Altered fire behavior and effects following mastication in a pine flatwoods ecosystems

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Abstract

Mastication of understory shrubs and small trees to reduce fire hazard has become a widespread forest management option, yet few empirical studies have quantified the effects of treatment on actual fire behavior and fire effects at the stand-scale. We conducted replicated experimental burns in long-unburned pine flatwoods with palmetto/gallberry understories, a common ecosystem of the Southern US Coastal Plain where treated fuels regain pre-treatment biomass within a few years. Fire behavior and fire effects were compared between treated and untreated sites burned in the typical winter burning season; and between treated sites burned in the winter and summer. Mastication effectively reduced fire intensity, but recovering shrubs quickly regained control over fire behavior, suggesting time-limited treatment effectiveness. Overstory tree mortality observed following summer burning in treated areas may have resulted from combustion of the compact surface fuels beneath the recovering shrub layer, where duff consumption was documented. Developing treatment regimes that utilize prescribed burning to reduce surface fuel loading following mastication will require special attention to treatment timing in order to ensure fuel consumption while minimizing potential ecological impacts.

Keywords: fire behavior models, fire effects, fire management, fuels treatments, tree mortality

1. Introduction

The use of mechanical fuels treatments to reduce fire hazard in forest and shrub ecosystems has become more widespread over the past decade, yet few empirical studies elucidate their effectiveness by quantifying fire behavior following implementation. While treatments may be used as a stand-alone option, they are often implemented as a pre-treatment strategy to reduce fire hazard during follow-up prescribed burning. Treatments aimed at these objectives are being widely implemented across the United States (Kane et al., 2009; Kobziar et al., 2009; Brockway et al., 2010; Battaglia et al., 2010; Menges and Gordon 2010) and elsewhere (Molina et al., 2009; Castro et al., 2010), ranging in scale from a few to several thousand hectares. In addition to reducing fire hazard, fuels treatments are often conducted to restore long-unburned ecosystems; retaining mature overstory trees and enhancing resistance to future fire (Agee and Skinner, 2005). Evaluating the effectiveness of mastication fuels treatments at reducing fire behavior, while enhancing overstory resistance to post-treatment burning, is key to determining treatment efficacy (Kobziar et al., 2009; Reiner et al., 2009; Knapp et al., 2011).

Mastication is a mechanical treatment that alters fuel structure through mowing, shredding, or chipping understory shrubs and small trees, not reducing but reallocating total fuel loading (Glitzenstein et al., 2006; Kane et al., 2009; Kobziar et al., 2009; Kreye, 2012). Following treatment, masticated debris is either left on site or burned as a follow-up treatment to reduce surface fuel loading. While research is being conducted to evaluate potential biomass utilization, prescribed burning remains the most economically feasible option to remove masticated surface fuels following treatment. Current work evaluating fire behavior and effects in masticated fuels is limited, with much of it focused on western US ecosystems (Busse et al., 2005; Bradley et al., 2006; Kobziar et al., 2009; Knapp et al., 2011; Kreye et al., 2011). Small-scale laboratory experiments have elucidated some of the effects of particle- or fuelbed-scale properties on moisture dynamics (Kreye et al., 2012) and fire behavior (Busse et al., 2005; Kreye et al., 2011; Kreye et al., 2013a), but few field-scale studies have examined treatment effectiveness in achieving their primary goal: to reduce wildfire hazard and subsequent ecological consequences. Those field-scale studies that have been conducted to address these issues have varied in their results (Bradley et al., 2006; Glitzenstein et al., 2006; Kobziar et al., 2009; Knapp et al., 2011).

Mastication treatments are increasingly being used in the southeastern US with limited understanding of their effectiveness (Brockway et al., 2010; Glitzenstein et al., 2006). The majority of pinelands across the Southeastern Coastal Plain are characterized by short fire return intervals, ranging from 1-3 years for pine uplands, flatwoods, and sandhill communities (FNAI 1990; Glitzenstein et al., 2003). Beyond this range, conditions promoting undesirable fire effects worsen due to rapid growth of flammable shrubs, vines acting as ladder fuels, and litter and duff accumulation (Varner et al., 2006; Robertson and Ostertag 2007). Whether wildfire hazard is mitigated by mechanical fuel reduction techniques in these systems is closely tied to pre-treatment conditions and post-treatment prescribed fire use, but has not yet been tested. The southeastern region, with an average of 2-3 million ha fuels treated annually (Wade et al., 2000), presents a compelling opportunity to quantify the effectiveness of mastication for reduction of potential wildfire behavior, and to explore additional ecological repercussions

One of the dominant natural pine communities found throughout the Southeastern US Coastal Plain is pine flatwoods, with slash pine (*Pinus elliottii* var. *elliottii* Engelm.) or longleaf pine (*Pinus palustris* Mill.) in the overstory and understories dominated by saw palmetto (*Serenoa repens* (Bartr.) Small) – a shrub-form palm – and gallberry (*Ilex glabra* (L.) Gray) shrubs (so-called “southern rough”; Hough and Albini, 1978). Mowing (the commonly used term in the region) in this ecosystem results in compact surface fuels comprised mostly of shredded palmetto fronds and a smaller proportion of small diameter woody fuels (Kreye, 2012). Small-scale burning experiments have revealed the relationship between surface fuel loading and fire behavior in masticated debris collected from treatments in this ecosystem (Kreye et al., 2013a), however it is unclear if surface fuels will be a significant driver of fire behavior at the stand-scale due to rapid post-treatment shrub recovery (Kreye, 2012). In other regions of the US, a key limitation to evaluating how the unique characteristics of masticated fuelbeds affect fire behavior is the challenge of employing post-treatment fire experiments or opportunistically investigating a wildfire event. Such research has been recommended as a key component of determining the efficacy of mastication (e.g. Kane et al., 2009).

Fire use practitioners implementing mastication prior to prescribed burning have little on which to base predictions of fire behavior and effects. They may look to commonly used fire behavior modeling systems, such as Behave Plus (Andrews et al., 2008, version 4.0) to help predict potential fire behavior and risk to overstory canopy trees, creating custom fuel models to reflect mowed stands. Whether such predictions are accurate is less the issue than whether they achieve a result that will dissuade burning under unsafe conditions or conditions which threaten overstory mortality. Because this study documents actual fire behavior following mowing treatments, and is based on a detailed characterization of the fuelbeds over time, we include a comparison of observed behavior characteristics to those predicted by Behave Plus. This comparison is meant to provide some context for fire use practitioners who employ the modeling system for unique and largely unquantified fuelbeds.

The objectives of this study were to 1) determine the effectiveness of mowing at reducing stand-scale fire behavior where masticated residues are litter-dominated and where shrub recovery is rapid; 2) determine if surface fuels or shrub fuels influenced fire behavior six months following mowing; 3) determine if fire-induced tree mortality would increase as a result of burning in masticated treatments; and 4) evaluate the accuracy of current models in predicting fire behavior following mowing.

2. Methods

2.1 Study site

Mechanical fuels treatments were conducted in the Osceola National Forest (Osceola) in northern peninsular (north-central) Florida, USA in pine flatwoods communities unburned for ca. 11+ years and where fuel accumulations posed a hazard within the wildland urban interface (WUI), being located in close proximity to Lake City, FL and with US Interstate 10 transecting the forest. Pine flatwoods in the Osceola are dominated by slash pine or longleaf pine in the overstory and by saw palmetto and gallberry shrubs in the understory.   Fire management goals in the Osceola include burning at least 30,000 ha per year, with the ultimate goal of maintaining a 3- year burn cycle in their mesic flatwoods forests. In long-unburned locations, mechanical mowing has been used to reduce the height of understory fuels to facilitate re-introduction of prescribed fire, and to reduce fire hazard in areas adjacent to communities, highways, and private pine plantations. During the course of this study, mowing treatments were implemented in mature pine flatwoods (ca. 80 yrs old) lacking a mid-story, where the primary fuel strata altered during mowing were understory shrubs, including palmetto, and few small trees. Mowing was conducted using front-mounted mastication heads (fixed teeth) attached to ground based (skidder and Gyro-Trac) equipment.

