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Research Article

Fire & Fuels Management

Mastication Fuels Did Not Alter Fire Severity or Stand Structure in an Upland Oak Woodland

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Abstract

In the eastern deciduous forest region, open oak woodlands once occupied significant areas that are now closed-canopy forests, negatively affecting wildlife habitat and biodiversity. We superimposed midstory mastication and prescribed fire treatments onto sites with ice storm damage, subsequently subjected to sanitation thinning for management restoration. Mastication reduced stem density and basal area, created a variable cover of masticated material, and increased cover of forbs, graminoids, and tree regeneration. Prescribed fire was implemented two years after mastication treatment. We examined fuel changes and whether masticated fuels altered fire severity. Masticated duff depth decreased significantly two years after treatment; no change occurred on nonmasticated treatments. Masticated 1-hour fuels decreased 80% compared to 35% in nonmasticated treatments and masticated 10 h fuels decreased 45% compared to 9.6% in treatments without mastication. Prescribed fire reduced 1, 10, and 100 h fuels on the burn only treatment, and 10 h fuels on the mastication/burn treatment. Burn severity, measured by composite burn index, did not differ between treatments, nor did we measure significant effects of mastication on fire temperature or char height. Fire had no significant effect on stand structure but should be reexamined in three to five years. Repeated burning at three to five y intervals may also be beneficial.

Study implications: This study examined the effects of mastication and prescribed fire on upland oak restoration. Findings suggest a single prescribed fire after mastication may not create stand structure reflective of oak woodland restoration priorities. Nonetheless, it will be important to examine fire effects several years later. Additional applications of prescribed fire may be effective in maintaining the stand structure initially achieved through ice storm disturbance, harvest, and mastication. Continued research could gauge the intensity and frequency of prescribed fire treatments needed to retain desired woodland stand structure and develop complex and diverse herbaceous understories characteristic of oak woodlands.

Keywords: Fuel loading; ecological restoration; woodland management; red maple

Forest management practices worldwide engage a varied combination of harvesting, understory mastication, and prescribed fire, all aimed at accomplishing specific management goals, whether determined by public agency personnel or private landowners. Despite the specificity of stated management objectives, a need exists for improved understanding of how these practices affect forest structure and function, species composition, and biodiversity, as well as the potentially interactive effects of different combinations of forest management practices. For example, understory mastication has the potential to alter the occurrence and severity of prescribed fire, but whether it decreases or increases burn severity may vary (Kreye et al. 2014).

Fire exclusion, along with shifting climatic patterns and changing land use, have caused ecosystems to depart from reference conditions (Hanberry et al., 2020; McEwan et al. 2011). For example, oak (*Quercus*) woodlands are an important community type that existed historically throughout the eastern United States but have become increasingly rare, currently occupying a tiny percentage of their extent prior to European settlement (Brewer 2001; Hanberry and Abrams 2018; Hanberry et al. 2014; Nuzzo 1986). Maintained through frequent fire, a key reason for the loss of these communities is the removal of fire as a disturbance agent and the concomitant increase in forest density (Hanberry et al. 2012, 2018; Nowacki and Abrams 2008). Along with this increased densification comes the loss of herbaceous species diversity (Taft 2009; Vander Yacht et al. 2020), wildlife species (Harper et al. 2016; Hunter et al. 2001), and the regeneration of shade-intolerant or midtolerant tree species (Peterson and Reich 2001). The latter process contributes to mesophication (*sensu* Nowacki and Abrams 2008), which in this region is typically dominated by red maple (*Acer rubrum;* Blankenship and Arthur 2006). Because of the biodiversity supported by woodlands, restoration of this community type is increasingly a priority for public land management agencies and conservation organizations (Maynard and Brewer 2013).

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However, the restoration process can be challenging due to widespread development of closed-canopy forests and effects of mesophication that have occurred over the past century in the absence of fire (Hanberry et al. 2014; Nowacki and Abrams 2008). Long-term repeated fire is one tool used to create and maintain oak woodland structure in this region, defined as having an oak-dominated overstory with basal area ranging from 30 to 80 ft^2 ac^{-1} (6.89–18.4 m^2 ha^{-1}; Dey et al. 2017). Acceleration of the restoration process can be accomplished through a combination of management techniques aimed at reducing stem density and basal area while targeting desired species composition (Bragg et al. 2020; Dey et al. 2017; Vander Yacht et al. 2017). Forest thinning and prescribed fire combined have been shown to support oak establishment (Brose et al. 2001; Waldrop et al. 2016) and promote the development of herbaceous and grass species found in fire-maintained open habitats (Brewer et al. 2015).

A review of silvicultural options for management of open forest conditions in the eastern United States notes that although more research is needed, multiple silvicultural approaches used together will typically be required to achieve success (Bragg et al. 2020). Mastication, wherein smaller diameter stems and shrubs are mechanically felled and mulched, has been applied in forest management for at least 50 years (Coates et al. 2020). This management tool has been used to accelerate the development of woodland structure across varied forest ecosystems (Black et al. 2019; Kane et al. 2010) and to reduce ladder fuels (Kreye et al. 2014; Stephens and Moghaddas 2005). Whereas mastication primarily affects midstory stems, the shrub layer may be reduced as well (Bradley et al. 2006; Collins et al. 2007; Waldrop et al. 2016). Felled and mulched material is left in place, where it can alter fire behavior (Kreye et al. 2016).

We examined the interactive effects of mastication and prescribed fire after forest thinning in a management project testing an approach to creating woodland structure from a closed-canopy upland oak forest in eastern Kentucky. In 2003, a region-wide ice storm affected overstory trees on the site, which was followed by a sanitation harvest in 2012–2013. As previously reported (Black et al. 2019), the mastication treatment implemented in 2016 further established the initial desired stand structure for an open oak woodland: canopy openness (basal area 30-80 ft^2 ac^{-1}; 6.89-18.4 m^2 ha^{-1}), virtually absent midstory, and increased herbaceous understory (Dey et al. 2017). The goal of this phase, in which a single prescribed fire treatment was conducted on the same sites, was to examine the interactive effects of prescribed fire and mastication on fuels, burn severity, and stand structure. We hypothesized that greater fuel loading on masticated treatments would lead to higher fire severity than nonmasticated treatments (H1). We also hypothesized that tree mortality due to fire would be minimal on the mastication and burn treatment, where trees up to 7.9 in. (20.1 cm) diameter at breast height (DBH) were felled during mastication, the same size class of trees that are typically killed by prescribed fire in this region (H2; Arthur et al. 2015; Blankenship and Arthur 2006). In contrast, we hypothesized that the burn-only treatment would experience fire-related mortality, especially in stems < 7.9 in. DBH (20.1 cm) (H3). As we expected midstory size classes to be reduced by mastication and burning, we hypothesized that red maple stem density in these size classes would also be reduced in these treatments and that after burning, the control would have higher red maple stem density than the M, MB, and B treatments (H4). We hypothesized that basal sprouting would increase in burn treatments compared with treatments without fire, similar to what we have seen in previous prescribed fire research (H5; Arthur et al. 2015; Blankenship and Arthur 2006). Finally, we hypothesized that crown vigor (measured using crown dieback class) would increase over the course of the study in masticated treatments due to increased resource availability (H6).

Methods

Site Description

Located within the Daniel Boone National Forest (DBNF), the two study sites, Buffalo Branch (38°12'38'' N, -83°21'27'' W) and Spartman (38°15'35'' N, -83°22'24'' W), are geographically located between the Interior Highlands, or Knobs, region and the Cumberland Plateau of eastern Kentucky. Elevation ranges from 800 ft to 1,100 ft (244 to 305 m) above sea level. The area is characterized by broad, level ridges atop rolling hills. Limestone, sandstone, siltstone, and shale parent material from the Mississippian and Pennsylvanian Ages have formed the acidic, loamy Ultisol soils of this area (Patterson et al. 1962; Simpson and Florea 2009). The Buffalo Branch study site covers 9 ac (3.6 ha) and Spartman covers 300 ac (121.4 ha).

