations were developed for estimating masticated debris load and utilize fuelbed depth as input. The masticated debris load averaged 192.4 Mg ha^{-1} in the 1st year post-treatment and was significantly higher than total fuel loading in burned (16.3 Mg ha^{-1}) and control (24.3 Mg ha^{-1}) stands. The treatments tested in this study provide different options for preparing SPB-killed areas for reforestation activities and may produce short-term reductions in fire hazard.

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1. Introduction

The southern pine beetle (SPB) (*Dendroctonus frontalis* Ehrh.) is native to pine (*Pinus* L. spp.) forests of the southeastern United States (Ward and Mistretta, 2002). During non-outbreak population levels, the SPB attacks storm-damaged, diseased, or lightning-struck pines (Hain et al., 2011) as well as low-vigor trees in overly dense, unthinned stands (Boyle et al., 2004). However, all trees are susceptible to attack when SPB populations reach outbreak levels (Hain et al., 2011). Major outbreaks occur in irregular cycles across the southern U.S., but may last several years and cause extensive tree mortality during these periods (Hedden 1978). The largest SPB outbreak on record lasted from 1999 to 2003 and caused the mortality of more than 28 million m^3 in tree volume (Pye et al., 2011) across more than 400,000 ha in eight southern U.S. states (Vose et al., 2009; Goelz et al., 2012), but was particularly widespread in Tennessee and South Carolina. In central America, an additional 90,000 ha of pine forest were affected by SPB during the same time period (Clarke and Nowak, 2009).

Southern pine beetle outbreaks have been particularly severe and recurrent in the Piedmont physiographic province (Ward and Mistretta, 2002) owing to a long legacy of agriculture and exploitative timber harvesting which reduced soil fertility (Callaham et al., 2006). Pines that are susceptible to SPB attack include loblolly (*Pinus taeda* L.), longleaf (*Pinus palustris* Mill.), shortleaf (*Pinus echinata* Mill.), and Virginia (*Pinus virginiana* Mill.) pines. Naturally regenerated and plantation loblolly pine stands, as well as mixed shortleaf pine-hardwood stands are the major forest types in the upper Piedmont region (Griffith et al., 2002) and are commonly attacked by SPB. When SPB infestations occur in pine plantations, a portion of the stand or nearly all of the trees may be killed in areas ranging from 0.5 to 2.5 ha in size (Stottlemyer, 2011)

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and are typically surrounded by unaffected pine-hardwood or mixed-hardwood forest. Woody debris that accumulates on the forest floor after pines die raises fire hazard concerns (Waldrop et al., 2007; Elliott et al., 2012) and may impede forest management activities.

Recent ecological research has been aimed at better understanding the influence of bark beetle outbreaks on fuels and fire behavior. To date, most of this work has been conducted following mountain pine beetle (*Dendroctonus ponderosae* Hopkins) outbreaks in western U.S. coniferous forests which raise concerns about wildfire risk and have thus been the focus of various fuels and fire behavior studies (Page and Jenkins, 2007a,b; Jenkins et al., 2008, 2014; Simard et al., 2011; Schoennagel et al., 2012; Page et al., 2014). The terms "endemic," "epidemic," and "post-epidemic" have been widely used to describe phases of a bark beetle outbreak in relation to changes in fuels (Jenkins et al., 2014). During endemic population levels, bark beetles attack individual or small groups of trees injured or weakened by lightning, disease, or other insects and have a limited effect on fuels beyond localized increases in downed wood (Jenkins et al., 2008). The beetle population increases during the epidemic phase and needles and fine woody material from dead and dying trees increase to peak levels (Page and Jenkins, 2007a,b,b; Jenkins et al., 2008, 2014; Schoennagel et al., 2012; Page et al., 2014). In the post-epidemic phase, the majority of susceptible host trees has been killed, litter and fine fuel levels decrease and eventually return to background levels (Jenkins et al., 2008). Over the course of several years to decades post-epidemic, large surface fuels accumulate as dead trees fall and the fuelbed becomes deeper (Jenkins et al., 2008, 2014; Schoennagel et al., 2012). A couple of studies have examined fuels following SPB outbreaks in post-epidemic mixed pine-hardwood forests in the southern Appalachian Mountains containing varying abundance of pines (loblolly, shortleaf, and Virginia) and mixed hardwood species as the dominant overstory trees. In one study, Waldrop et al. (2007) found that approximately 2–4 years after an outbreak, SPB tree mortality led to increased loading of all size classes of woody surface fuels as well as depth of the fuelbed. This study, along with another in the same region (Elliott et al., 2012), provide detailed fuels information for post-epidemic pine-hardwood forests, but it is unclear whether these characterizations reflect fuel conditions following SPB outbreak in pine plantations and we are not aware of any studies in these areas.

Without intervention, SPB-killed stands may be at increased risk for catastrophic wildfire (Agee and Skinner, 2005) particularly during high fire danger periods (e.g., January through mid-April) or the heavy loading of woody debris may impede management activities, such as the establishment of a new pine plantation (Schultz, 1997). Prescribed fire can be an effective management tool for reducing fuel loads and preparing sites for regeneration in the southeastern U.S. (Waldrop and Goodrick, 2012), although we are not aware of any research evaluating the impacts of prescribed burning in SPB-killed pine plantations. Thus, it is not clear whether prescribed burning will sufficiently reduce heavy fuel loads or if severe fires will have deleterious effects on site productivity. One study involved prescribed burning in a pine-hardwood ecosystem following SPB tree mortality and heavy accumulations of woody surface fuels (Elliott et al., 2012). The burns consumed 50% of litter plus fine woody fuel mass and 18% of large woody fuel mass. However, the duff (Oe + Oa) layer, which is one factor involved in short-term site recovery and long-term site productivity (Clinton et al., 1996; Elliott and Vose, 2005; Waldrop et al., 2010), remained largely intact. These results suggest that burning may be effective for fuel reduction in SPB-killed pine plantations while having minimal impacts on site productivity.