2.2 Experimental burning treatments

Two treatment locations were used to evaluate the influence of mowing on subsequent fire behavior and effects. The first was located in a 100 m wide fire buffer on the perimeter of the Osceola's SW corner, adjacent to a private pine plantation (Fig. 1). The buffer was mowed in August 2009, as an Osceola management objective, and subsequently burned in July 2010 for this study to examine fire behavior. The second location included experimental block treatments subsequently established to further examine the influence of mowing on fire behavior and effects (Fig. 1). Due to management objectives, experimental blocks could not be located near the buffer treatment and were thus established in nearby sites with similar stand ages, fire histories, vegetation, and soil conditions. Mowed and unmowed treatments (~2 ha each) were replicated three times. Mow treatments were mowed in August 2010 and both mowed and unmowed treatments were burned in February 2011. Because the treatment timing differed for the two different sites, we were able to evaluate the effects of mowing on fire behavior and effects during dormant season (winter) burning in the blocked site, (typical of the management regime), and also compare fire behavior and effects between the dormant season burn and a growing (summer) season burn in the buffer site. Treatments are referred to here by the season of the experimental burn (summer versus winter) and whether treatments were mowed; the buffer including summer burning in mowed treatments (Summer M+B) and the block treatments including winter burning in mowed (Winter M+B) and unmowed (Winter B) treatments.

Nine plots were allocated to each of the three treatments (Summer M+B, Winter M+B, and Winter B) for a total of 27 plots across the study. Plots were systematically established to facilitate coordination between ignition operations and fire behavior observations. Within the buffer (Summer M+B), plots were systematically established into three triplets (Fig. 1). Within the block treatments (Winter M+B and Winter B) three plots were established in each of the three 2 ha replicates, per treatment (Fig. 1).

Because the timing of burns were constrained by weather and resource availability, full vegetation and fuels measurements could not be conducted immediately prior to burning. Comprehensive sampling of vegetation and fuels, however, were conducted four months prior to each burn within all plots, including those not used in fire behavior analysis. Sampling occurred in March 2010 prior to the 28 July 2010 summer burn in the buffer site, and in October 2010 prior to the 23 February 2011 winter burn in the block site. Within each 200 m^2 circular plot, height, diameter at breast height (DBH), and crown base height (CBH) were measured for all trees and tree density, basal area, and quadratic mean diameter (QMD) were quantified for each plot. Total shrub biomass and shrub foliar biomass were estimated from allometric equations and shrub measurements (height and basal diameter) taken in two 1×4 m belt transects. Litter depth, duff depth, as well as litter, duff, and woody (1h, 10, and 100h) fuel biomass were estimated using the planer intercept method (Brown, 1974) from four 10m fuel transects. A full description of sampling methods and biomass estimations can be found in Kreye (2012).

2.3 Fire behavior measurements

All treatments were burned using strip-head fire techniques by Osceola personnel. Due to operational and personnel limitations, fire behavior observations were recorded in only 18 (6 per treatment) of the 27 plots, however all plots were subsequently used to assess post-fire tree mortality (see below). Shrub vegetation and surface fuels were minimally assessed on the days of burning. Average shrub height was estimated across each plot and three subsamples of surface litter were collected, and pooled, just prior to ignition to determine surface fuel moisture on a gravimetric basis. Temperature, relative humidity, and wind speed were recorded hourly and the Keetch Byram Drought Index (KBDI), a coarse indicator of moisture conditions, was recorded. For the winter burns (Winter M+B and Winter B), average shrub cover was also estimated at each plot to be used to correlate with fire behavior (see data analysis below).

Fire behavior was estimated during burning using plot-level measurements. In each plot, three rebar were located 8 m apart and oriented in line with predicted wind direction and anticipated fire movement. Each rebar was exposed 3 m above the surface litter and marked in 50 cm increments using fluorescent paint. Strip-head firing was conducted using drip torches with ignition lines occurring 15–20 m upwind of plots. Observers followed the flaming front through each plot, marked the time of the arrival of the flame front at each rebar location, and estimated flame height as the flaming front passed each rebar. ROS was calculated for each plot and flame heights averaged across all three rebar locations.

2.4 Fire effects

Within a week of burning, tree injury was assessed for all trees within each 200 m^2 circular plot, including the nine plots not monitored during burning, and surface fuels were resampled along the same planar intercept transects (4 per plot) established prior to burning. Bole char was measured in two ways: percent of the bole circumference at DBH charred and maximum char height. Crown injury was assessed by visually estimating the proportion of the crown volume scorched (CVS). Scorch occurs when foliage is desiccated from heating, but initially retained on branches, and quick assessments were conducted to quantify CVS prior to needle loss. Scorched needles were not observed on the forest floor at the time of injury assessments. Surface litter and duff consumption were calculated for each plot using pre- and post-burn fuels measurements. Litter and duff depths were re-measured, using the same methods as pre-burn sampling, and consumption estimated as the difference between pre- and post-burn values. Tree mortality was then assessed in March 2012 (1 yr following winter burns; 20 mos following summer burns) and again in May 2013 (26 mos following winter burns; 32 mos following summer burns). Because hardwoods composed a minor proportion across all sites (9 of 172 trees), we report and analyze data only for the pines.

2.5 Data Analysis

For fire behavior evaluation, comparisons were not made simultaneously across all three treatments (Winter B, Winter M+B, and Summer M+B), rather planned comparisons were made between Winter B and Winter M+B treatments, and then between the Winter M+B sites and the Summer M+B sites. Therefore, separate analyses isolated the effect of mowing on fire behavior by comparing B and M+B sites burned in adjacent experimental treatments and on the same day, but also evaluated the effect of season of burn between two mowed treatments. For each analysis, pre-burn vegetation and fuels measurements were compared between treatments. All subsamples within plots were averaged for analysis. And fire behavior (ROS and flame height), fuel consumption (litter and duff), and overstory effects (CVS, char at DBH, and char height), of pines, were compared between respective treatments. Statistical comparisons were made using a two-sample T-test (α=0.05). Model assumptions were evaluated using the Shapiro-Wilk test of normality and the Modified-Levene test for equal variance. Where model assumptions were not met, log or square root transformations were used to meet normality assumptions and the Aspin-Welch Test used for unequal variances.

To evaluate whether shrubs or surface litter were better linked with observed fire behavior, linear regression was used to determine the correlation between observed flame height and estimated shrub cover, shrub height, and litter mass, separately. Linear regression was also used to determine the correlation between ROS and shrub cover, shrub height, and litter mass, separately. Only data from the experimental winter burning blocks were used for this analysis, limiting potential external factors (e.g. differences in weather conditions), and with all plots pooled. Shrub cover and shrub height values were those estimated on the day of the burn, as described above.

Tree mortality was evaluated across all 27 plots in the study. Although fire behavior was not monitored in nine plots, vegetation and fuels sampling was conducted within all plots. Because a low number of trees died in this study, a rigorous statistical analysis of mortality rates was not conducted. Evaluation of the effects of mowing or season of burning on tree mortality were assessed through simple evaluation of the proportion of trees dead within each treatment.

2.6 Modeled versus observed fire behavior

Predicted fire behavior was compared to observed fire behavior in this field study. Rothermel's (1972) fire spread model was used to predict rate of spread ($m{\cdot}min^{-1}$), flame length (cm), and fireline intensity ($kW{\cdot}m^{-1}$) at the plot level using measured fuel loading, fuel moisture, and observed weather conditions. Modeling was conducted in the Behave Plus Fire Modeling

System (Andrews et al., 2008, version 4.0) and fuel parameters were input as a custom fuel model. Fuel moisture of 10h woody and live shrub foliage was not measured in the Summer M+B plots, and 100h fuel moisture was not measured during any burning. Live fuel moisture was set at 100%, a reasonable assumption based on measured values in the winter burns (113% ± 8 s.d.), and the value recommended in Behave Plus when moisture is unknown (Andrews et al., 2008). Fuel moisture was input using litter moisture measured on the day of the burn. Fuelbed depth was input as the average shrub height, since shrubs carry fire in these fuelbeds. Live woody fuel loading was input as total shrub foliar biomass, which is the portion of shrubs involved in flaming combustion. Observed rate of spread, fuel consumption, and fuel energy content (18.622 kJ·kg, weighted value from Hough and Albini, 1978) were used to estimate fireline intensity for each plot during the burns (Kreye et al., 2013a). Because all observable shrub foliage was consumed during burning, measured pre-burn shrub foliar mass was assumed to have been consumed. Modeled outputs, by plot, were compared with the observed rate of spread, flame length, and fireline intensity. Because the model predicts flame length, not flame height, the observed flame lengths were estimated from measured flame heights assuming a flame tilt angle of 30˚, based on general observations during burning. Observed and predicted values were compared using linear regression.