Timber damaged during an ice storm in 2003 was removed during a sanitation harvest in 2012–2013. The sanitation harvest reduced basal area from approximately 120 ft^2 ac^{-1} (27.5 m^2 ha^{-1}) to an average basal area of 65.1 ft^2 ac^{-1} (14.9 m^2 ha^{-1}) at Buffalo Branch and 72.4 ft^2 ac^{-1} (16.6 m^2 ha^{-1}) at Spartman on sites with site index of 70 for white oak. After harvest, the dominant overstory trees across the two study sites were white oak (*Quercus alba* L.), scarlet oak (*Q. coccinea* Münchh.), chestnut oak (*Q. montana* Willd.), and red maple, whereas pignut hickory (*Carya glabra* (Mill.) Sweet), mockernut hickory (*Carya tomentosa* [Lam.] Nutt), yellow-poplar (*Liriodendron tulipifera* L.), black oak (*Q. velutina* Lam.), blackgum (*Nyssa sylvatica* Marshall.), sourwood (*Oxydendrum arboreum* [L.] D.C.), and sassafras (*Sassafras albidum* [Nutt.] Nees.) were associate species.

Study Design

In summer 2015, 20 study plots (each 0.1 ac, 37.2 ft radius; 0.04 ha) were established on both the Spartman and Buffalo Branch study sites ($n = 40$). Initially, each study plot was assigned at random to receive no treatment (control, C) or mastication treatment (M), yielding ten plots for each designation on each study site. Prior to field data collection, a few treatment designations were reassigned among plots so that control plots would have sufficiently large borders to protect them from any impacts from mastication. Mastication treatment was applied on ten study plots within each of the two sites in 2016 and targeted midstory stems < 5.0 in. (<12.7 cm) DBH. Mastication was conducted using a tracked excavator style Bobcat machine (model E85) with an extendable arm attached to a rotating masticating head that can orient horizontally or vertically. At the discretion of the equipment operator, selected stems up to 7.9 in. DBH (20.1 cm) were approved for mastication for stand improvement. The mastication treatment resulted in an 84% reduction of stems < 5.0 in. DBH (<12.7 cm DBH) and a 32% reduction of stems 5–7.9 in. (12.7–20.1 cm) DBH and decreased total basal area (all stems ≥ 2 in.; ≥5.08 cm DBH) compared with pretreatment basal area on treated plots. Mastication increased 1 h (0–0.25 in.; <0.635 cm diameter) and 100 h (1–3 in.; 2.5–7.6 cm diameter) fuels compared with untreated plots (Black et al. 2019). After the mastication treatment, half of the control plots were selected as burn (B) plots and half of the mastication plots (M) were selected as mastication plus burn (MB) plots, resulting in five plots of each treatment or treatment combination (C, M, B, or MB) per study site.

Prescribed Fire

Both sites were burned on April 11, 2018, following established prescription parameters (USDA Forest Service 2015). USDA Forest Service personnel implemented prescribed fire using multiple small burns around one or more plots, ignited using drip torches. Before the burn, eight pyrometers made from aluminum tags painted with seven Tempilac temperature-sensitive paints (174°F [79°C], 325°F [163°C], 475°F [246°C], 601°F [316°C], 750°F [399°C], 900°F [482°C], and 950°F [510°C]) were installed in each B and MB plot (at 20 ft [6.1 m] and 45 ft [14 m] from plot center along 45°, 135°, 225°, and 315° lines; $n = 80$). Each pyrometer consisted of three painted tags wrapped in a single layer of aluminum foil (melting point 1,220°F [660°C]) attached to a pin flag at three heights above the forest floor: 1.2 in. (3 cm), 7.9 in. (20 cm), and 15.7 in. (40 cm). On the day of the burn, daytime air temperature ranged from 47°F to 67°F (8°C–19°C). Relative humidity at the time of ignition was 53%, dropped to 29% midday, and had recovered to 39% by completion of the burns; wind speeds ranged from 3 to 5 mph (4.8–8 kph) with gusts 6–10 mph (9.7–16.1 kph) throughout the burn period. The sites are quite flat, so there was little to no slope-driven fire behavior. Observed fire behavior was a backing fire with some flanking, with rates of spread ranging from 2.4 ft min^{-1} (0.73 m min^{-1}) to 3 ft min^{-1} (0.91 m min^{-1}) and flame lengths 0.5 to 3 ft (0.15 to 0.91 m).

Data Collection

Fuels data were collected using protocols described in Black et al. (2019) in June 2016, after the winter 2016 mastication and before implementation of the prescribed fire treatment, in February–March 2018. Woody fuels on C and B plots were measured using the planar intercept method (Brown 1974) along three 50 ft (15 m) transects (45°, 225°, and 315°). On each transect 1 h (<0.25 in.), 10 h (0.025 - 1 in.), and 100 h (1-3 in.) fuels (<0.635 cm, 0.635–2.54 cm, and 2.54–7.62 cm, respectively) were tallied along a 12 ft (3.7 m) transect segment; 1,000 h (3–8 in. diameter; 7.62–20.32 cm) fuels were tallied along the entire 50 ft (15.2-m) fuels transect. On all mastication plots (M and MB), woody fuels were measured using a hybrid sampling method (Black et al. 2019; Kane et al. 2009). The 1 h and 10 h fuel data were collected using a plot-based sampling method in which all woody fuels falling within those timelag size classes were removed from three 10.8 ft^2 (1 m^2) sampling areas, and larger 100 h and 1,000 h fuels were tallied using the same planar intercept methods described for C and B plots. Depths of litter, duff, and masticated materials (where applicable) were taken at 5 ft (1.5 m) increments along the three 50 ft (15.2 m) fuels transects for all plots. Additionally, leaf litter and duff samples were collected from all plots in two 10.8 ft^2 (1 m^2) sampling areas per plot. All collected samples were sorted into 1 h and 10 h size classes, oven-dried at 60°C to constant mass, and weighed.

Immediately following fire treatment, pyrometers were examined to determine the paint-based temperature exceeded, which was recorded for each plot-transect-position combination. The temperature-exceeded reading conveyed the fire temperature was at least as hot as the number recorded or it exceeded that temperature, but the next highest temperature (based on paint temperature sensitivity) was not reached.

In April 2018, two weeks after the prescribed burn, all fuels measurements were repeated for the B and MB treatments. Also, on MB plots, all 1 and 10 h woody fuels were tallied (in addition to plot-based sampling) along transect lines to enable more direct comparisons with C and B plots. Burn severity data were collected along each fuels transect at 5 ft (1.5 m) increments, where a degree of damage (0–5; where 5 = unburned, 4 = scorched, 3 = lightly burned, 2 = moderately burned, 1 = heavily burned, and 0 = not applicable) was assigned to each location according to Fire Service burn severity rating protocols. Values were averaged for each transect. For 1,000 h fuels intersecting the transect, the proportion of wood consumed (%) and the presence of heavy char were noted. Additionally, any burn damage to trees was noted on burn plots (B and MB). A composite burn index (CBI) score was computed from these burn severity measurements for each burn plot using a CBI scoring rubric (Key and Benson 2006).

We measured stand data in 2015 before mastication, after mastication in 2016, and after burning in 2018. For all stems ≥ 2.0 in. DBH (5.1 cm DBH), we recorded species, DBH, crown dieback class, and number of sprouts. Crown dieback was assessed using a live crown ratio on a scale of 1 to 3, with 1 = >50% dieback, 2 = 25%–50% dieback, and 3 = <25% dieback; "0" was recorded for dead trees. We measured char height on all trees at the highest point of char on the tree bole after burning.