Mechanical treatments have become increasingly common for fuels management particularly in the wildland–urban interface where the use of prescribed fire is constrained by public perception, risk to property, or concerns over effects of smoke emissions on air quality (Agee and Skinner, 2005). Mechanical methods are used in lieu of prescribed fire or as an initial treatment to moderate fire behavior (Stephens and Moghaddas, 2005). Mastication is a mechanical treatment where a machine equipped with a rotary drum with flailing knives or cleats shreds, grinds, or chips live and dead standing trees and shrubs, as well as down woody surface fuels (Kane et al., 2009). Larger fuels are fractured into smaller, irregularly sized particles and all masticated debris is deposited onto the forest floor (Battaglia et al., 2010) and typically left on-site (e.g., Fig. 2). Mastication has been used to achieve different fuels management objectives including the treatment of logging slash (Stephens and Moghaddas, 2005; Kane et al., 2009) and midstory sapling and shrub layers (Glitzenstein et al., 2006; Brockway et al., 2009; Kane et al., 2010; Outcalt and Brockway, 2010; Potts et al., 2010; Knapp et al., 2011; Kreye et al., 2013) as well as reducing canopy fuel loads (Stephens and Moghaddas, 2005; Reiner et al., 2009; Battaglia et al., 2010). These studies generally found that mastication results in a mixture of fuel particle shapes and sizes in a shallow, continuous fuelbed having high mass and bulk density (Kreye et al., 2014). The fractured nature of masticated fuels gives them high surface area to volume ratios (Knapp et al., 2011) which would be expected to decrease drying time (Anderson, 1990). While this characteristic might normally increase fire behavior in other types of activity fuels (Rothermel, 1972); masticated fuelbeds are compact which may slow drying time and suppress fire behavior (Kreye et al., 2011). For example, Glitzenstein et al. (2006) used mastication to treat large woody surface fuels and a continuous sapling and shrub understory post-Hurricane Hugo in South Carolina, USA. Masticated plots had lower flame lengths and rates of spread and less area burned compared to un-masticated plots, although slower wind speeds in the masticated plots may have contributed to the differences. We are not aware of any studies where mastication has been used for fuels management in areas where a severe insect outbreak caused near complete mortality of the overstory trees. Thus, information thought to be critical for modeling fire behavior and effects in masticated fuel is currently unavailable to forest managers. In particular, properties including depth, loading, and bulk density have been suggested to be critical to understanding fire behavior in masticated fuels (Kreye et al., 2014).

Forest managers have expressed interest in using prescribed burning or mastication as fuels treatments to simultaneously reduce the fire hazard and clear woody debris in SPB-killed stands to facilitate reforestation activities. Yet prudent management decisions require information about the fuel complex and how the treatments affect fuels which is currently unavailable. Therefore, the objectives of our study were to (1) characterize surface fuels; (2) compare custom fuel models to existing slash-blowdown fuel models for simulating fire behavior; and (3) examine impacts of prescribed burning and mastication as separate treatments on fuel loading and fuelbed structure in SPB-killed loblolly pine plantations.

2. Materials and methods

2.1. Site selection and plot establishment

This study was conducted in the Clemson Experimental Forest (CEF; latitude 34°40′, longitude 82°49′) which lies in the upper portion of South Carolina's physiographic Piedmont province (Myers et al., 1986). Maximum July temperature averages 31 °C in this region and total annual precipitation is 137 cm, on average (National Climatic Data Center). Soils in the study area are Cecil series and classified as fine, kaolinitic, thermic, Typic Kanhapludults. These soils are well-drained, moderately deep to bedrock and weathered from felsic, igneous and high-grade metamorphic rocks (Soil Survey Staff, 2005). Slope did not exceed 10% in the study area.

Our study was conducted in 12 beetle-killed loblolly pine plantations in the CEF that ranged from 0.3 to 0.7 ha in size and 18–33 years in age when killed between 1999 and 2001. Each beetle-killed area was easily accessible and surrounded by mixed hardwood–pine forest. Live trees in beetle-killed stands included a few scattered pine trees that escaped beetle infestation and hardwoods that developed along with pines or beneath the pine overstory (Fig. 1a). There were 79 dead pines and 51 live hardwood trees on average per hectare in pre-treatment stands, which together comprised over 85% of stems greater than or equal to 10 cm dbh. A 25 m × 25 m grid system was established within each stand by using metal stakes which served as permanent references for fuel sampling plots.

2.2. Experimental design and treatment implementation

The 12 stands were experimental units and randomly assigned to three treatments in an unbalanced, completely randomized design. There were three replications of mastication and six replications of prescribed burning which were individual fuels treatments and not used in combination. Three of the beetle-killed stands were un-manipulated and used as controls. Mastication was performed using a tracked Beaver B425 (Kodiak Kutters, Louisville, KY) equipped with a FAE225C drum-style masticating head (Fig. 2a). Instructions given to the machine operator were to maintain large, vigorous, well-formed trees as seed sources. All other live vegetation, as well as live trees, snags, and down dead woody material was masticated. The masticating head was operated in the full-down position (e.g., Fig. 2a) which allowed the cutting teeth to penetrate the soil surface to approximately 5 cm deep in some places. Mastication began in late May 2005 and was completed by late June 2005. An unbalanced experimental design was not intended; the original study plan was to conduct three dormant and three growing season burns, but unfavorable weather conditions delayed all burning until spring 2006. Prescribed burning was conducted on three separate days between 30-March and 03-May 2006 (Table 1). A backing fire was manually ignited parallel to and within 10 m of the downwind side of each burn unit. Rows of spot fires were ignited parallel to and upwind of the backing fire with approximately 10 m between spots and 10–20 m between rows. Fuel moisture was measured for live understory plants, litter, duff, and 1-, 10-, and 100-h woody fuels prior to ignition. Air temperature, relative humidity, and wind speeds were measured before and during all six burns using a belt weather kit (Table 1). To measure peak flame temperature and duration (in minutes) of heating >60 °C (Busse et al., 2005), bare Type K thermocouples (length = 30 cm; diameter = 0.5 cm; model TCP6-K12, Onset Computer Corp., Cape Cod Massachusetts) and data loggers (model U12 K, Onset Computer Corp.) were placed 30 cm above mineral soil in 12–16 fuel sampling plots in each stand. Visual estimates of flame heights were made from multiple vantage points during the burning operations.

2.3. Surface fuel sampling

The number of fuel sampling plots varied with the size of each stand, but ranged from 14 to 35 and averaged 23 plots across the 12 stands. Brown's (1974) planar intersect method was used to tally dead and down woody surface fuels and forest floor horizons along three 15.2 m sampling transects per sampling plot. Transects were established using measuring tapes anchored 2 m from the metal stakes (to minimize effects of foot traffic on the fuelbed) in the 25 m × 25 m grid layout. The middle transect was extended in a random direction and the other two transects were placed at +22° and −23° angles, respectively, from the middle transect which formed a 45° angle by the two outer transects. The same random direction was used for all middle transects in a given stand to eliminate the possibility that transects associated with adjacent fuel sampling plots would overlap. Fuel variables measured included quantities of 1-, 10-, 100-, and 1000-h timelag size classes of dead and down woody surface fuels, depths of the fuelbed, forest floor litter (Oi) and duff (Oe + Oa) depths with measurements following the same protocol outlined by Stottlemyer et al. (2009). Each transect was divided into quadrants with lengths of 1.8 m for 1-h fuels, 1.8 m for 10-h fuels, 3.7 m for 100-h fuels, and 15.2 m for 1000-h fuels. Depths of the fuelbed, litter, and duff layers were measured at 3.7 m, 7.6 m, and 12.2 m along each transect. Fuelbed depth was measured from the bottom of the litter layer to the highest dead and down woody fuel particle that intersected the transect (Brown, 1974). Fuelbed bulk density (kg m^{-3}) was calculated by dividing dead and down fuel loading (in kg m^{-2}) by fuelbed depth (m). The same transects and quadrants were re-measured post-treatment with the exception of post-mastication stands where alternate methods were used to sample fuels. Fuel quantities for each size class of woody fuel were converted to Mg ha^{-1} after alternate values for specific gravities of southeastern US fuels (1- and 10-h = 0.7, 100-h and 1000-h, sound = 0.58, and 1000-h, rotten = 0.3; Anderson, 1978) were substituted into Brown's (1974) equations. The planar intersect theory also assumes that fuel particles lie horizontal with the sampling plane, but in piled or slash fuels the angles can be steep.