3. Results

3.1 Effect of pre-burn mowing on fire behavior in winter: Winter M+B vs. Winter B

Overstory vegetation did not differ between Winter B and M+B treatments, however shrubs were much reduced in M+B treatments compared to B treatments two months after mowing (4 months prior to burning) (Table 1). Tree density, BA, QMD, height, and CBH averaged 336 tph, 17.1 m^2 per ha, 25.9 cm, 20.9 m, and 14.9 m, respectively, across treatments. Tree composition, by density, was 74% longleaf pine, 25% slash pine, and <2% hardwoods in M+B stands and 74% longleaf pine, 17% slash pine, and 9% hardwoods in the B stands. Shrub cover (33%), height (58 cm), total biomass (0.6 $Mg{\cdot}ha^{-1}$), and foliar biomass (0.4 $Mg{\cdot}ha^{-1}$) were all lower ($p<0.001$) in the mowed (M+B) treatments, four months prior to burning, compared to the unmowed (B) treatments, averaging 78 %, 145 cm, 4.4 $Mg{\cdot}ha^{-1}$, and 4.1 $Mg{\cdot}ha^{-1}$, respectively. Litter depth was lower in the M+B treatments (6.0 cm) compared with B treatments (7.4 cm) ($p=0.035$), however, litter mass, averaging 13.4 $Mg{\cdot}ha^{-1}$, was higher than the 8.6 $Mg{\cdot}ha^{-1}$ in the B plots ($p=0.001$). Duff depth, averaging 4.2 cm ($p=0.230$), and mass, averaging 46.0 $Mg{\cdot}ha^{-1}$ ($p=0.238$), did not differ between treatments. 1h woody fuel mass was higher in the M+B treatments (1.1 $Mg{\cdot}ha^{-1}$) compared to B treatments (0.5 $Mg{\cdot}ha^{-1}$) ($p=0.015$), but 10h fuels, averaging 1.6 $Mg{\cdot}ha^{-1}$,did not differ ($p=0.105$). 100h fuels, averaging 0.9 $Mg{\cdot}ha^{-1}$, also did not differ ($p=0.534$) between B and M+B treatments. Litter moisture content in M+B treatments (12.1%) was lower than in B treatments (17.8%) ($p=0.047$). KBDI during these winter burns was 107, which is at the wetter end of the spectrum for Florida's dry season.

Temperature during the winter burns (23 Feb 2011, 11:00–14:30) ranged from 17 to 24 ˚C, relative humidity from 47 to 62%, and wind speed from 1.6 to 4.8 $km{\cdot}hr^{-1}$. Flame heights during burning in mowed (M+B) treatments (1.1 m) were one-third of those observed in the unmowed (B) treatments (3.3 m) ($p=0.003$, Table 1). ROS did not differ between treatments ($p=0.150$), but was moderately slow (3.4-7.1 $m{\cdot}min^{-1}$) during these controlled burns. Litter mass consumed was higher in M+B treatments (9.6 Mg·ha^{-1}) compared to B treatments (6.4 Mg·ha^{-1}) ($p=0.007$), however percent litter consumption, averaging 73%, did not ($p=0.459$). Neither duff mass (5.8 Mg·ha^{-1}, $p=0.154$) nor percent duff consumed (9%, $p=0.186$) differed between treatments. Average crown scorch was greater ($p<0.001$) in the unmowed (B) treatments (57%) compared to the mowed (M+B) treatments (29%). Maximum char height was also greater ($p=0.038$) in B (6.7 m) versus M+B (5.6 m) treatments, however percent of bole circumference charred at DBH, averaging 91%, did not differ ($p=0.215$). While shrub consumption was not quantified, nearly 100% of the understory area was burned and almost all shrub foliage consumed during burning (Fig. 2).

Flame heights, across all treatment plots pooled, were positively related to both shrub cover ($R^2=0.80$, $p<0.001$) and shrub height ($R^2=0.63$, $p=0.002$), but unrelated to litter mass ($p=0.962$) (Fig. 3). Shrub cover and height were also correlated ($r=0.862$). There was also marginal evidence that rate of spread was positively related to shrub cover ($R^2=0.31$, $p=0.058$) and shrub height ($R^2=0.27$, $p=0.084$), but not to litter mass ($p=0.991$). When conducting regression of fire behavior and fuel components within treatments, shrub cover was marginally related to flame heights in B sites ($R^2=0.575$, $p=0.081$) and in M+B sites ($R^2=0.628$, $p=0.060$), however shrub height was significantly related to flame heights in the B treatments ($R^2=0.712$, $p=0.035$), but not in the M+B treatments ($R^2=0.003$, $p=0.914$). Litter mass was not related to flame heights in B ($R^2=0.063$, $p=0.631$) or M+B ($R^2=0.070$, $p=0.613$) treatments. There was marginal evidence, however, that litter moisture influenced flame heights in M+B treatments ($R^2=0.548$, $p=0.092$), but not in B treatments ($R^2=0.000$, $p=0.998$). Live moisture was not related to flame heights in either treatments. Using multiple regression techniques, none of the above fuel variables were significant when shrub cover, a significant variable, was included as a predictor variable. Rate of spread was not related to any quantified fuel characteristic within treatments.

3.2 Effect of season on fire behavior following mowing: Winter M+B vs. Summer M+B

In regard to mowed treatments burned in the winter (Winter M+B) versus summer (Summer M+B) treatments, post treatment overstory conditions did not differ between sites, however average tree height was slightly higher in the Summer M+B treatments (23.3±0.9 m) compared to Winter M+B (21.0±0.7), but differences were marginal (p=0.054) (Table 2). Tree density, BA, QMD, and CBH averaged 299 tph, 21 m^2 per ha, 29.9 cm, and 12.3 m, respectively. Tree composition, by density, was 74% longleaf pine, 25% slash pine, and <2% hardwoods in Winter M+B stands and 63% longleaf pine, 33% slash pine, and 4% hardwoods in the Summer M+B stands. Four months prior to burning, shrub height, averaging 64 cm, did not differ between treatments (p=0.467). While shrub cover was not quantified in the summer burning treatment, total shrub biomass, averaging 0.75 $Mg{\cdot}ha^{-1}$, did not differ between treatments (p=0.663), nor did shrub foliar biomass (0.45 $Mg{\cdot}ha^{-1}$; p=0.648), quantified four months prior to burning. Surface litter depth (5.5 cm) and duff depth (4.4 cm) were not different between treatments, nor were litter (12.2 $Mg{\cdot}ha^{-1}$) or duff (48.8 $Mg{\cdot}ha^{-1}$) mass. Woody fuels, however, differed in the smallest diameter (1 and 10h) classes. 1h fuels averaged 4.1 $Mg{\cdot}ha^{-1}$ in Summer M+B treatments, higher (p=0.016) than the 1.1 $Mg{\cdot}ha^{-1}$ in the Winter M+B treatments. 100h fuels did not differ (p=0.301), averaging 1.8 $Mg{\cdot}ha^{-1}$, and were sparse.