Statistical Analyses

We investigated differences in fuel availability, fire severity (based on CBI), and stand structure among treatments and sampling dates. For fuel availability, we compared responses with four different groups of sampling dates: (1) All time periods (2016, 2018 preburn, and 2018 postburn), (2) 2016 to 2018 preburn, (3) 2018 preburn to 2018 postburn, and (4) 2018 postburn treatment differences (Table 1). We collected fuel data in all treatments during the 2016 and 2018 preburn sampling dates. Only the B and MB treatments were surveyed during the 2018 postburn sampling date. Litter mass and duff mass were not collected in 2016; therefore, for these variables, we only compared 2018 preburn and postburn measurements. Plot-based fuel measurements (for M and MB plots) were analyzed separately from transect-based fuel measurements. Fire temperatures measured with paint tags were averaged for each plot at each paint tag height for analysis ($n = 5$ for each treatment).

We fit linear mixed effects models with a random effect for plot nested within site for all models except for fire temperature data, for which plot-level measurements were composited by plot (Zuur et al. 2009). Fixed effects for models with > 1 treatment and > 1 sampling date included treatment, sampling date, site, and an interaction between treatment and sampling date (Table 1). Models with only one treatment included fixed

Table 1. All response variables, sampling dates, and fixed and random effects in the statistical analyses for mastication and prescribed fire treatments in the Daniel Boone National Forest, Kentucky. Those that were conducted are marked with a "X." Fuels sampling dates included 2016, 2018 preburn, and 2018 postburn. Stand structure sampling dates included 2015, 2016, and 2018 postburn.

	Treatment					Fixed effects				Random effect
Response variables	Control	Burn	Mastication	Mast/Burn	Sample dates	Trt	Sample	Trt:Sample	Site	Site/Plot[1]
100 h fuels 1,000 h fuels Litter depth Duff depth	X	X	X	X	2016 2018 preburn	X	X	X	X	X
100 h fuels 1,000 h fuels Litter depth Duff depth		X		X	2016 2018 preburn 2018 postburn	X	X	X	X	X
Litter mass Duff mass	X	X	X	X	2018 preburn	X			X	X
Litter mass Duff mass		X		X	2018 preburn 2018 postburn	X	X	X	X	X
Plot-based 1 h, 10 h fuels			X	X	2016 2018 preburn	X	X	X	X	X
Plot-based 1 h, 10 h fuels				X	2016 2018 preburn 2018 postburn		X		X	X
Transect-based 1 h, 10 h fuels	X	X			2016 2018 preburn	X	X	X	X	X
Transect-based 1 h, 10 hr fuels		X		X	2018 postburn	X			X	X
Transect-based 1 h, 10 hr fuels		X			2016 2018 preburn 2018 postburn		X		X	X
CBI Flame temp Char height		X		X	2018 postburn	X			X	
Crown dieback class	X	X	X	X	2015 2016 2018	X	X	X	X[2]	X[3]
Density Basal area Relative density Relative BA Sprouts stem^{-1}	X	X	X	X	2015 2016 2018	X	X	X	X	X

[1]Random effect of plot nested within site.
[2]Crown dieback class included species group (oak, red maple, other) as a fixed effect.
[3]Crown dieback class included a random effect of plot, which was not nested within site.

effects for sampling date and site (Table 1). Models with only one sampling date included fixed effects for treatment and site (Table 1). Paint tag data did not have a random effect in the model due to only one data point for each plot. We fit these models in JMP Pro 14.0 (JMP 2019) and checked for nonnormal residuals in all models. Any response variables with residuals that did not meet assumptions of normality were transformed using log or square root transformations to achieve or approach normality. We refit the models using the transformed data. We tested for significant differences among treatment × sampling date pairs (or among treatments or sampling dates individually if both terms were not present in the model) using a Tukey HSD all pairwise comparisons test with an α of 0.05.

We used linear mixed effects models to investigate the effect of fuel loading on CBI. CBI was the response variable and random effects were plot nested in sites. We fit one model for both the burn and mastication and burn plots: site + sum (preburn litter mass, 1 h, 10 h fuels). We fit one model for the burn plots: site + sum (preburn litter mass, 1 h, 10 h, 100 h fuels). Finally, we fit one model for the mastication and burn plots: site + sum (preburn litter mass, 1 h, 10 h fuels, mastication mass). We modeled MB plots separately from the B plots because of the differences in the types of fuels and how they were measured.

To assess changes in stand structure and species composition from 2016 to 2018, trees were separated into three diameter classes for analyses: small midstory (2.0–4.9 in. DBH; 5.1–12.6 cm DBH), large midstory (5.0–7.9 in. DBH; 12.7–20.1 cm DBH) and canopy (≥8.0 in. DBH; ≥20.2 cm DBH). We compared mean total density, basal area, and sprouts per stem for all size classes as well as relative density and relative basal area of oak species (all species combined) and red maple.

We used cumulative link mixed models for crown dieback class, which was an ordered response with 1 = >50% dieback, 2 = 25%–50% dieback, and 3 = <25% dieback. We fit this model with the ordinal package in R version 4.0.3 (Christensen 2019; R Core Team 2020). The model could not include site as a random effect as there were only two levels, and random effects with only two levels (our two sites) cannot be used in this model; therefore, plot was used as the only random effect. Fixed effects were treatment, sampling date, site, species group (oak, red maple, or other) and an interaction between treatment and sampling date. We checked for model convergence; if the original model did not converge, then we simplified the model by removing interactions, random effects, or covariates until convergence was attained. We tested for significant differences among fixed effects using a Tukey HSD all pairwise comparisons test with an α of 0.05 in the *emmeans* package in R (Lenth 2019; R Core Team 2020).

Results

Fuel Changes After Mastication and Before Prescribed Fire

Mastication generally resulted in increased fuel mass, but those differences declined between 2016 and preburn 2018 measurements. Mastication of stems < 7.9 in. DBH (20.1 cm) led to initially high volume and mass of woody material on the forest floor and greater duff depth (Figure 1). To investigate how or whether mastication altered the fuel bed, we examined changes in masticated fuels through time and between treatments, leading up to prescribed burning. Fuel loading of fine fuels (1 and 10 h fuels) was not directly compared between masticated and nonmasticated treatments due to differences in the way fuels were measured to accommodate the very different fuel beds created by mastication.

In 2016, duff depth, 1 h fuels and 100 h fuels were greater in mastication treatments (M and MB) than in treatments that were not masticated (C and B; Black et al. 2019). Mastication did not affect litter depth or 10 h fuels; mastication treatments had lower 1,000 h fuels than the control (Black et al. 2019). Litter depth averaged 0.72 in. (1.8 cm) on nonmasticated treatments compared with 0.85 in. (2.2 cm) on mastication treatments (Figure 1A). Duff depth on nonmasticated treatments averaged 0.45 in. (1.1 cm), lower than masticated duff depth, which averaged 0.87 in. (2.2 cm, Figure 1C). Differences in fuel loading in nonmasticated compared with mastication treatments in 2016 were highly variable, with lower mass of 1 h and 100 h fuels in nonmasticated treatments but the reverse trend for 10 h and 1,000 h fuels (Figures 2 and 3).

The initial differences in duff depth between non masticated and mastication treatments (measured in 2016) had declined by preburn 2018 measurements (Figure 1C). Duff depth on C and B treatments remained similar between 2016 and preburn 2018, whereas on mastication treatments, it decreased significantly from 2016 to preburn 2018 ($p_M < 0.0001$; $p_{MB} = 0.0002$; Figure 1C). In preburn 2018 measurements, duff depth on MB was significantly lower than on C treatment ($p = 0.038$) and similar to B and M ($p = 0.918$; Figure 1C). Duff mass was similar across treatments in preburn 2018 (Figure 1D; duff mass was not measured in 2016).

We found no differences in litter depth and mass among treatments preburn 2018 (Figures 1A and 1B). Litter depth and mass had a different trend from that of duff. Litter depth measured preburn in 2018 was significantly greater than litter depth measured in summer 2016 in every treatment ($p_C < 0.0001$; $p_B < 0.0001$; $p_M = 0.013$; $p_{MB} = 0.0005$; Figure 1A); the timing of the sampling also differed, from June 2016, after the mastication treatment was complete, to February–March in 2018, before the April 2018 prescribed burning. Depth ($p < 0.0001$; Figure 1E) and mass of masticated materials decreased significantly on both M and MB treatments from 2016 to preburn 2018 ($p_M < 0.0001$; $p_{MB} = 0.014$; Figure 1F).