Fig. 1. Beetle-killed pine plantation in South Carolina's Upper Piedmont Region shown in April 2005 (a) which was four years after the infestation. The stand was prescribe burned and photographed from the same point immediately following the treatment in June 2006 (b).

Fig. 2. Mechanical mastication was used as a fuel treatment in beetle-killed southern pine stands. A tracked excavator was equipped with a FAE225C drum-style masticating head (a) which treated dead and down surface fuels, live saplings and shrubs, and remaining pine snags (b).

Therefore, correction factors for non-horizontal particle angles (1-h = 1.15, 10-h = 1.13, and 100-h = 1.10) (Brown, 1974) were used in the calculations. Mineral soil exposure was measured as the percentage of duff measurement points along fuel transects in the 1st year post-burn and control stands where duff depth values equaled zero.

The organic (O-) horizon was also destructively sampled in the pre-treatment stands to develop regression equations that relate mass of litter and duff to the depth of these layers. A plywood frame measuring 30.5 cm × 30.5 cm (930 cm^2) was placed on the ground, within 1 m of the mid-point of the center transect in each fuel sampling plot. A sharpened spade was used to cut around the edges of the sampling frame through the litter and duff layers. All organic materials inside the 930 cm^2 area was collected down to mineral soil and placed into a paper bag. Depth measurements were obtained in undisturbed litter and duff at or near the four corners of the destructively sampled area. Samples were returned to the laboratory, oven-dried (85 °C for 48 h), and then sorted by litter, duff, and other material (e.g., rocks, woody fuels, cones, etc.). Duff was floated in water to allow soil and rocks to settle out, and then re-dried in an oven as previously described. Litter and duff fractions were weighed separately to determine their mass. The resulting equations would be used to estimate litter and duff loading from depth measurements obtained from the fuel sampling transects.

2.4. Surface fuel loading in masticated stands

Alternate methods were used to quantify total masticated debris loading since much of the resulting material was non-cylindrical (Fig. 2b) which violates an assumption of Brown's (1974) planar intercept method. The methods first involved evaluating the relationship between masticated debris loading and depth. Rather than transport large quantities of masticated material back to the laboratory, a wooden box (length = 113.7 cm; width = 121.3 cm; and height = 91.4 cm) was constructed of plywood and used to weigh freshly collected woody debris samples in the field during the 1st year post-mastication. The box was filled with masticated debris in 10 approximately equal increments to a maximum depth of 76.2 cm. At each increment, depth was measured to the nearest centimeter using a measuring stick attached to the inside of the box and fresh weight was determined using a portable scale (model CW250, Intercomp Co., 450 kg maximum capacity, 0.2 kg graduation) resting on firm, level ground. This procedure was performed in each of the three masticated stands at two to four randomly selected locations scattered throughout the stands, resulting in 99 pairs of fuelbed depth-debris fresh weight measurements. We did not examine the proportions of different fuel size classes in the samples. Within 2–3 h of weighing debris in the field, we collected grab samples at 10 random locations throughout each stand from the top, middle, and lower portions of the debris profile placed in a sealed plastic bag

Table 1
Means and ranges (in parentheses) of pre-burn fuel moisture, fire weather, and fire behavior in six beetle-killed pine stands in the upper South Carolina Piedmont.

Site	Burn date	Fuel moisture (% wet weight)			Fire weather				Fire behavior[e]		
		Forest floor[a]	DDW[b]	Live fuels[c]	Air temp. (°C)	Relative humidity (%)	Wind speed[d] ($km\,h^{-1}$)	Wind direction	Flame height (m)	Maximum temp. (°C)	Heating duration (# min > 60 °C)
Rocky Ford	30-Mar-06	26 (18–32)	15 (13–16)	62 (59–64)	22 (19–25)	54 (52–55)	4.0 (3.2–4.8)	S	0.3–3.0	254 (84–480)	15 (5–27)
Transfer Station	30-Mar-06	25 (19–30)	13 (12–15)	53 (50–66)	22 (20–24)	50 (48–52)	2.4 (0–4.8)	W	0.3–3.0	104 (33-290)	8 (0–22)
Dove Field	11-Apr-06	34 (27–38)	23 (17–29)	63 (57–70)	20 (17–21)	37 (36–38)	8.0 (6.4–9.7)	SW	0.3–3.0	105 (38–309)	7 (0–14)
Issaqueena	12-Apr-06	27 (24–29)	15 (12–17)	60 (58–62)	21 (19–23)	51 (43–58)	1.9 (0–7.2)	SW	0.3–3.0	232 (57–418)	16 (8–33)
Bombing Range East	03-May-06	22 (21–24)	12 (11–12)	64 (63–65)	26 (23–28)	44 (39–54)	2.7 (0–8.0)	W	0.3–3.0	292 (140–546)	74 (15–310)
Bombing Range West	03-May-06	22 (19–24)	17 (14–20)	69 (69–72)	30 (29–31)	29 (24–34)	3.8 (0–11.3)	W	0.3–3.0	213 (81–449)	43 (7–368)

[a] Average of litter (Oi) + duff (Oe + Oa) layers.
[b] Down and dead woody fuel; average of 1-, 10-, and 100-h timelag fuels.
[c] Average of shrubs, vines, grasses, and forbs.
[d] Measured at eye-level.
[e] Maximum temperature and heating duration measured 30 cm above the surface of mineral soil using Type K thermocouples and data loggers. Data are means and/or ranges.

and returned to the laboratory for moisture content analysis. After fresh weights were obtained, the 90 grab samples were oven-dried (85 °C for 48 h) and weighed dry to determine percentage moisture. The average moisture content of the debris layer in each stand (48.5, 45.5, and 46.6%) was used to calculate dry weights of the box samples. The information obtained using the methods described above was used to develop equations for predicting masticated debris load from depth measurements. Three additional field measurements of debris depth were obtained 2 m away and at 120° angles from each metal stake (approx. 60 measurements per stand) in the 1st and 2nd year post-mastication. The equations were used to convert average depth to stand-level estimates of fuel loading.