Observed fire weather during the summer burn treatment contrasted sharply with winter burns. Temperatures and relative humidities were higher in the summer, ranging from 31-34 ˚C and 61-76%, respectively, and wind speeds, ranging from 1.6 to 7.2 km·hr^{-1}, were slightly more variable than those in the winter. Atmospheric conditions during the winter treatments were cooler (17 to 24 ˚C), drier (47 to 62% RH), and winds only ranged from 1.6 to 4.8 km·hr^{-1} (Table 2). Surface litter moisture was slightly higher during summer burning (14.7±1.1 %) compared to winter burning (12.1±0.6 %), however differences were marginal (p=0.064). While KBDI was 107 (moist) during winter burns, KBDI rose to 425 for summer burns, indicating drier soil (and potentially duff) conditions during the day of the summer burn. Total precipitation, recorded from a nearby remote automatic weather station (RAWS), within 30 days prior to the 28 Jul 2010 (summer) burn was 13.2 cm, with precipitation in the preceding 10 days occurring on 22 Jul (1.2 cm) and 24 Jul (0.5 cm). Total precipitation within 30 days prior to the 23 Feb 2011 (winter) burn was higher (17.5 cm) than preceding the summer burn, but with none occurring 10 days prior to the burn.

In spite of the differences in fire weather, quantified fire behavior did not differ between the summer and winter burns (Table 2). Average flame heights did not differ, averaging 1.5±0.1 m during summer burns and 1.1±0.3 m during winter burns (p=0.267). Similarly, rate of spread did not differ, averaging 5.9±1.8 m·min^{-1} during summer burning and 3.4±1.0 m·min^{-1} during winter burning (p=0.276). Proportion of litter consumed was lower (p=0.014) during summer burns (48±7%) compared to winter burns (71±4%), and total litter mass consumed was also lower (p=0.023) during summer (5.5±1.3 Mg·ha^{-1}) compared to winter (9.6±0.9 Mg·ha^{-1}) burns. Percent duff consumption, however, was greater during summer burns (32±11%) compared to winter burns (5±3%), but variation was high enough that differences were marginal (p=0.067). Average duff mass consumed was also higher in summer (23.1±10.1 Mg·ha^{-1}) versus winter (2.6±1.9 Mg·ha^{-1}) burns, with high variation and marginal differences (p=0.098). Neither crown scorch, averaging 27% ($p=0.623$), nor maximum char height, averaging 5.5 m ($p=0.656$), differed between treatments. Percent of bole circumference charred at DBH was 69±4% following summer burns, lower ($p<0.001$) than during the winter burns (88±2%). The proportion of understory area burned was almost 100% during summer burns as was observed during winter burns.

3.3 Modeled versus observed fire behavior

Using the Rothermel (1972) fire spread model, within the BehavePlus fire modeling system (Andrews et al., 2008, version 4.0), to predict fire behavior at the plot level, prediction error rates for flame length, ROS, and fireline intensity ranged from 8–104%, 28–64%, and 6–38%, respectively, for the unmowed (B) treatment sites (Fig. 4). Error rates for the mowed sites (Winter and Summer M+B), however, ranged from 6–78%, 24–90%, and 23–179% for flame length, ROS, and fireline intensity, respectively. While average error rates for flame length in mowed sites (46%, Winter M+B; 41%, Summer M+B) were similar to unmowed (Winter B) sites (44%), error rates of ROS were slightly higher in mowed sites (66%, Winter M+B, 63%; Summer M+B; 53%, Winter B) and error rates of fireline intensity were much higher in mowed, versus unmowed sites (89%, Winter M+B; 66%, Summer M+B; 23%, Winter B). Flame lengths were generally over-predicted in the mowed sites, while under-predicted in the unmowed sites (Fig. 4). ROS was over-predicted for most plots burned, even in the non-mowed treatment. And while fireline intensity was over-predicted more often than under-predicted, errors were much larger for mowed sites compared to unmowed sites.

3.4 Tree mortality

Across all treatment plots (Winter B, Winter M+B, and Summer M+B), 164 pine trees were assessed for mortality, all of which were alive prior to burning. One year following winter burning (1.5 yr post summer burn) 4 of 59 trees in Winter B sites were dead, while 1 of 60 was dead in Winter M+B sites (Table 3). In Summer M+B sites, 3 out of 45 had died.. As a reference for background mortality, 1 of 61 trees assessed in nearby controls died during the study (longleaf pine, 9 cm DBH) and 0 of 52 trees assessed in unburned mowed sites died. One year later, (2 yrs post winter burn, 2.5 yrs post summer burns) three additional trees had died, two in B and one in Summer M+B. Of the six tree that died in the unmowed (B) sites, all but one were <20 cm DBH, while the tree that died in the Winter M+B sites was 26.6 cm and three of the four trees that died during summer burning in mowed sites (Summer M+B) were >30 cm (Fig 5). All dead trees were longleaf pines except for a 17.5 cm slash pine in the B treatment and the large (41.9 cm) slash pine in the Summer M+B sites. Most trees that died had succumbed to substantial crown scorch, except for the large (41.9 cm) slash pine with <10% scorch (Fig 5).

4. Discussion

While mechanical fuels treatments are being widely implemented to mitigate fire hazard, evaluating their effectiveness with field-level burning experiments is often difficult, resulting in limited empirical studies. This work capitalized on the consistent and predictable use of prescribed fire in north Florida, which allowed for an examination of season and treatment effects on fire behavior and tree recovery. As mowing is most commonly employed in this region to reduce subsequent prescribed fire behavior, quantification of its effects is key to determining its value as a fuels treatment option.

Recent research has begun to characterize the post-mastication fuel environment in various ecosystems, however much of this research has been focused in the western US (Hood and Wu, 2006; Kobziar et al., 2009; Kane et al., 2009; Battaglia et al., 2010). Published reports have shown that surface fuels resulting from mastication of shrubs and small trees in these ecosystems are primarily composed of woody fuels (Kane et al., 2009; Battaglia et al., 2010). Laboratory-scale fire behavior studies have revealed that burning in these compact, woody-dominated fuelbeds result in long duration surface (Kreye et al., 2011) and soil (Busse et al., 2005) heating. Some field studies have also shown unexpected tree mortality following burning in these treatments (Bradley et al., 2006; Knapp et al., 2011). Mastication ("mowing") in palmetto/gallberry pine flatwoods of the southeastern US results in litter-dominated surface fuels (Kreye, 2012), much different than other areas studied. This work broadens our understanding of fire behavior in masticated forests and shrublands in general, and provides insight into their effectiveness in this region.

Flame heights were reduced by two-thirds following mowing in this ecosystem, however shrubs regained control over fire behavior as quickly as six months following mowing. Small-scale fire behavior experiments conducted with collected surface material following mowing in these sites revealed precise control of litter biomass over fire behavior (Kreye et al., 2013a), which was not evidenced in this study. Shrubs were much reduced in the treated sites, yet their quick recovery was best represented by a shrub-type fuel model (Scott and Burgen, 2005) soon after treatment as evidenced by their influence over fire behavior. While mastication in many shrub and forest ecosystems may result in a surface fuel-type for some time, treatments in areas where shrubs resprout vigorously will likely return to a shrub fuel-type quickly and fire behavior reduction may be short-lived. Results here indicate that if follow-up prescribed burning is conducted soon after mowing, treatments are effective at reducing fire intensity, but as early as six months following mowing, shrubs will influence fire behavior. When used as a pre-burn treatment where sites have gone long unburned, mastication may serve to enhance control during burning, however, if used as a stand-alone treatment, the effect of reducing fire hazard and increasing suppression effectiveness may be short-lived.