Due to sampling differences necessitated by different fuel materials, we could only compare 1 h and 10 h fuels on the B and C treatments to each other and M and MB to each other in 2016 and preburn 2018. In 2016, we found no differences in 1 h and 10 h fuels between B and C or between M and MB (Figures 2A and 2B). In preburn 2018, we found no difference between B and C, but preburn M 1 h fuels were significantly lower than the preburn MB 1 h fuels ($p = 0.043$). The 1 h fuels decreased significantly from 2016 to 2018 preburn measurements on all treatments ($p_C = 0.010$, $p_B = 0.0013$, $p_M < 0.0001$, $p_{MB} < 0.0001$; Figure 2A). Although we could not test it directly, 1 h fuels decreased much more on masticated (79%) than nonmasticated treatments (35%; Figure 2A). The 10 h fuels also decreased significantly on the M treatment ($p = 0.0003$) between 2016 and preburn 2018, whereas these larger fuels were unchanged during this period on the other treatments ($p_C = 0.71$, $p_B = 0.99$, $p_{MB} = 0.18$; Figure 2B). Despite the significant decline in 10 h fuels on the M treatment but not the MB, these fuels on M and MB were not significantly different preburn 2018 (Figure 2B). Between 2016 and preburn 2018, 100 h fuels did not change significantly for any treatment (Figure 3A). Nonsignificant decreases in 100 h fuels on mastication treatments led to similar preburn 2018 measurements on all treatments (Figure 3A). The 1,000 h fuels increased on the MB treatment from 2016 to preburn 2018 ($p = 0.008$) but remained significantly lower than C ($p = 0.045$) and B ($p = 0.006$) preburn 2018 (Figure 3B).

Prescribed Fire

The prescribed fires were low intensity and burned similarly across sites and treatments. Mean minimum fire temperatures recorded were highest closest to the soil surface and ranged from 93°F to 819°F (34°C to 437°C) at 3.2 in. (8 cm), from 74°F to 682°F (24°C to 361°C) at 9.8 in. (25 cm), and from 60°F to 469°F (16°C to 243 °C) at 17 in. (43 cm) height above the surface. Fire severity was also low. The CBI was within the low intensity CBI category (> 0 to < 1.5) for both treatments across sites (Table 2). We found no significant differences between treatments or sites for CBI or fire temperatures at any height (Table 2). We also found no significant differences in char height between treatments or between sites. Char height averaged 7.68 in. (19.5 cm) on the B treatment and 7.73 in. (19.6 cm) on the MB treatment.

Fire and Fuels

We found no significant relationships between any of the measures of fuel loading on either MB or B treatments (analyzed separately due to different fuel measures) and CBI, fire temperature, or char height. In contrast, fuel consumption

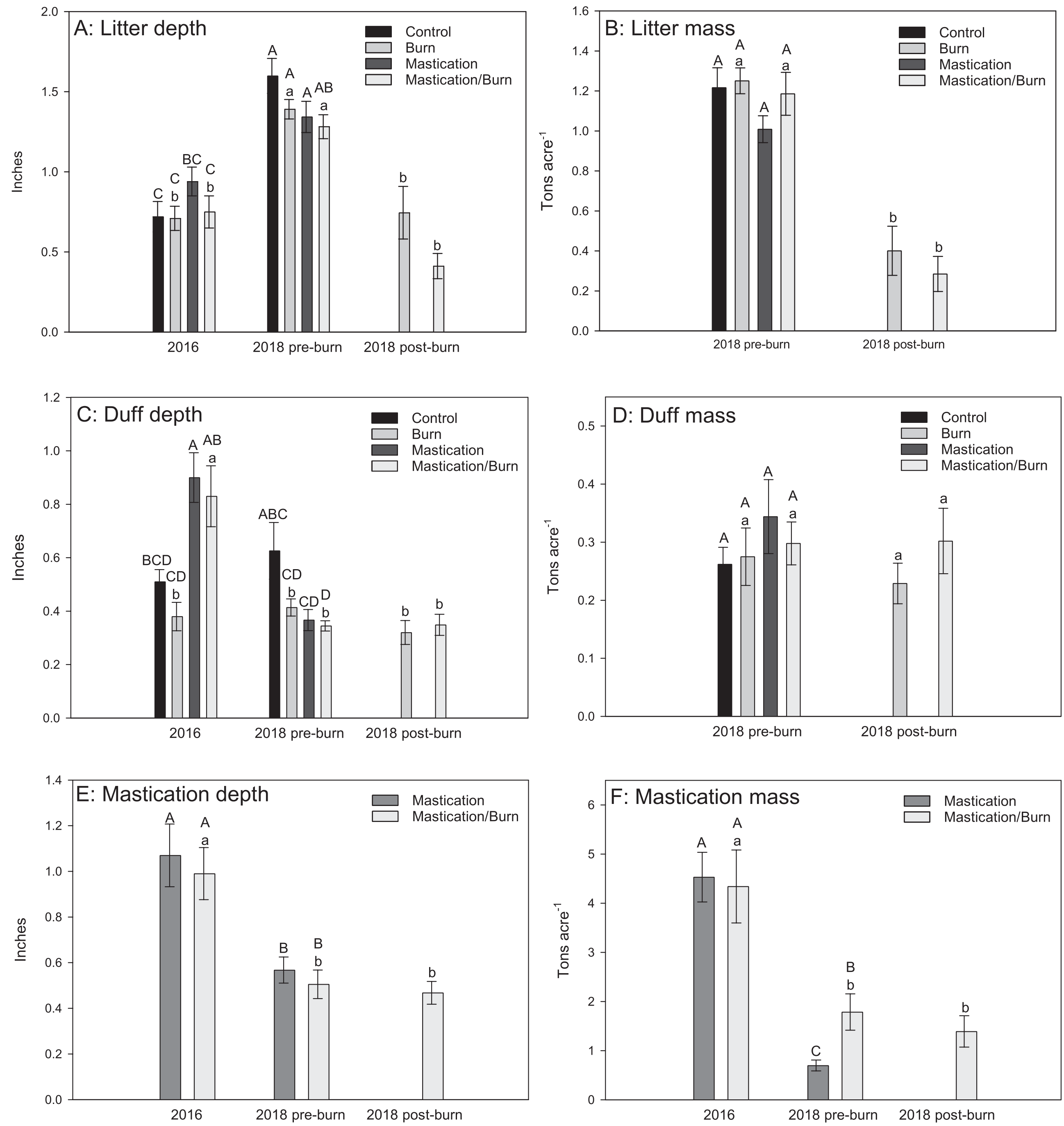

Figure 1. A: Litter depth (in.), B: litter mass (tons ac^{-1}), C: duff depth (in.), D: duff mass (tons ac^{-1}), E: masticated depth (in.), and F: masticated mass (tons ac^{-1}) as measured postmastication in 2016 and before and after 2018 prescribed fire in the Daniel Boone National Forest, Kentucky. Different uppercase letters indicate significant differences at α = 0.05 for model comparing all treatments between 2016 and 2018 preburn. Different lowercase letters indicate significant differences for model comparing burn and mastication/burn treatments across all dates (2016, 2018 preburn, and 2018 postburn). Error bars are ± 1 standard error of the mean.

varied between MB and B treatments. Fire consumed significant amounts of 1 h fuels on the B treatment ($p < 0.0001$) and these postburn 1 h fuels were significantly lower than in 2016 ($p < 0.0001$; Figure 2A). In contrast, fire did not significantly alter 1 h fuels on MB, and postburn 1 h fuel on MB remained significantly lower than in 2016 ($p = 0.0006$). Fire significantly reduced 10 h fuels on both B ($p < 0.0001$) and MB treatments ($p = 0.014$; Figure 2B). For 1 h and 10 h fuels, site was significantly different in all models of analysis, with Buffalo Branch having higher fuel mass than Spartman. Fire significantly reduced 100 h fuels on the B treatment ($p = 0.044$), but not on MB ($p = 0.45$). The prescribed burns had no effect on 1,000 h fuels for either treatment, but B had significantly more 1,000 h fuels than MB preburn ($p = 0.006$) and postburn ($p = 0.006$; Figure 3B).