2.5. Pine snag mass

Dead standing pines represented a considerable source of future surface fuels in pre-treatment stands (e.g., Fig. 1a). Therefore, two grid points were randomly selected in each stand and marked the corners of two permanent 10 m × 50 m (0.05 ha) sampling plots in which pine snags were measured. Height and dbh (1.37 m) were measured for all pine snags greater than or equal to 10 cm dbh. Some snags had sloughing bark in which case outside diameter was measured with bark pulled tightly to the bole so that loadings of dead standing fuels were comparable to downed 1000-h fuels. These measurements were input to a regional equation for estimating pine volume (Saucier and Clark, 1985) to calculate dry weight using the equation:

$$W = SG \times D_{water} \times V \quad (1)$$

where W = dry weight, SG = specific gravity of loblolly pine = 0.47 (Peter et al., 2007), D = density of water (1000 kg m^{-3}), and V = snag volume.

2.6. Fire behavior simulation

The BehavePlus fire modeling system (Andrews et al., 2008) was used to produce prescribed fire behavior simulations with custom SPB fuel models and standard slash-blowdown fuel models (Scott and Burgan, 2005) used as input. To determine whether custom fuel models were appropriate for beetle-killed fuels, three fuel loading scenarios were developed. For the low loading scenario, mean fuel values were calculated from the three stands containing the lowest pre-treatment loadings for each of four fuel parameters used as input to BehavePlus including 1-, 10-, and 100-h fuels and fuelbed depth. The system does not incorporate the burning of 1000-h fuels. The moderate loading scenario was developed from the six stands containing moderate loadings and the high loading scenario was based on the three stands containing the highest loadings of each of the fuel variables. In each of the above scenarios, 1-h fuel loading was the sum of 1-h woody fuel and litter loading. The fuel parameter values were input to the BehavePlus fire modeling system to simulate flame length and rate of spread under the low, moderate, and high loading scenarios. Fire behavior predictions from the custom fuel loading scenarios were compared to BehavePlus predictions for standard slash-blowdown fuel models SB1–SB4 (Scott and Burgan, 2005). Fire behavior simulations were performed at moderate (5%) slope and under average fuel moisture and wind speed observed during our prescribed burns: 1-h fuels = 14%, 10-h fuels = 14%, 100-h fuels = 19%, and wind speed = 2 km h^{-1}. Starting values for 1-h surface area to volume ratio (6562 m^2 m^{-3}), dead fuel moisture of extinction (25%), and dead fuel heat content (18,622 kJ kg^{-1}) given for slash-blowdown fuel models (Scott and Burgan, 2005) were used in the current study for all BehavePlus simulations.

2.7. Statistical analysis

Linear regression analysis (PROC REG, SAS Institute, 2002) was used to develop equations for predicting dry masticated debris load using fuelbed depth as the independent variable from the 99 depth-weight observations collected in masticated stands. The slopes of the regression lines were tested for significant differences (PROC GLM) to determine whether stand-specific equations were appropriate for calculating masticated debris loading from fuelbed depth measurements collected in 2005. The resulting equations were used to calculate total fuel load in 1st year post-masticated stands. Regression equations were also developed (PROC REG) for estimating dry litter and duff loading based on measurements from forest floor samples collected pre-treatment.

Prescribed burning was only tested (PROC GLM) against the control for its effects on litter and duff mass and 1-, 10-, 100-, and 1000-h fuel loading because these variables were not examined in masticated fuelbeds. All treatments were examined for differences in their effects on pine snag mass, total fuel loading, fuelbed depth, and fuelbed bulk density using PROC GLM. A significance level of α = 0.05 was used for all statistical analyses.

Fuels data were taken from Waldrop et al. (2007) who examined fuels following SPB outbreaks in southern Appalachian pine-hardwood stands. The data included mean litter, 1-, 10-, 100-, and 1000-h fuel loading across five topographic positions and were compared to the same set of variables from the current study's pine-dominated stands. Multivariate analysis of variance (PROC MANOVA) was used to test whether fuel complexes were statistically different between the two ecoregions with respect to the set of fuel variables and based on Hotelling's T^2 statistic.

3. Results

3.1. Surface fuel characteristics in SPB-killed stands

Surface fuels were variable within SPB-killed stands, although there were no significant differences among stands with respect to any of the fuel variables prior to treatment implementation (Table 2). The litter layer was generally thin, ranging from 3.4 to 4.8 cm across the 12 stands, and was comprised of leaves from midstory shrubs and saplings over partly decomposed pine needles. The duff layer was 1.9–3.3 cm in depth and contained mostly pine needles in an advanced stage of decomposition. Analyses of litter and duff samples collected in pre-treatment stands revealed that depth of these layers were significant predictors of litter (data range = 3-61 mm; n = 193; P < 0.0001; R^2 = 0.29) and duff (data range = 0–60 mm; n = 183; P < 0.0001; R^2 = 0.70) mass, respectively. The resulting equations were:

$$\text{litter mass (Mg ha}^{-1}) = (0.17 \times \text{litter depth [mm]}) + 5.07 \text{ and} \quad (2)$$

$$\text{duff mass (Mg ha}^{-1}) = (0.49 \times \text{duff depth [mm]}) + 1.76. \quad (3)$$

With these equations used to estimate loading, litter ranged between 10.9 and 13.2 Mg ha^{-1} and duff ranged between 11.1 and 17.9 Mg ha−1 ha^{-1} across the 12 pre-treatment stands.

Many of the pine trees that were killed during the southern pine beetle outbreak of the early 2000's fell by the time our study commenced in 2004. However, there were 79 dead stems ha^{-1} and 8.2 Mg ha−1 ha^{-1} in pine snags, on average, remaining during pre-treatment sampling. Snags represented a considerable source of future surface fuels and fell continually throughout the study. Fine (1-, 10-, and 100-h) woody fuel loading varied widely among stands, ranging from 7.3 to 24.5 Mg ha^{-1} and averaging 14.5 Mg ha^{-1}. Large-diameter (1000-h) woody fuel loading ranged between

Table 2
Means, standard error of the means (SEM; in parentheses), and ranges of fuel characteristics in beetle-killed stands where prescribed burning or mastication was used to reduce fuel loading. Values are in Mg ha^{-1} unless otherwise noted. For a given sampling year, means followed by the same letter are not significantly different among treatments at the 0.05 level.