Although shrub cover and height were closely correlated with flame heights in this study, combustion in the surface litter created from mowing may still be an important management concern. There was evidence here that burning in mowed sites resulted in less crown scorch, likely due to lower flame heights (Van Wagner, 1973), however some tree mortality was evidenced following summer burning in mowed sites. Litter consumption during winter burns was high, but little duff was consumed. During summer burns, less litter consumption occurred, but there was marginal evidence of greater duff consumption, and soil conditions were likely drier, as indicated by higher KBDI. While high flammability in these historically frequently burned ecosystems may alleviate long duration surface and soil heating (Gagnon 2010), long duration heating in surface material following mastication treatments (Busse et al., 2005; Kreye et al., 2011; Kreye et al., 2013a) in conjunction with duff accumulation in long-unburned sites (Varner et al., 2005) may result in duff ignition (Kreye et al., 2013b) and subsequently fine root or bole injury to residual trees (O'Brien et al., 2010). While southern pines are capable of recovering from substantial crown injury (Waldrop and Van Lear, 1984; Johansen and Wade, 1987), effects of fine root or bole injury may result in delayed mortality (O'Brien et al., 2010). Although few trees that we assessed for mortality died in this study, thus limiting more rigorous analysis, there was some evidence that suggested that mowing limited mortality during winter burns, likely because of less crown damage. Mortality observed during summer burning in mowed sites, however, may suggest an effect of season or from combustion of underlying duff (Varner et al., 2005), however results are not clear. The effectiveness of mastication in reducing fire behavior may be important for restoration of long-unburned sites, but timing of prescribed burns should take into consideration potential ecological repercussions.

Since mastication treatments only alter fuel structure and do not reduce fuel loading, follow-up burning objectives will likely include the consumption of surface fuels created from treatments since increasing surface litter may elevate the risk of wildfire ignition (Perryman et al., 2012). The mulching effect of moisture retention in masticated fuelbeds (Kreye et al., 2012) may mean that attaining desired fuel consumption may be difficult, especially under wetter surface conditions. Although KBDI was higher during summer burning in this study, indicating drier soil conditions, litter moisture was no different than during the winter burns, and litter consumption rates were actually lower. While more precipitation occurred in the month prior to winter burns, no rain had fallen within 10 days prior to ignition. Prior to summer burning, however, some rain fell four (0.5 cm) and six (1.2 cm) days prior to ignition and these dense fuelbeds may have been slow to dry (Kreye et al., 2012). In contrast, shrub reduction following mowing in this ecosystem can result in drier surface fuels (Kreye, 2012), potentially due to increased solar radiation or surface winds. Litter, during winter burns, were actually drier in mowed treatments versus un-mowed treatments. Drier surface fuels could mean a higher risk of wildfire ignition (Dimitrakopoulos and Papaioannou, 2001). The complex moisture dynamics in masticated sites will need to be much better understood in order for prescribed burning objectives to be met when used as a follow-up treatment and to understand treatment efficacy at mitigating wildfire hazard.

When prescribed burning is used as a management tool on a large scale, as in this region, meeting frequent fire cycles can be difficult under the constraints of "burn windows". If burning conditions required for surface fuel consumption are such that burn windows are narrowed, it may be difficult to burn masticated sites soon enough to avoid substantial shrub recovery, but also during conditions to avoid potential tree mortality. Developing treatment regimes that incorporate mowing and burning may require strategic timing to meet management goals without resulting in unintended ecological consequences. Not following up quickly enough with fire may result in dense surface fuels on top of accumulated duff, but under heavy shrub loading within just a few years following treatments.

Model predictability of fire behavior in these treatments varied depending on the fire metric, but error rates but were generally higher in the mowed versus the unmowed sites. Flame lengths were more often over-predicted in mowed sites and under-predicted in unmowed sites, but with similar error rates. Prediction accuracies for rates of spread were worse than for flame lengths and were generally over-predicted in both mowed and un-mowed sites. Fireline intensity was well-predicted in unmowed sites, but error rates for mowed sites were highest of all fire metrics modeled. Cruz and Alexander (2013) have suggested that a 35% error rate is a reasonable performance for models predicting surface and crown fire rates of spread. Using this as a guideline, only predictions for fireline intensity in unmowed sites seemed reasonable.

Several factors could lead to errors in model predictability. Observed flame lengths were adjusted for an assumed flame tilt of 30°. It is difficult, however, to quantify actual flame length during burning, especially in shrub fuels. A 30° tilt is likely a liberal estimate, given the light wind conditions, however flame length is only calculated to be 15% longer than vertical flame height under this assumption. One additional point is that flame heights were measured from the litter surface to the top of the flame, however model predictions are such that flame length extends from the top of the fuelbed surface, in this case the average shrub height. In some cases, two-thirds of shrub height is used for modeling (Hough and Albini, 1978). Nonetheless, if estimated flame lengths from field burning were adjusted to include only the flaming portion above the shrubs, model performance would be even poorer with drastic over-estimations in mowed sites. Flame length above the forest floor is likely a more important metric as a tool to assess fire suppression tactics during a wildfire in mowed sites or controllability during prescribed burning. Fireline intensity is calculated from fuel consumption and ROS, and also should be related to flame lengths (Byram, 1959). One major shortcoming of the Rothermel (1972) model is that it assumes a homogenous fuelbed. In shrub dominated sites there is a vertically oriented shrub fuel layer above a denser, horizontally oriented surface layer, even when un-mowed. The heterogeneous quality of these fuels is exaggerated following mastication, where higher surface fuel loads are even more compact, but under a quickly recovering vertical shrub layer. In experimental burns where these mowed fuelbeds were reconstructed, Kreye et al. (2013a), showed fireline intensity was observed to be greater per unit flame length than Byram's (1959) relationship, which is used to predict flame lengths in the Behave model. The relationship between flame lengths and fireline intensity may not be consistent in these types of heterogeneous fuel scenarios, where shrubs are burning above combustion in a much denser surface layer beneath.

Using current fire modeling techniques to assess fuel treatment effectiveness may be problematic (Varner and Keyes, 2009) and their use likely depends upon the specific ecosystems in which treatments occur. Research that compares model predictions with fire behavior observed in masticated treatments is lacking and the few that exist vary in regard to how well models predicted fire behavior (Kobziar et al., 2009; Knapp et al., 2011). Models are generally used as a prediction tool across a site, stand, or landscape, and are typically not used to predict fire behavior at a more localized plot scale. Inaccurate predictions at our plot scale does not necessarily mean that the underlying physical processes involved in combustion are not accurately portrayed by the model, even though average error rates across our plots were generally high (Cruz and Alexander, 2013). Mismatches between observed and predicted outputs may occur for several reasons. Whether fuel or meteorological inputs were inaccurate at our scale, if model parameters are inappropriate for these kinds of fuelbeds, or if the model has fundamental errors is unknown. But, even if models are sufficient to predict fire behavior for management purposes, predicting fire effects may be limited where dense surface fuels, beneath a burning shrub layer, may be generating localized heat for long durations. Fuel models developed specifically for masticated sites will need to incorporate the heterogeneous aspect of the fuelbed to better predict potential heating of surface and soil layers, and ultimately fire effects to the ecosystem.

Empirical evaluation of the efficacy of mechanical fuel treatment at altering fire behavior and effects is difficult, especially under experimental control. We have observed here that the mitigating effect of mowing on fire hazard in a common pine ecosystem of the southeastern US is applicable to observed fire behavior, but not necessarily to fire effects. When planning treatment regimes that incorporate both mowing and prescribed fire, timing will likely be critical in order to mitigate rapid fuel recovery and burn under conditions to avoid potential unforeseen consequences, all while meeting management objectives.