Fire also decreased litter depth ($p_B = 0.001$, $p_{MB} < 0.0001$; Figure 1A) and litter mass on both B and MB treatments ($p < 0.0001$ for both; Figure 1B) such that postburn litter

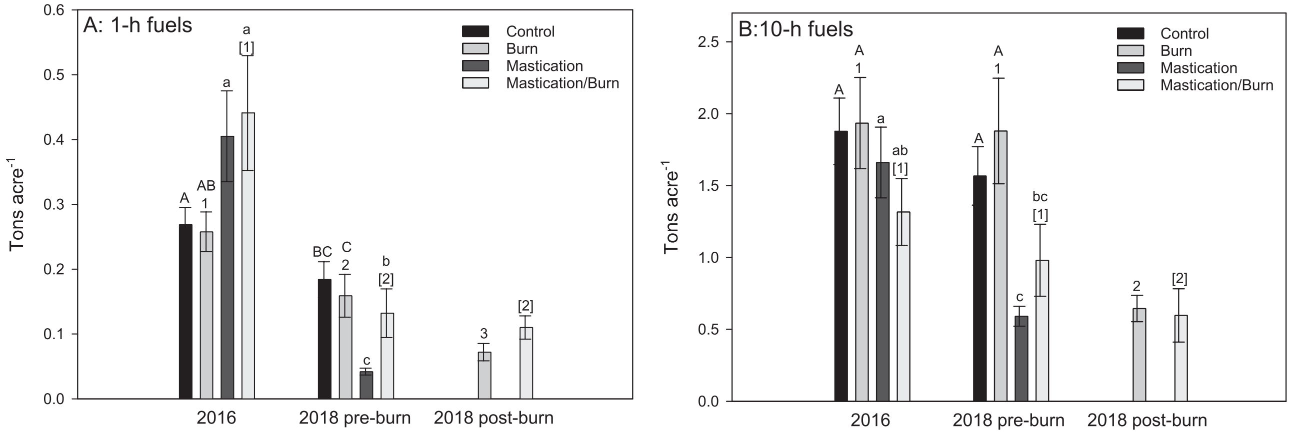

Figure 2. A: 1 h and B: 10 h fuels (tons ac-1) measured postmastication in 2016 and before and after 2018 prescribed fire in the Daniel Boone National Forest, Kentucky. Different uppercase letters indicate significant differences at α = 0.05 for model comparing control and burn treatments for the 2016 and 2018 preburn sampling dates. Different lowercase letters indicate significant differences for model comparing mastication and mastication/burn treatments for the 2016 and 2018 preburn sampling dates. Different numbers without brackets indicate significant differences for model comparing all three sampling dates for the burn treatment. Different numbers in brackets indicate significant differences for model comparing all three sampling dates for the mastication/burn treatment. Error bars are ± 1 standard error of the mean.

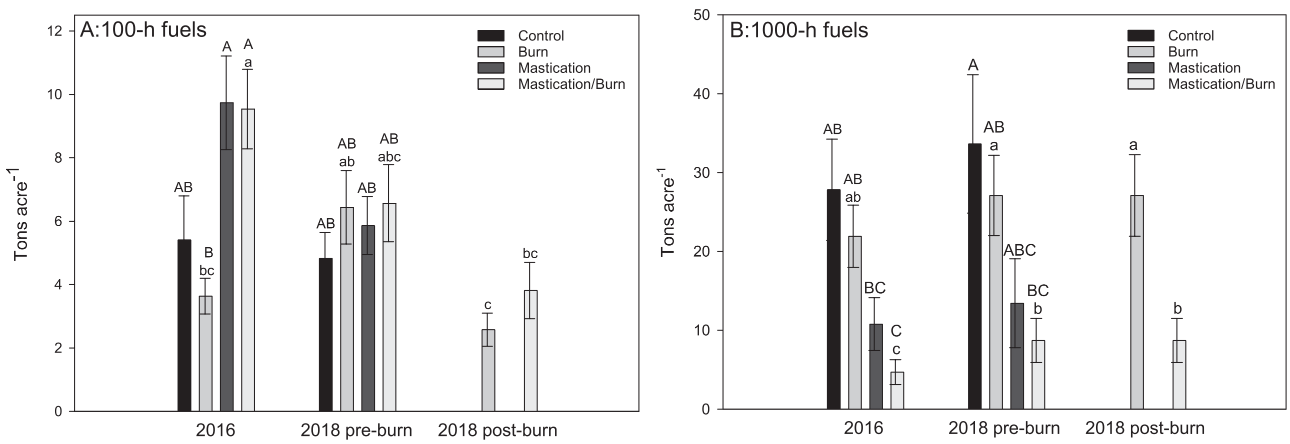

Figure 3. A: 100 h and B: 1,000 h (tons ac-1) fuel loads as measured postmastication in 2016 and before and after 2018 prescribed fire in the Daniel Boone National Forest, Kentucky. Different uppercase letters indicate significant differences at α = 0.05 for model comparing all treatments for 2016 and 2018 preburn sample dates. Different lowercase letters indicate significant differences for model comparing burn and mastication/burn treatments for all sample dates (2016, 2018 preburn, and 2018 postburn). Error bars are ± 1 standard error of the mean.

Table 2. Mean minimum fire temperatures as measured with Tempilac paints and mean composite burn index (CBI) for B and MB treatments in Buffalo Branch and Spartman sites, Daniel Boone National Forest, Kentucky.

Site	Treatment	Mean fire temp 3.2 in. (8 cm)	Mean fire temp 9.8 in. (25 cm)	Mean fire temp 17 in. (43 cm)	Mean CBI
Buffalo Branch	B	453°F (234°C)	252°F (122°C)	156°F (68.9°C)	0.349
Spartman	B	657°F (347°C)	370°F (188°C)	246°F (119°C)	0.444
Mean B	B	556°F (291°C)	311°F (155°C)	201°F (94°C)	0.396
Buffalo Branch	MB	619°F (326°C)	367°F (186°C)	235°F (113°C)	0.339
Spartman	MB	612°F (322°C)	311°F (155°C)	244°F (118°C)	0.281
Mean MB	MB	615°F (324°C)	340°F (171°C)	241°F (116°C)	0.310
Mean Buffalo Branch	B and MB	536°F (280°C)	309°F (154°C)	196°F (91.0°C)	0.344
Mean Spartman	B and MB	635°F (335°C)	340°F (171°C)	246°F (119°C)	0.362

depth was similar to that measured in 2016. The prescribed fires did not alter duff depth or duff mass (Figure 1C, 1D). There were no significant changes in depth or mass of masticated material with fire (Figure 1E, 1F).