Fuel variable		Pre-treatment			1st year post-treatment			2nd year post-treatment		
		Control (n = 3)	Burn (n = 6)	Mastication (n = 3)	Control (n = 3)	Burn (n = 6)	Mastication (n = 3)[a]	Control (n = 3)	Burn (n = 6)	Mastication (n = 3)[a,b]
1-h fuel loading (Mg ha^{-1})	Mean	0.9 (0.1) a	1.1 (0.1) a	0.8 (0.1) a	1.0 (0.1) a	0.3 (0.1) b		1.1 (0.1) a	0.7 (0.1) a	
	Range	(0.8–1.0)	(0.9–1.5)	(0.8–0.9)	(0.7–1.2)	(0.1–0.8)		(1.0–1.3)	(0.3–1.1)	
10-h fuel loading		6.1 (2.1) a	5.2 (0.7) a	7.2 (1.1) a	4.2 (0.6) a	1.4 (0.3) b		4.5 (0.1) a	2.4 (0.4) b	
		(2.5–10.9)	(3.6–7.6)	(6.1–9.3)	(3.6–5.3)	(0.3–2.5)		(4.3–4.7)	(1.0–3.3)	
100-h fuel loading		6.6 (2.5) a	5.5 (1.0) a	9.9 (2.0) a	9.2 (1.0) a	4.8 (0.8) b		9.8 (0.8) a	7.1 (1.2) a	
		(3.3–12.6)	(2.8–8.7)	(7.6–14.0)	(7.2–10.5)	(1.5–7.8)		(8.2–10.8)	(3.1–10.8)	
1000-h fuel loading		8.3 (1.0) a	6.2 (0.7) a	8.8 (1.4) a	10.0 (0.9) a	9.8 (0.6) a		7.5 (0.8) a	7.4 (0.6) a	
		(5.9–9.7)	(4.6–9.2)	(6.0–10.4)	(8.6–11.8)	(8.3–12.2)		(6.1–8.9)	(5.5–9.2)	
Total dead and down woody fuel loading		21.9 (5.0) a	18.1 (2.0) a	26.8 (4.0) a	24.3 (1.9) b	16.3 (1.6) c	192.4 (37.9) a	22.8 (1.4) a	17.6 (2.1) a	
		(14.8–34.2)	(13.5–25.8)	(21.2–34.4)	(20.6–26.4)	(10.2–21.3)	(126.2–257.7)	(20.3–25.0)	(9.9–24.0)	
Litter (Oi) loading		11.6 (0.2) a	11.9 (0.4) a	11.7 (0.2) a	11.7 (5.8) a	6.1 (5.4) b		13.6 (5.8) a	7.3 (5.9) b	
		(11.3–12.1)	(10.9–13.3)	(11.4–12.0)	(10.9–12.9)	(5.4–7.5)		(12.4–14.3)	(5.8–10.5)	
Duff (Oe + Oa) loading		15.0 (1.3) a	13.5 (0.6) a	16.3 (1.1) a	14.0 (5.2) a	3.2 (2.3) b		9.1 (2.7) a	4.7 (2.7) b	
		(13.8–17.6)	(11.2–15.0)	(14.1–17.9)	(9.1–20.4)	(0.0–5.2)		(8.1–10.6)	(2.3–8.1)	
Fuelbed depth (cm)		28.0 (5.0) a	24.7 (3.7) a	31.3 (5.3) a	34.0 (7.4) a	18.1 (2.1) b	15.1 (1.4) b	24.8 (0.1) a	26.1 (3.3) a	8.3 (1.3) b
		(15.7–34.8)	(16.9–42.2)	(23.6–41.4)	(23.3–48.3)	(9.2–24.1)	(12.2–16.6)	(24.7–25.0)	(12.0–36.0)	(6.6–10.9)
Fuelbed bulk density (kg m^{-3})		0.8 (0.2) a	0.8 (0.1) a	0.9 (0.0) a	0.8 (0.2) b	0.9 (0.1) b	131.3 (23.5) a	0.9 (0.1) a	0.7 (0.0) a	
		(0.5–1.0)	(0.6–1.1)	(0.8–0.9)	(0.4–1.1)	(0.6–1.1)	(84.5–157.7)	(0.8–1.0)	(0.6–0.8)	
Pine snag mass[c]		5.7 (1.4) a	7.3 (1.2) a	11.5 (5.7) a	4.5 (1.3) a	2.5 (0.7) ab	0.0 (0.0) b	0.1 (0.0) a	0.1 (0.0) a	0.0 (0.0) a
		(3.3–8.0)	(3.0–11.7)	(2.6–22.1)	(2.1–6.3)	(0.9–5.0)	(0.0–0.0)	(0.0–0.2)	(0.0–0.2)	(0.0–0.0)

[a] Masticated debris was not classified by individual timelag size class because most material violated Brown's (1974) assumption of cylindrical particle shape. In addition, litter and duff materials were mixed together with woody debris during the treatment such that these layers could not be measured in masticated stands.
[b] Settling of the debris layer between years 1 and 2 prevented the use of predictive equations to estimate total fine fuel loading in 2nd year post-masticated stands.
[c] Calculated using an allometric equation given by Saucier and Clark (1985).

4.6 and 10.4 Mg ha^{-1} and averaged 7.8 Mg ha^{-1}. The fuelbeds varied from moderately shallow (15.7 cm) where fine fuels were scattered to deep (42.2 cm) where fine- and large-diameter fuels were piled, but were relatively loose and aerated, with bulk density ranging from 0.5 to 1.1 kg m^{-3} and averaging 0.8 kg m^{-3}. The multivariate analysis of variance test for differences in the fuel complexes resulting from SPB outbreak in different ecoregions was significant ($T^2 = 34.52$, $P < 0.0001$) which indicated that accumulation of fuels following SPB infestation in pine plantations creates a surface fuel complex that is distinct from pine-hardwoods stands previously described by Waldrop et al. (2007).

3.2. Fire characteristics

Moisture content of forest floor, dead and down woody, and live fuels was similar among the burn stands prior to ignition (Table 1). Fire weather was also similar among stands with the exception of two sites where humidity was lower and wind speed was higher during the operations, on average, compared to other burn units. However, fire characteristics did not appear to be greatly affected, because average peak measured temperature was actually lower in these stands compared to the other burn stands probably because dead and down woody fuel moisture was higher in these areas (Table 1). Across burn units, average maximum flame temperature ranged from 152 to 510 °C, but varied widely (from 90 to 850 °C) within stands (Table 1). The lower ends of the ranges clearly indicated that there were unburned patches with temperatures measuring below the estimated ignition threshold for dry forest fuels (320 °C) (McAllister et al., 2012). Duration of heating ≥60 °C ranged from zero minutes to over 6 h within beetle-killed stands and averaged 7–74 min among stands. Flame heights varied as the fires progressed through each stand, ranging from 0.3 to 3 m (Table 1).