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Table 1. Weather, overstory, fuel conditions, fire behavior, and fire effects during experimental burning of mechanically treated (mow+burn) and untreated (burn) stands of palmetto/gallberry pine flatwoods in north-central Florida, USA. Values sharing letters within metrics are not statistically different (Tukey-Kramer Test, α=0.05). ǂ indicates marginal differences (p<0.10)

	Burn Date	Temp	RH	Windspeed	Litter Moisture	KBDI
		˚C	*%*	*km·hr^{-1}*	*%*	
Mow+Burn	23 Feb 2011	17-24	47-62	1.6-4.8	12.1 (0.6)^{A}	107
Burn Only					17.8 (2.4)^{B}	107

	Tree Density	Basal Area	QMD	Height	CBH
	trees·ha^{-1}	*m^{2}·ha^{-1}*	*cm*	*m*	*m*
Mow+Burn	307 (64)^{A}	18.9 (4.4)^{A}	27.8 (1.6)^{A}	21.0 (0.7)^{A}	14.7 (0.9)^{A}
Burn Only	365 (63)^{A}	15.2 (1.7)^{A}	23.9 (1.9)^{A}	20.7 (1.6)^{A}	15.1 (1.1)^{A}

	Shrub Cover	Shrub Height	Shrubs	Shrub Foliage
	%	*cm*	----------------*Mg·ha^{-1}*-------------	
Mow+Burn	32.5 (3.6)^{A}	58 (13)^{A}	0.6 (0.3)^{A}	0.4 (0.2)^{A}
Burn Only	77.5 (4.0)^{B}	145 (8)^{B}	4.4 (0.5)^{B}	4.1 (0.5)^{B}

Surface Fuels

	Litter Depth	Duff Depth	Litter	Duff	1 h	10 h	100 h
	------------*cm*----------		---------------------------------*Mg·ha^{-1}*---------------------------				
Mow+Burn	6.0 (0.4)^{A}	3.5 (0.6)^{A}	13.4 (0.9)^{A}	38.8 (6.5)^{A}	1.1 (0.2)^{A}	2.1 (0.3)^{A}	1.1 (0.6)^{A}
Burn Only	7.4 (0.4)^{B}	4.8 (0.9)^{A}	8.6 (0.5)^{B}	53.3 (9.5)^{A}	0.5 (0.1)^{B}	1.1 (0.4)^{A}	0.7 (0.3)^{A}

Fire Behavior and Effects

		ROS	Consumption				Tree Injury		
			Litter	Duff	Litter	Duff	Scorch	Char	Char Ht
	m	*m·min^{-1}*	-------*Mg·ha^{-1}*---------		-------*%*-------		*%*	*%*	*m*
Mow+Burn	1.1 (0.3)^{A}	3.4 (1.0)^{A}	9.6 (0.9)^{A}	2.6 (1.9)^{A}	71 (4)^{A}	5 (3)^{A}	29 (5)^{A}	88 (2)^{A}	5.6 (0.3)^{A}
Burn Only	3.3 (0.5)^{B}	7.1 (2.1)^{A}	6.4 (0.4)^{B}	9.0 (3.7)^{A}	75 (2)^{A}	13 (5)^{A}	57 (6)^{B}	93 (3)^{A}	6.7 (0.4)^{B}

Table 2. Comparison of burning conditions (weather, overstory, and fuels) between a summer and winter burn in masticated palmetto/gallberry pine flatwoods of north-central Florida, USA. Values sharing letters within metrics are not statistically different (Tukey-Kramer Test, α=0.05). Ɨ indicates marginal differences (p<0.10)

	Burn Date	Temp	RH	Windspeed	Litter Moisture	KBDI
		°C	*%*	*$km \cdot hr^{-1}$*	*%*	
Summer	28 Jul 2010	31-34	61-76	1.6-7.2	14.7 (1.1)$^{\text{A}}$	425
Winter	23 Feb 2011	23-24	47-49	1.6-2.7	12.1 (0.6)$^{\text{AƗ}}$	107

	Tree Density	Basal Area	QMD	Height	CBH
	$trees \cdot ha^{-1}$	*$m^2 \cdot ha^{-1}$*	*cm*	*m*	*m*
Summer	290 (27)$^{\text{A}}$	23.1 (3.0)$^{\text{A}}$	32.0 (2.6)$^{\text{A}}$	23.3 (0.9)$^{\text{A}}$	15.8 (0.8)$^{\text{A}}$
Winter	307 (64)$^{\text{A}}$	18.9 (4.4)$^{\text{A}}$	27.8 (1.6)$^{\text{A}}$	21.0 (0.7)$^{\text{AƗ}}$	14.7 (0.9)$^{\text{A}}$

	Shrub Cover	Shrub Height	Shrubs	Shrub Foliage
	%	*cm*	-----------------*$Mg \cdot ha^{-1}$*--------------	
Summer	na	69 (7)$^{\text{A}}$	0.9 (0.5)$^{\text{A}}$	0.5 (0.2)$^{\text{A}}$
Winter	na	58 (13)$^{\text{A}}$	0.6 (0.3)$^{\text{A}}$	0.4 (0.2)$^{\text{A}}$

<u>Surface Fuels</u>

	Litter Depth	Duff Depth	Litter	Duff	1 h	10 h	100 h
	------------*cm*----------		--------------------------------*$Mg \cdot ha^{-1}$*---------------------------				
Summer	4.9 (0.7)$^{\text{A}}$	5.3 (0.8)$^{\text{A}}$	10.9 (1.6)$^{\text{A}}$	58.8 (9.4)$^{\text{A}}$	4.1 (1.0)$^{\text{A}}$	6.6 (0.6)$^{\text{A}}$	2.5 (1.1)$^{\text{A}}$
Winter	6.0 (0.4)$^{\text{A}}$	3.5 (0.6)$^{\text{A}}$	13.4 (0.9)$^{\text{A}}$	38.8 (6.5)$^{\text{A}}$	1.1 (0.2)$^{\text{B}}$	2.1 (0.3)$^{\text{B}}$	1.1 (0.6)$^{\text{A}}$

<u>Fire Behavior and Effects</u>

	Flame Ht	ROS	Consumption				Tree Injury		
			Litter	Duff	Litter	Duff	Scorch	Char	Char Ht
	m	*$m \cdot min^{-1}$*	-------*$Mg \cdot ha^{-1}$*---------		-------*%*-------		*%*	*%*	*m*
Summer	1.5 (0.1)$^{\text{A}}$	5.9 (1.8)$^{\text{A}}$	5.5 (1.3)$^{\text{A}}$	23.1 (10.1)$^{\text{AƗ}}$	48 (7)$^{\text{A}}$	32 (11)$^{\text{AƗ}}$	25 (5)$^{\text{A}}$	69 (4)$^{\text{A}}$	5.3 (0.4)$^{\text{A}}$
Winter	1.1 (0.3)$^{\text{A}}$	3.4 (1.0)$^{\text{A}}$	9.6 (0.9)$^{\text{B}}$	2.6 (1.9)$^{\text{A}}$	71 (4)$^{\text{B}}$	5 (3)$^{\text{A}}$	29 (5)$^{\text{A}}$	88 (2)$^{\text{B}}$	5.6 (0.3)$^{\text{A}}$

Table 3. Number of trees (longleaf or slash pine) dead or alive across three treatments at two years following burning in palmetto/gallberry pine flatwoods.

	Burn Only[a] (winter)	Mow+Burn[b] (winter)	Mow+Burn[c] (summer)	Total
Dead	6	1	3	10
Alive	53	59	41	153
Total	59	60	44	163

Note: All trees were alive prior to burning.