Stand Structure

Mastication reduced midstory stem density and basal area (as previously reported in Black et al. 2019), but fire had no additional measurable effects on stand structure in the

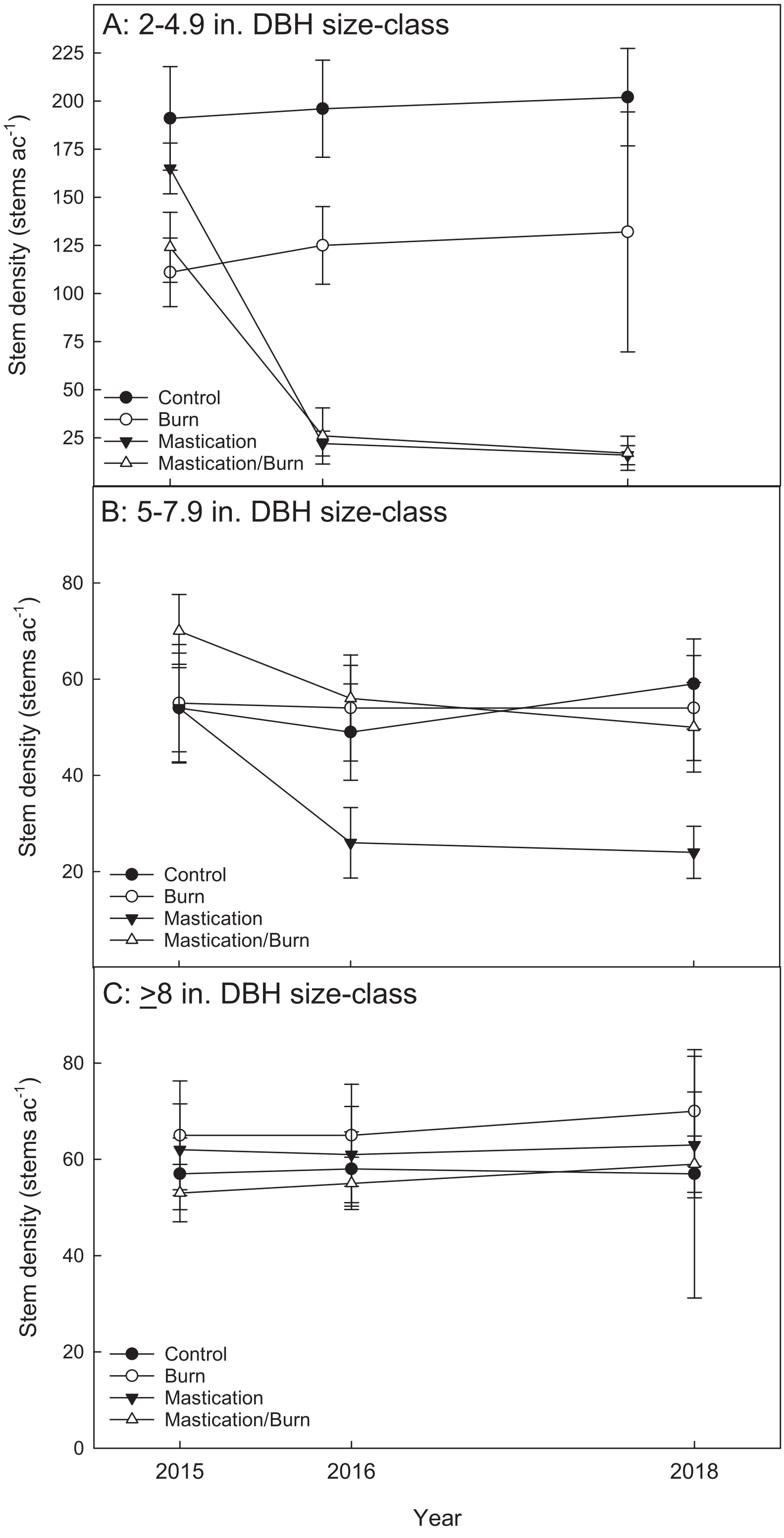

Figure 4. Stem density (stems ac-1) for all treatments in all size classes. A: 2–4.9 in. DBH size-class, B: 5–7.9 in. DBH size-class, and C: ≥8 in. DBH size-class in the Daniel Boone National Forest, Kentucky. Measurements were made in 2015 prior to any treatment, in 2016 after mastication, and in 2018 after prescribed fire. Error bars are ± 1 standard error of the mean.

mastication treatment. From 2015 to 2016, density of small midstory stems (2–4.9 in. DBH; 5.1–12.6 cm DBH) on the M and MB treatments decreased significantly (87% and 79%, $p < 0.0001$; Figure 4A, Table S1). Mastication also reduced large (5–7.9 in. DBH; 12.7–20.1 cm DBH) midstory stem density significantly on the M treatment (52% from 2015 to 2016, $p = 0.004$; 56% from 2015 to 2018, $p = 0.002$) but not significantly on the MB treatment (20%, $p = 0.87$; Figure 4B, Table S1). The M and MB treatments had significantly lower small midstory stem density than the C and

B treatments in 2016 ($p < 0.0001$) and postburn in 2018 ($p < 0.0001$). Basal area followed the same pattern (Table S1). No effect of fire was measured on these size classes. Stand structure in the B treatment did not differ from C either before or after prescribed fire for any size class nor did any size class significantly change on the B treatment over time.

We also investigated whether treatment affected absolute and relative stem density and basal area of red maple and oaks. Mastication reduced small midstory red maple stems but fire alone did not (Table S3). Small midstory red maple stem density was reduced on M and MB treatments from 2015 to 2016 (86% and 73%, respectively; $p < 0.0001$) and into 2018 (90% and 86%, respectively; $p < 0.0001$; Table S3). Basal area of small midstory red maple also decreased significantly on M and MB treatments following mastication (83%, $p < 0.0001$; 65%, $p = 0.0007$) and in 2018 (88%, $p < 0.0001$ for both treatments; Table S3). Small midstory red maple density and basal area did not change on the control and in 2016 and 2018 was significantly higher on C (2018: 103 stems ac^{-1}; 255 stems ha^{-1}) than on M (8.0 stems ac^{-1}; 19.8 stems ha^{-1}; $p < 0.0001$) and MB (6.0 stems ac^{-1}; 14.8 stems ha^{-1}; $p < 0.0001$; Table S3). We measured no changes in large midstory red maple density and basal area (Table S3). Small midstory oak stem density and basal area also declined significantly following mastication on the MB treatment (2015–2016, 68%, $p = 0.012$; 2015–2018, 84%, $p = 0.005$; BA 69%, $p = 0.006$; 81%, $p = 0.002$; Table S5). Similarly, we measured a 100% loss of small midstory oak stems on the M treatment following mastication but with initial low stem density (4 stems ac^{-1}; 9.9 stems ha^{-1}), the change was statistically nonsignificant. On the M treatment, large midstory oak density decreased 79% and basal area decreased 74% from 2015 to 2018 ($p = 0.0008$ and $p = 0.007$; Table S5). Much of this change was the result of large midstory stems growing into the overstory size class. We found no differences among treatments for midstory oak density and basal area.

Relative density of small midstory red maple stems decreased significantly on the MB treatment from 2015 to 2018 (from 42% to 13%; $p = 0.002$), and in 2018 was significantly less than the C treatment (13% vs. 52%; $p = 0.01$; Figure 5A). Relative basal area of small midstory red maple stems also decreased significantly on both M and MB treatments following mastication (52% to 26%; $p = 0.006$; 40% to 22%; $p = 0.030$) and remained lower in 2018 (27%, $p = 0.010$; 8.2%; $p < 0.0001$). We measured no changes in small midstory oak relative density but relative basal area decreased significantly on the MB treatment following mastication (from 22% to 11%; $p = 0.045$) and into 2018 (9.5%; $p = 0.035$). Relative density of large midstory oaks decreased significantly from 2015 to 2018 on the M treatment (26% to 7.8%, $p = 0.025$) as well as relative basal area for the same time period (28% to 8.4%; $p = 0.025$; Figure 5B).

Mastication and burn treatments had no effect on stem density or basal area in the canopy size class (Figure 4C), but canopy basal area across all treatments in 2018 (52.3 ft^2 ac^{-1}; 12.0 m^2 ha^{-1}) was significantly greater than in 2016 (47.3 ft^2 ac^{-1}; 10.9 m^2 ha^{-1}; $p = 0.004$) and 2015 (46.7 ft^2 ac^{-1}; 10.7 m^2 ha^{-1}; $p = 0.002$; Table S2). Overall, canopy red maple density and basal area were higher on Spartman (15.5 stems ac^{-1}; 38.3 stems ha^{-1} and 8.34 ft^2 ac^{-1}; 1.91 m^2 ha^{-1}) than on Buffalo Branch (5.0 stems ac^{-1}; 12 stems ha^{-1} and 2.95 ft^2 ac^{-1}; 0.677 m^2 ha^{-1}; $p = 0.01$ for both). Canopy oak basal area increased significantly across all treatments from 2016 (35.5 ft^2 ac^{-1}; 8.15 m^2 ha^{-1}) to 2018 (41.0 ft^2 ac^{-1}; 9.41 m^2 ha^{-1}; $p = 0.033$). Treatment did not change relative density and basal area for red maple and oaks in the canopy size class (Figure 5C; Tables S4 and S6).