3.3. Treatment effects on fuel characteristics

Prescribed burning consumed 63% of forest floor (litter plus duff) mass (Table 2) which resulted in the exposure of mineral soil across 73% of burned stands (e.g., Fig. 1b). Fine woody fuels were significantly reduced with prescribed burning which consumed 71 and 73% of 1- and 10-h fuels, respectively (Table 2; Fig. 1b). Small tree saplings and shrubs top-killed by fire added to fine fuel loading and by the 2nd year post-treatment, 1-h fuel loading increased more than two-fold and was not significantly different than the control. One hundred hour fuel loading decreased by 13% in the 1st year post-burn and was significantly less than the unburned control (Table 2). Loading of 1000-h fuels was not significantly different after prescribed burning when compared to the control (Table 2). Nonetheless, many whole 1000-h fuels were consumed by fire since many lines of white ash were observed on the blackened forest floor immediately post-treatment (Stottlemyer, personal observation). Pine snag mass decreased by approximately

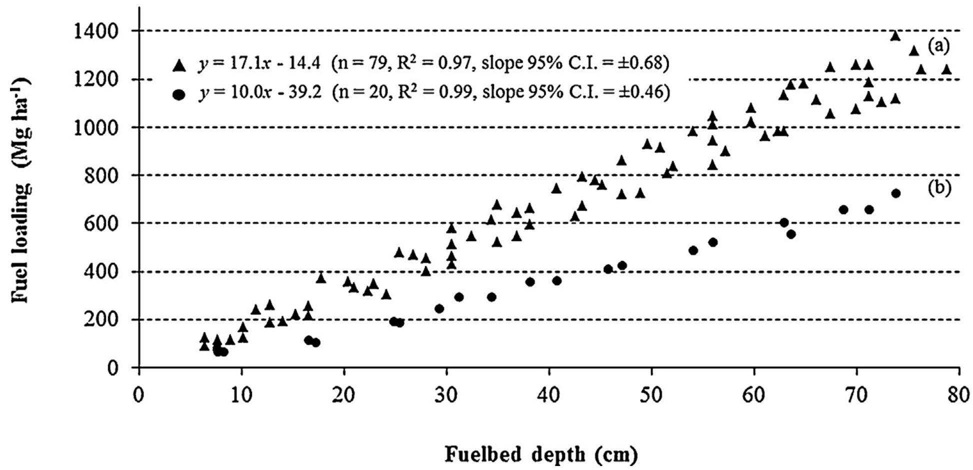

Fig. 3. Relationship between fuelbed depth and woody fuel loading in beetle-killed and masticated southern pine stands. Symbols represent measured depth (data range = 7.6–76.0 cm) dry weight of samples collected in three different stands. Relationships are significant (P-values < 0.0001) and vary from two of the stands (a) to the other stand (b) due to different proportions of hardwood debris.

20% across control stands between the 1st and 2nd year of the study as dead trees continued to fall, which increased 100-h and 1000-h fuels along with total fuel loading in these areas (Table 2). Pine snag mass was lower in the 1st year post-burn, but not significantly different than the control, while no snags remained in any of the 1st year post-masticated stands. The 2nd year of the study was 6–8 years after the SPB infestation and few pine snags remained in control and burned stands (Table 2). Prescribed burning accelerated pine snag failure which is reflected in a 36% increase in 1000-h fuel loading in the 1st year post-burn (Table 2). Our results show 10% consumption of total dead and down fuel loading, but this estimate is confounded by the increase in 1000-h fuel loading caused by falling snags post-burn. Fuelbed depth was initially reduced with prescribed burning, but increased rapidly with the accumulation of fallen pine snags and top-killed woody stems and did not differ from the control by the 2nd year post-burn (Table 2).

Mastication chipped or shredded midstory saplings and shrubs, pine snags, and some live trees in addition to dead and down woody fuels. The resulting surface fuels were a mixture of chipped, fractured, and shredded wood pieces, and bark of various shapes, as well as leaves, twigs, and other plant parts (Fig. 2b). In addition, much of the forest floor and some mineral soil were churned together with masticated debris during the treatment. Not only did mastication result in an average increase of 165.6 Mg ha^{-1} in total surface fuel loading, the depth of the fuelbed decreased by more than 50% (Fig. 2b), which greatly increased fuelbed bulk density (Table 2). Masticated fuel loading was strongly related to fuelbed depth across the stands ($R^2 \geq 0.97$) (Fig. 3). The regression lines for two of the masticated stands had slope coefficients that were not significantly different from one another ($P = 0.3685$); thus, the datasets were combined and modeled using a single equation. Dry mass of samples from one of the masticated stands did not increase as rapidly with increasing depth as that of samples from the other two stands and the regression line had slope that was significantly lower ($P < 0.0001$) when compared to the combined dataset. For this reason, a separate equation was used to model the depth to loading relationship and estimate total fuel load in this stand.

3.4. Simulated fire behavior

Three custom fuel loading scenarios ranging from low to high are given for untreated beetle-killed stands (Table 3). When the custom models were input to BehavePlus, simulated fire rate of spread and flame length ranged from 0.7 to 1.1 m min^{-1} and 0.7 to 1.0 m, respectively, under average fuel moisture, wind, and slope conditions observed during prescribed burns in our study. When four standard slash-blowdown fuel models (Scott and Burgan, 2005) were used to simulate fire behavior under the same environmental conditions, two had fuel parameters that produced fire behavior that was very similar to the custom fuel models. Specifically, fuel model SB2 (moderate load activity fuel) produced fire rate of spread and flame length predictions that were the same as the custom low load model despite being approximately

Table 3
Values for custom fuel models and select slash-blowdown fuel models input to BehavePlus to simulate prescribed fire behavior in SPB-killed fuels.

	Fuel parameter				Fire behavior	
Fuel Model	1-h[a]	10-h	100-h	Fuelbed depth (cm)	Rate of spread (m min^{-1})	Flame length (m)
Custom						
Low loading (Mg ha^{-1})	12.1	3.3	3.3	17.0	0.7	0.7
Moderate loading	12.6	5.6	6.2	26.1	0.9	0.8
High loading	13.8	9.3	11.8	39.5	1.1	1.0
Standard (Mg ha^{-1})[b]						
SB1	3.4	6.7	24.6	30.5	0.3	0.4
SB2	10.1	9.5	9.0	30.5	0.7	0.7
SB3	12.3	6.2	6.7	36.6	1.3	1.0
SB4	11.8	7.8	11.8	82.3	2.3	1.4

[a] Includes leaf litter.
[b] From Scott and Burgan (2005).

10 Mg ha^{-1} higher in total fuel loading (Table 3). In addition, SB2 had total fuel loading within 4.2 Mg ha^{-1} of the custom moderate load model and similar fuelbed depth which resulted in simulated rate of spread and flame length that were only 0.2 m min^{-1} and 0.1 m different, respectively, between the two models. When compared to the custom high load model, fuel model SB3 (high load activity fuel) had total fuel loading that was approximately 10 Mg ha^{-1} lower and comparable fuelbed depth which produced the same flame length prediction and only 0.2 m min^{-1} higher rate of spread. There were greater departures from custom model predictions when fuel models SB1 (low load activity fuel) and SB4 (high load blowdown) were input to BehavePlus (Table 3) and were, therefore, considered less appropriate than SB2 and SB3 for simulating fire behavior in SPB-killed fuels.