[a] Unmowed, burned Feb, 2011

[b] Mowed Aug, 2010, burned Feb, 2011

[c] Mowed Aug 2009, burned Jul, 2010

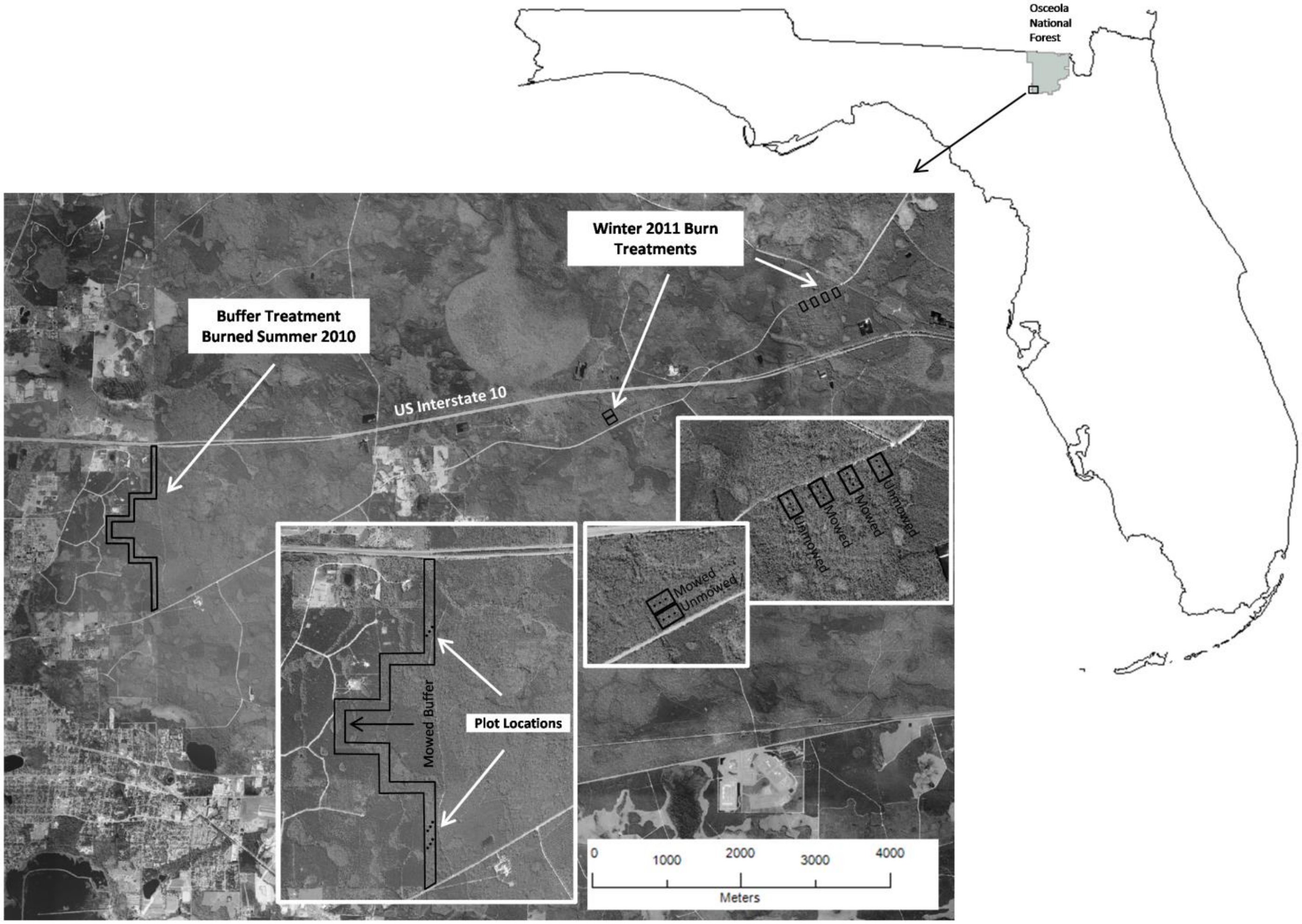
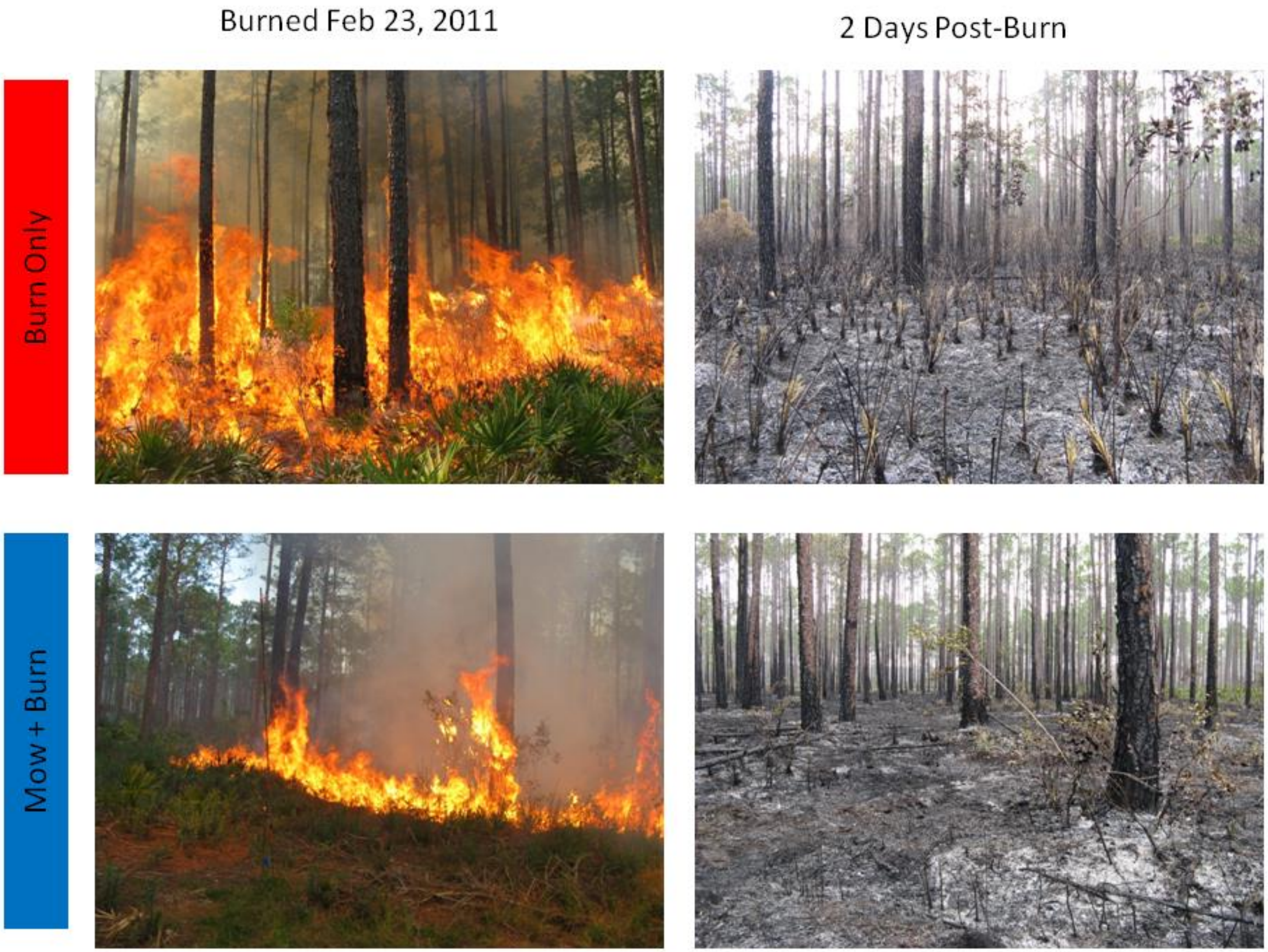


Figure 1. Experimental mowing and burning treatments in pine flatwoods in north-central Florida, USA (Osceola National Forest). Systematic plot locations are indicated in the subset figures.



654 Figure 2. Fire behavior in experimental mowing and burning treatments in pine flatwoods of north-central FL, USA. Burn only
655 treatments were unmowed, mow+burn treatments were mowed 6 months prior to burning.