Crown vigor as measured by crown dieback class increased (less dieback) over time regardless of treatment. We were not able to test for an interaction between treatment and sampling date for crown vigor in canopy and small midstory trees as models with the interaction did not converge. Treatment and sample date were included as additive terms instead for these two models. Crown vigor in canopy trees was higher in 2018 than in 2015 or 2016 ($p < 0.0001$ for both comparisons). No differences among treatments, sites, or species groups were seen for crown vigor among canopy trees.

Crown vigor varied among sampling dates for large midstory trees. Crown vigor of large midstory trees in all treatments increased between 2015 and 2018 ($p_B = 0.013$, $p_M = 0.0096$, $p_{MB} = 0.0002$, $p_C = 0.008$). In the MB treatment, crown vigor also increased from 2015 to 2016 ($p = 0.0199$). Crown vigor in large midstory trees was higher at Spartman than Buffalo Branch ($p = 0.028$). There were no differences among treatments during any sampling date or among species groups.

Crown vigor increased over time in small midstory trees as well, with lower crown vigor in 2015 than 2016 ($p = 0.006$) or 2018 ($p < 0.0001$) and lower crown vigor in 2016 than

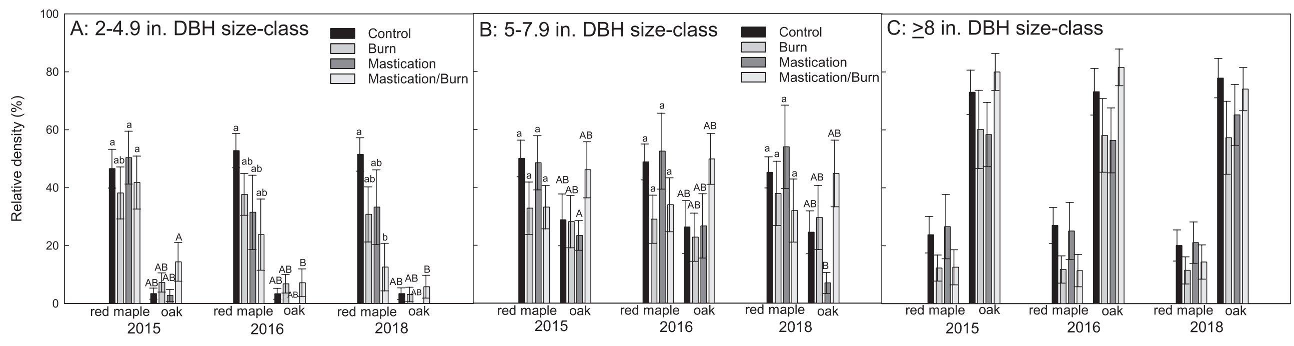

Figure 5. Relative density (%) for red maple and oak species on all treatments in all size-classes in the Daniel Boone National Forest, Kentucky. Measurements were made in 2015 before any treatment, in 2016 after mastication, and in 2018 after prescribed fire. Lower case letters indicate significant differences at α = 0.05 among treatments for red maple. Upper case letters indicate significant differences among treatments for oaks. No significant differences were found for canopy size relative densities. Error bars are ± 1 standard error of the mean.

2018 ($p < 0.0001$). No differences among treatments, sites, or species groups were observed. We found no treatment effect on sprouting response of trees in any size class.

Discussion

The oak-dominated ecosystems common throughout the eastern deciduous and central Appalachian hardwood regions vary in structure and canopy openness, ranging from closed-canopy forests to woodlands (Johnson et al. 2009). In the last century, a suite of factors, including agricultural conversion, forest harvesting, cessation of burning, and shifting climate, have led to increasingly closed-canopy structure, with attendant loss of biodiversity and community diversity (McEwan et al. 2011). Oak woodlands, once much more common across these regions, were maintained by periodic disturbance, such as fire that disrupts the development of a midstory stratum, coupled with canopy disturbances, such as wind and ice storm events (Dey et al. 2014; Ryan et al. 2013). The loss of oak woodlands and the associated biodiversity has led forest managers to develop methods for creating woodland structure through silvicultural prescriptions that include prescribed fire, harvesting, and thinning (Clark and Schweitzer 2016; Dey et al. 2014).

Mastication is used in forest systems globally, alone or in combination with harvesting or prescribed fire, to achieve a range of management goals including alteration of forest structure, reduction of hazardous fuels, and ecological restoration (Kane et al. 2010; Kreye et al. 2014; Reemts and Cimprich 2014). Despite its increased use, the effects of mastication on ecological function, fuels, fire behavior, forest structure, and species composition have not been fully elucidated (Coates et al. 2020; Glitzenstein et al. 2006). Although mastication has been used extensively in the western United States, in eastern forests, it has been used for reducing wildfire severity (Kreye and Kobziar 2015), promoting pinelands (Brockway et al 2009), and to alter forest structure to accelerate oak woodland restoration (Black et al. 2019).

This study originated with an ice storm that created the initial conditions on the landscape upon which managers saw potential for creating woodland structure through additional disturbance. Essentially, this study incorporates natural disturbance (ice storm), forest harvesting (sanitation harvest), forest thinning (via mastication), and prescribed fire to test several hypotheses regarding the effectiveness of these strategies for creating and maintaining woodland structure. Here, we focused on the effects of prescribed burning both with and without mastication, to follow up on our previous work examining mastication effects on woodland structure development.

One potential concern with mastication beyond its higher cost relative to prescribed fire alone (Coates et al. 2020) and potential for introduction of invasive species (Black et al. 2019) is that it may increase fire severity. In this study, the fire treatment was applied two years after mastication because the masticated fuels were too wet to burn and because masticated woody fuels covered the litter layer. Since it is the litter that carries fire in these ecosystems (Arthur et al. 2017; Loucks et al. 2008), it was important to wait until there was a continuous litter layer before burning. As noted previously (Black et al. 2019), mastication greatly increased fuel loading initially, but significant declines in masticated fuels over the two years between mastication and prescribed fire led to reductions in masticated fuel mass and depth. Because of minimal differences in fuel loading between treatments at the time of prescribed burning, we found no differences in fire severity between MB and B treatments, contradictory to our first hypothesis (H1). The decline in fuels on mastication treatments was likely due to rapid decomposition rates in this region and the two-year lag period between treatments.

Fire had no effect on stand structure regardless of treatment. We hypothesized (H2) that tree mortality following prescribed fire would be minimal on the mastication (MB) treatment. Trees ≤ 7.9 in. (20.1 cm) DBH, which were felled during the mastication treatment (Black et al. 2019), are also the size class of trees typically most affected by prescribed fire in this region (Arthur et al. 2015; Blankenship and Arthur 2006); rarely are trees larger than this size killed by prescribed fire. As hypothesized, we found no additional tree mortality following burning on the MB treatment. However, we also found no mortality of stems in any size class on the B treatment (Figure 4), a surprising result given a single fire in upland oak forests in this region generally leads to significant mortality of stems ≤ 7.9 in. (20.1 cm). This finding is contrary to hypothesis H3; we expected mortality in trees in ≤ 7.9 (20.1 cm) DBH would occur in the B treatment, where small stems were still present. The lack of tree mortality in the B treatment may be due to low-severity fire across all sites regardless of mastication treatment and tied more to the flat topography and burn conditions than to the fuels. This finding points to the need for additional research, as noted by Kreye et al. (2014).