4. Discussion

4.1. Fuels in Untreated SPB-Killed Pine Plantations

Extensive tree mortality following outbreaks of *Dendroctonus* beetles can cause dramatic changes in fuels which raise fire hazard concerns (Page and Jenkins, 2007a,b,b; Jenkins et al., 2008, 2014; Simard et al., 2011; Schoennagel et al., 2012; Page et al., 2014) and may impede forest management. In may pine forests throughout the southeastern U.S., SPB infestations have resulted in heavy accumulations of surface fuels (Waldrop et al., 2007; Elliott et al., 2012). Our study focused on post-epidemic (Jenkins et al., 2014) pine plantations, but SPB outbreaks also occur in pine-hardwood forests of the southern Appalachian Mountains for which a couple of studies previously characterized surface fuels. Between the studies of Waldrop et al. (2007) and Elliott et al. (2012), post-epidemic pine-hardwood stands had lower loadings of litter and woody fuels <7.6 cm, more shallow fuelbeds, and higher loadings of duff and larger (≥7.6 cm) woody fuels when compared to SPB-killed pine plantations in the current study. Differences in the fuel complexes between neighboring SPB-killed ecosystems likely result from interactions between various factors including tree fall rate (Jenkins et al., 2014), wood specific gravities of representative pines (Hubbard et al., 2004), proportion of hardwood trees (Stottlemyer et al., 2009), and decomposition rates (Abbott and Crossley, 1982) and underscore the value of site-specific fuels information (Jenkins et al., 2008).

Published fuel models are available for a wide range of wildland fuel applications across the U.S. (Scott and Burgan, 2005) but it was unclear which, if any, of these would be appropriate for SPB-killed pine plantations. BehavePlus fire behavior simulations with custom fuel models as input were very similar to ones based on two standard slash-blowdown fuel models. Results of these comparisons indicate that SB2 is a reasonable choice of fuel models when SPB-killed pine plantations are estimated to contain low to moderate surface fuel loadings and fuelbed depths and prescribed burns are to be conducted under conditions similar to those observed in the current study (Table 1). Fuel model SB3 is more appropriate for higher loadings of surface fuels and deeper fuelbeds which will occur after most wood from dead pines has accumulated on the forest floor (Jenkins et al., 2008). The fuel models in BehavePlus do not incorporate the burning of 1000-h fuels which, under conditions conducive to their ignition and consumption, could lead to underestimates of fire behavior and unanticipated fire effects (Knapp et al., 2005).

4.2. Treatment impacts on surface fuels

In our study, prescribed burning resulted in substantial reduction of the forest floor. The long heating durations measured during the burns were the result of prolonged flaming and smoldering in the heavy fuel accumulations which likely preheated and dried the forest floor, leading to its consumption in many areas (Harrington, 1987; Robichaud and Waldrop, 1994; Elliott et al., 2012). These results are consistent with a study in a mature hardwood forest in the southern Appalachian Mountains where after felling small trees and shrubs, total loading of woody surface fuels was 22.3 Mg ha^{-1} (Waldrop et al., 2010), the same as pretreatment SPB-killed stands in the current study. Follow-up prescribed burning in these fuels resulted in a 46% reduction in forest floor mass. However, burning in heavy fuel loads has not always been associated with large reductions in the forest floor. For example, a degraded pine-hardwood forest in the southern Appalachian Mountains contained 21.2 Mg ha^{-1} in total woody surface fuel loading prior to a prescribed stand replacement fire (Vose et al., 1999). The burns consumed 40% of all woody surface fuels, but less than eight percent of the forest floor. In reality, forest floor reduction during prescribed burns is likely influenced by additional factors including environment, fuel moisture, fire intensity and duration (Elliott et al., 2012). With virtually no overstory tree cover, consumption of the forest floor in our study may have been influenced by its exposure to the drying effects of solar radiation and surface wind (Jenkins et al., 2008; Simard et al., 2011), although there is currently little direct evidence of these changes in the literature (Jenkins et al., 2014). The duff layer is involved in the storage and cycling of nitrogen and other soil nutrients and the site where other important biological processes take place in forest ecosystems (Sylvia et al., 2005). In addition, the duff layer insulates soil from high fire temperatures that can volatilize nutrients and kill beneficial soil organisms (Neary et al., 2005) and helps to prevent erosion (Waldrop et al., 2010). Although little surface erosion was observed in burn plots even in areas with exposed mineral soil, slopes of the study sites never exceeded 10%. In another study, post-harvest slash burning was conducted on 24 to 39% slopes in the southern Appalachian Mountains (Robichaud and Waldrop, 1994). Sediment losses were 40 times greater in areas where most of the organic layer was consumed compared to areas where the organic layer remained largely intact. Therefore, high-intensity site preparation burning on steep slopes in beetle-killed areas could cause increased soil erosion and decreased site productivity (Neary et al., 2005). While an intact duff layer helps to ensure post-disturbance site recovery and long-term productivity (Clinton et al., 1996; Elliott and Vose, 2005; Waldrop et al., 2010), site preparation objectives may call for its reduction or even complete removal. For example, seedling survival and establishment for pine (Schultz, 1997) and hardwoods such as yellow-poplar (Clark, 1970; Shearin et al., 1972), sweetgum (Phillips and Waldrop, 2008), and oak and hickory (Abrams, 2000; Brose et al., 2001; Wang et al., 2005) are improved on exposed mineral soil or thin duff.

Leaf litter along with small woody fuels form a horizontally continuous fuel layer that carries fire through a fuelbed, strongly influences rate of spread, and is important for the ignition of larger fuels (Rothermel, 1972, 1983; Anderson, 1982). In their study of post-beetle outbreak fuels and simulated fire behavior in western conifer forests, Jenkins et al. (2008) found that an increase in surface fire spread rate and intensity was associated with the accumulation of needles and fine woody fuels from dead trees on the forest floor. Our results also showed that burning reduced loading of litter plus woody fuels <7.6 cm by 47% which would probably result in decreased ignitability, spread potential, and fire intensity in the event of a re-burn. New leaf litter along with top-killed saplings and shrubs replaced these fuels, increasing by 4.9 Mg ha^{-1} between the 1st and 2nd year of the study which is a common observation in post-fire fuel complexes (Phillips and Waldrop, 2008; Waldrop et al., 2008, 2010; Elliott et al., 2012). It is likely that the loading of 1000-h fuels was also reduced with burning despite our data showing an overall 58% increase in these fuels from pre-treatment to the 1st year post-burn. The reason for this change was that in the control, pine snag mass decreased and 1000-h fuel loading increased by essentially the same amount (approx. 20%) indicating that more large surface fuels accumulated when some remaining pine snags fell to the forest floor. However, while pine snag mass decreased by 65% in the 1st year post-burn stands, 1000-h fuel loading increased by 58%. These results suggest that there could have been as much as seven percent consumption of 1000-h fuels and an even larger percentage 100-h fuel consumption that could not be discerned from our data due to rapid re-accumulation of surface fuels during the period between the burn treatment and 1st year post-treatment fuel sampling. The difference between pine snags that became surface fuels during our study in burned versus control stands also suggests that burning greatly accelerated the toppling of pine snags relative to the control in the 1st year post-burn. In their study of fuel dynamics following prescribed burning in a Sierra Nevada mixed conifer forest, Knapp et al. (2005) observed an 84% mass reduction in logs >7.6 cm in diameter when moisture of these fuels averaged 11%. It is possible that in our study, fuel moisture levels prevented greater consumption of large fuels (Brown et al., 1991) and/or that fine fuel combustion was insufficient to ignite larger fuels (Rothermel, 1972). Therefore, greater consumption of large surface fuels may be possible under certain burning conditions.