We hypothesized that mastication (M and MB) and burning (MB and B) would reduce small and large midstory red maple stems compared to the C treatment (H4). Contrary to this, we measured no fire-related mortality and midstory red maple stems did not change on the B treatment (Table S3). Partially supporting H4, mastication significantly reduced red maple small midstory stems (M and MB; Table S3). In 2018, the control had significantly more small midstory red maple than the M or MB, but B remained unchanged and not significantly different from other treatments; in 2015, it was similar across treatments. Among large midstory stems, red maple stem density and basal area did not change in any treatment (Table S3). In addition, the relative basal area of large midstory oaks declined from 2015 to 2018 on the M treatment (data not shown), despite the absence of changes to red maple relative density (Figure 5) or basal area (data not shown). However, rather than this finding being the result of oaks losing ground in this treatment, this outcome was the result of numerous large midstory oak stems growing into the canopy size class between 2016 and 2018 (Table S6). Shifts in relative density (Figure 5C) and basal area (data not shown) in canopy stems were not significant, however. This continued in-growth of red maple stems is an important finding, as it signals what is occurring across the region in the absence of fire or other disturbance. For example, we found a significant increase in midstory red maple stem density in the absence of fire treatment in a nearby study site (Winkenbach 2020). The trend toward increasing red maple midstory stems and static density of oaks on the C treatment suggests this is likely occurring on our study sites but will not be statistically detectable until more time has passed.

We also measured a very low rate of postfire sprouting compared to that found in previous research (Arthur et al.

2015; Blankenship and Arthur 2006), contrary to our hypothesis (H5) that basal sprouting would increase following fire in both B and MB treatments. This may be attributable to relatively low fire severity across treatments.

Finally, we hypothesized that crown vigor as measured by crown dieback class would increase on mastication treatments regardless of burning. Our results corroborated this hypothesis (H6); in addition, crown vigor increased across all treatments. Possible explanations for this response are greater resource availability (likely both light and water) across the study area due to the reduction in overstory stems, resulting first from the ice storm in 2003 and then the additional reduction in overstory basal area stemming from a sanitation harvest in 2012–2013. In addition, oak basal area in the canopy increased across all treatments over the duration of this study (Table S6). Oaks dominate the overstory at these sites and neither fire nor mastication affected stems in this size class, an expected but important outcome for a project aimed at creating oak woodland structure and species composition through salvage harvesting. Importantly, the addition of masticated fuels to the fuel bed did not lead to higher fire severity, which could have had negative impacts on the overstory trees that were conserved by the salvage cut. Even so, prior research on burn only sites in this region have demonstrated repeatedly that prescribed fires generally do not cause canopy stem mortality (Arthur et al. 2015; Blankenship and Arthur 2006; Hutchinson et al. 2012).

Of the six hypotheses that guided this study, only two were fully borne out by the findings: We found that prescribed fire on mastication treatments did not lead to additional mortality of midstory stems (H2) and that tree crown vigor did improve over the course of the study (H6). H4 was partially supported, in that mastication significantly reduced red maple small midstory stems; however, fire did not. The combined treatments (and especially the salvage thinning and mastication) created more open habitat and less competition for resources.

This study provides insights for the use of mastication and prescribed fire for restoration of upland oak woodlands in the Central Appalachians while pointing to the need for further research. High midstory stem density of red maple and other mesophytic species is a key challenge for oak woodland restoration. Mastication following an ice storm and sanitation thinning reduced stem density and basal area of trees ≤ 7.9 in (20.1 cm) DBH by 69% and 46%, respectively, and increased ground cover of forbs and native graminoids (Black et al. 2019). Prescribed fire, however, did not further alter stand structure. The lack of additional reduction in red maple midstory stems is a potential challenge for ongoing restoration goals. As with other research on prescribed fire in this region, it may be that repeated fire will be needed for continued reduction of midstory stems (Arthur et al. 2015; Blankenship et al. 2006).

Our findings differ somewhat compared to those from other regions. For example, mastication is often used to reduce ladder fuels, as has been shown in longleaf pine (Brockway et al. 2009), California mixed conifer (Stephens and Moghaddas 2005), and ponderosa pine (Kane et al. 2010) forests. In our region, ladder fuels are not an important component of the fuel bed and thus not a key objective for mastication. In other regions where mastication has been used, climates are generally dryer, with implications for decomposition of the masticated fuels and for fuel flammability. We found that masticated fuels were initially too wet to burn and lacked the leaf litter cover that provides the primary fuel for burning, which resulted in waiting two years to burn after mastication. During that period, the masticated fuels decomposed, leading to reduced mastication fuel mass and depth and low-severity fire comparable to that in the sites without mastication.

The management goal was to accelerate formation of woodland structure by targeting red maple midstory stems for removal to create a more open canopy structure with increased cover of native forbs and graminoids. Although mastication reduced canopy cover and increased species diversity of forbs and grasses, repeated fire will be needed to maintain a low understory and midstory stem density (Winkenbach 2020). Of related concern is the presence of invasive species, the most notable of which in this study is *Microstegium vimineum* (Black et al. 2019) that our preliminary findings showed increased after a single fire. Exacerbation of invasive species challenges will require ongoing consideration.

Acknowledgments

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Conflict of Interest

None declared.

Supplemental Tables

Supplementary data are available at *Forest Science* online.

Table S1. Total stem density (stems ac^{-1}) and basal area (ft^2 ac^{-1}) of small midstory stems 2–4.9 in. DBH on all treatments on Buffalo Branch and Spartman sites in the Daniel Boone National Forest, Kentucky. Measurements were made in 2015 before any treatment, in 2016 after mastication, and in 2018 after prescribed fire. Significant differences among treatments and dates are noted by different superscript letters. SE are in parentheses.

Table S2. Total stem density (stems ac^{-1}) and basal area (ft^2 ac^{-1}) of canopy stems ≥ 8 in. DBH on all treatments on Buffalo Branch and Spartman sites in the Daniel Boone National

Forest, Kentucky. Measurements were made in 2015 before any treatment, in 2016 after mastication, and in 2018 after prescribed fire. There were no significant effects of treatment for canopy stems. SE are in parentheses.

Table S3. Total stem density (stems ac^{-1}) and basal area (ft^2 ac^{-1}) of small (2–4.9 in. DBH) and large (5–7.9 in. DBH) midstory red maple on all treatments on Buffalo Branch and Spartman sites in the Daniel Boone National Forest, Kentucky. Measurements were made in 2015 before any treatment, in 2016 after mastication, and in 2018 after prescribed fire. Significant differences among treatments and dates for small midstory stems are noted by different superscript letters. There were no significant effects of treatment for large (5–7.9 in. DBH) midstory stems. SE are in parentheses.

Table S4. Total stem density (stems ac^{-1}) and basal area (ft^2 ac^{-1}) of canopy (≥8 in. DBH) red maple on all treatments on Buffalo Branch and Spartman sites in the Daniel Boone National Forest, Kentucky. Measurements were made in 2015 before any treatment, in 2016 after mastication, and in 2018 after prescribed fire. There were no significant effects of treatment for canopy stems. SE are in parentheses.

Table S5. Total stem density (stems ac^{-1}) and basal area (ft^2 ac^{-1}) of small (2–4.9 in. DBH) and large (5–7.9 in. DBH) midstory oaks on all treatments on Buffalo Branch and Spartman sites in the Daniel Boone National Forest, Kentucky. Measurements were made in 2015 before any treatment, in 2016 after mastication, and in 2018 after prescribed fire. Significant differences among treatments and dates are noted by different superscript letters. SE are in parentheses.

Table S6. Total stem density (stems ac^{-1}) and basal area (ft^2 ac^{-1}) of canopy (≥8 in. DBH) oaks on all treatments on Buffalo Branch and Spartman sites in the Daniel Boone National Forest, Kentucky. Measurements were made in 2015 before any treatment, in 2016 after mastication, and in 2018 after prescribed fire. There were no significant effects of treatment for canopy stems. SE are in parentheses.

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