Mastication had markedly different effects on the fuel complex in SPB-killed stands. Instead of consuming fuels as with burning, mastication increased total surface fuels to more than seven times the pre-treatment loading by first toppling most standing trees. Larger fuels are then converted into small chips and narrow shredded pieces which comprise a substantial proportion of the total fuel load (Kreye et al., 2014). In our study, pre-treatment pine snag mass accounted for most, but not all of the increase in total dead and down fuel loading in masticated stands; mid-story trees, shrubs, and overstory hardwoods were masticated and contributed to the debris load along with masticated pine snags. The increase in total fuel loading together with the reduction in fuelbed depth resulted in a compacted fuelbed with high bulk density. The nature of the depth to loading relationship in our study varied in one of the masticated stands compared to the other two which was likely the result of differences in the amounts of hardwood debris. The stand that contained debris that increased in mass most gradually with increasing depth (Fig. 3b) had lower density of live hardwood trees (by 14 and 43%) compared to the other two stands (Fig. 3a) prior to mastication (Stottlemyer, 2011). In addition, the reduction in live hardwood tree density due to mastication was 25 and 100% lower in this same stand compared to the other stands. Therefore, mass of the debris per unit volume was probably lower in this stand because the fuelbed contained a lower proportion of hardwood debris which has higher specific gravity than softwood debris (Anderson, 1978). The equations developed in our study for predicting masticated debris load were based on fuelbed depth measurements collected two months after the mastication treatment was completed. Our experience was that materials throughout the profile of the debris layer remained sound in the 2nd year post-mastication, suggesting that little decomposition occurred between 1st and 2nd year post-treatment. Instead, the decrease in fuelbed depth was probably due to settling of the debris over time. Therefore, modifications of the current equations would be necessary for accurate assessments of fuelbed structure and debris loading in masticated stands treated more than one year prior.

Other studies that have characterized masticated fuel complexes have reported fuelbed depths ranging from <1 cm to 15 cm and loadings ranging from and 27 to 195 Mg ha^{-1} (Kreye et al., 2014). Glitzenstein et al. (2006) reported the values at the upper ends of these ranges after mastication in a wind-damaged loblolly pine forest in South Carolina and the masticated fuelbed in our study had essentially the same average depth and only slightly lower total loading. In our study, the combined increase in loading and decrease in depth created a compacted fuelbed with bulk density (131.3 kg m^{-3}) at the upper end of the range reported for masticated wood-dominated fuels in other recent studies (Kreye et al., 2014). Research findings on the efficacy of mastication for reducing fire hazard are currently limited, but the few studies that have been conducted suggest that the compactness of the fuels moderates fire behavior (Kreye et al., 2014). These studies have generally found that masticated fuels burn with low to moderate flame lengths and slow rates of spread (Glitzenstein et al., 2006; Knapp et al., 2011). These results are likely related to the tendency for these dense fuelbeds to retain moisture (Kreye et al., 2011, 2012, 2013). In addition, the mixing of mineral soil with masticated debris that was anecdotally observed in our study and documented elsewhere (Hood and Wu, 2006) may contribute to the suppression of fire behavior (Kane et al., 2009; Battaglia et al., 2010). However, in areas such as SPB-killed stands that lack overstory trees or midstory vegetation, masticated debris are exposed to solar radiation and wind which may accelerate the drying of these fuels thereby affecting the potential for ignition and consumption (Kane et al., 2009). Prolonged flaming and smoldering combustion is frequently observed in masticated fuels (Kreye et al., 2014). In one study, Busse et al. (2005) concluded that the potential for biological damage exists when long durations of soil heating results from burning masticated debris layers ≥7.5 cm, which is only half of the average fuelbed depth that we observed in SPB-killed stands post-mastication. Follow-up burning under prescribed levels of fuel moisture may reduce the potential for accidental ignition of masticated fuels and adverse effects of burning on important ecosystem processes.

5. Management implications

Managers should carefully monitor beetle-killed stands to ensure that the timing of treatments is appropriate for specific site preparation goals. If prescribed fire is used closer to the end of the outbreak, the fuelbed will be more exposed with higher and more continuous litter and fine fuel loadings which will help to carry fire through the fuelbed. The reduction in these fuels along with the depth of the fuelbed should make beetle-killed stands more resistant to intense fires, at least in the short-term. Burning will accelerate the falling of snags, but large surface fuels will continue to accumulate over a 5–10 year period post-outbreak unless snags are mechanically felled. Otherwise, multiple prescribed burns may be necessary to achieve specific fuel reduction goals. Quantitative information and fuel model recommendations resulting from this study can be input to available software programs for predicting fire behavior and effects, emissions, and fuel consumption. Maximum reduction of surface fuels can be achieved under conditions where humidity and fuel moisture are low and there is a slight wind to help carry fire through the fuelbed. Southern pine beetle-killed plantations are usually limited in area and may be surrounded by hardwood-dominated stands with lower fuel loading. Under these circumstances, prescribed burns should be easily implemented and contained. The recent prescribed fire guide compiled by Waldrop and Goodrick (2012) can further assist managers in planning and executing burns in these areas.

With mastication, no dead standing trees remained because the machinery pushed them over during the operation which greatly reduced occupational hazards and improved stand accessibility. Managers may also prefer mastication over prescribed burning to prepare sites for artificial plantings because of the ability to achieve near-complete treatment of dead and down woody material, mid-story vegetation, and dead standing trees. The data from this study can be used to parameterize future fuel models for masticated fuelbeds. In addition, the depth:load equations given should be useful for estimating fuel loading in recently masticated areas or measuring debris consumption from follow-up prescribed burning. Managers can use this study to help them accomplish specific management objectives in SPB-killed stands. Future research should focus on ecological impacts associated with prescribed burning and mastication in heavy fuel accumulations that follow SPB outbreaks.

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