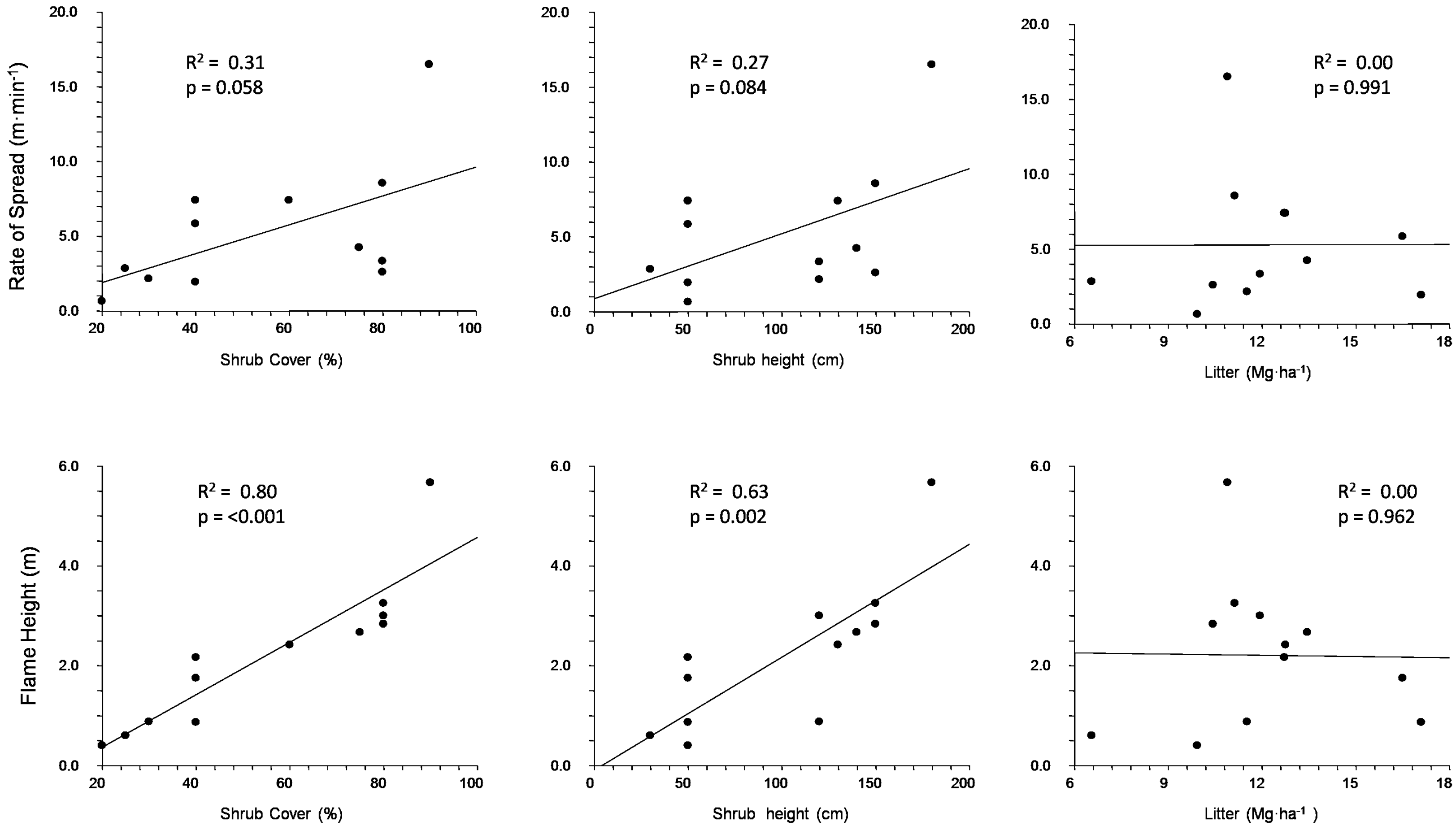

Rate of Spread (m·min-1)
R2 = 0.31
p = 0.058
Shrub Cover (%)
R2 = 0.27
p = 0.084
Shrub height (cm)
R2 = 0.00
p = 0.991
Litter (Mg·ha-1)
Flame Height (m)
R2 = 0.80
p = <0.001
Shrub Cover (%)
R2 = 0.63
p = 0.002
Shrub height (cm)
R2 = 0.00
p = 0.962
Litter (Mg·ha-1)

Figure 3. Fire behavior measurements (rate of spread, above; flame height, below) as a function of shrub cover (left), shrub height (middle), and litter mass (right) during the burning of mowed and un-mowed experimental treatments in pine flatwoods.

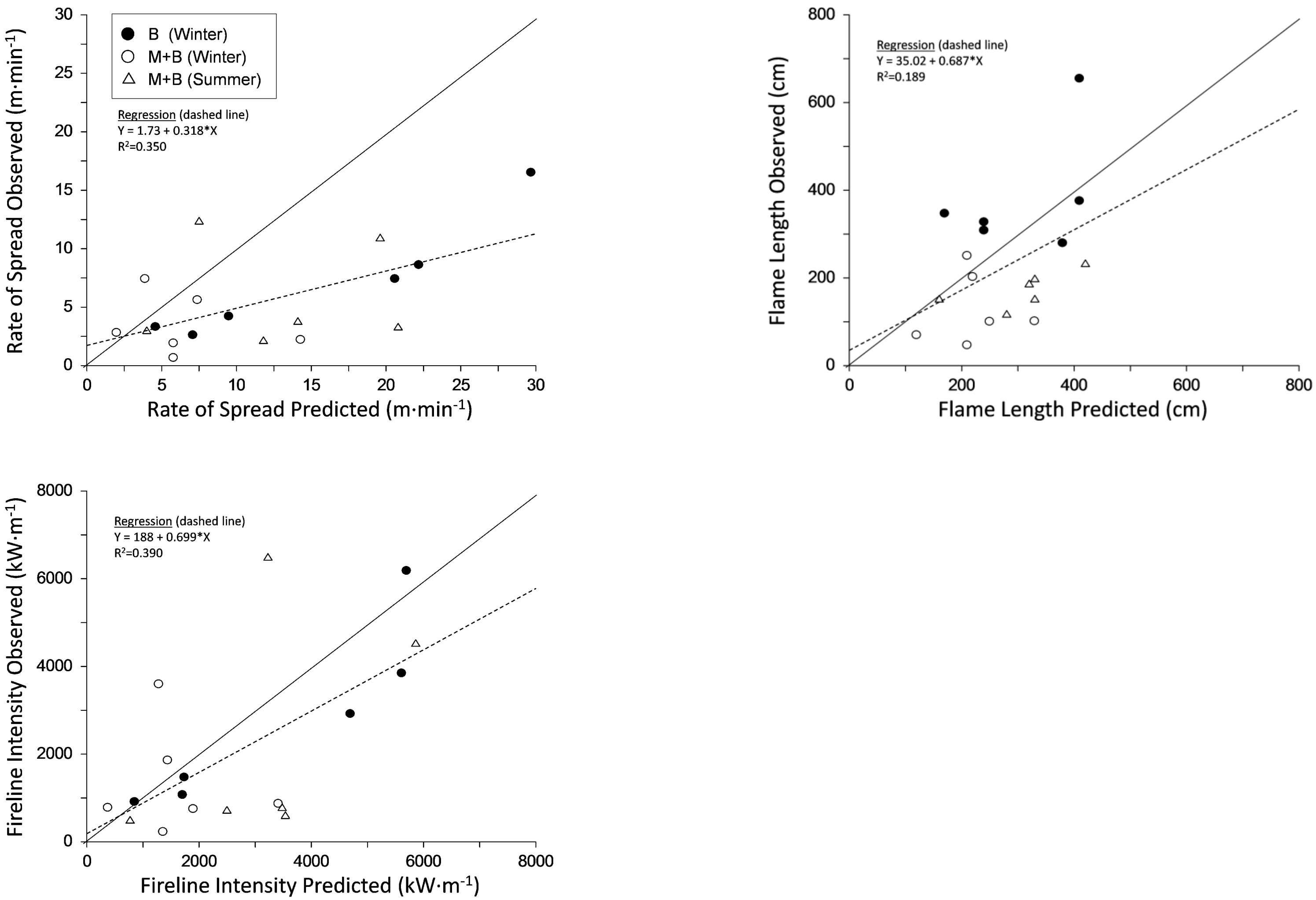

B (Winter)
M+B (Winter)
M+B (Summer)
Regression (dashed line)
Y = 1.73 + 0.318*X
R²=0.350
Rate of Spread Observed (m·min⁻¹)
Rate of Spread Predicted (m·min⁻¹)
Regression (dashed line)
Y = 35.02 + 0.687*X
R²=0.189
Flame Length Observed (cm)
Flame Length Predicted (cm)
Regression (dashed line)
Y = 188 + 0.699*X
R²=0.390
Fireline Intensity Observed (kW·m⁻¹)
Fireline Intensity Predicted (kW·m⁻¹)

Figure 4. Observed versus predicted fire behavior across burning treatments within mowed (M+B) and un-mowed (B) palmetto/gallberry pine flatwoods burned in the winter (Feb) and mowed treatments burned in the summer (M+B summer). Solid line, 1:1 ratio; Dashed line, linear regression.

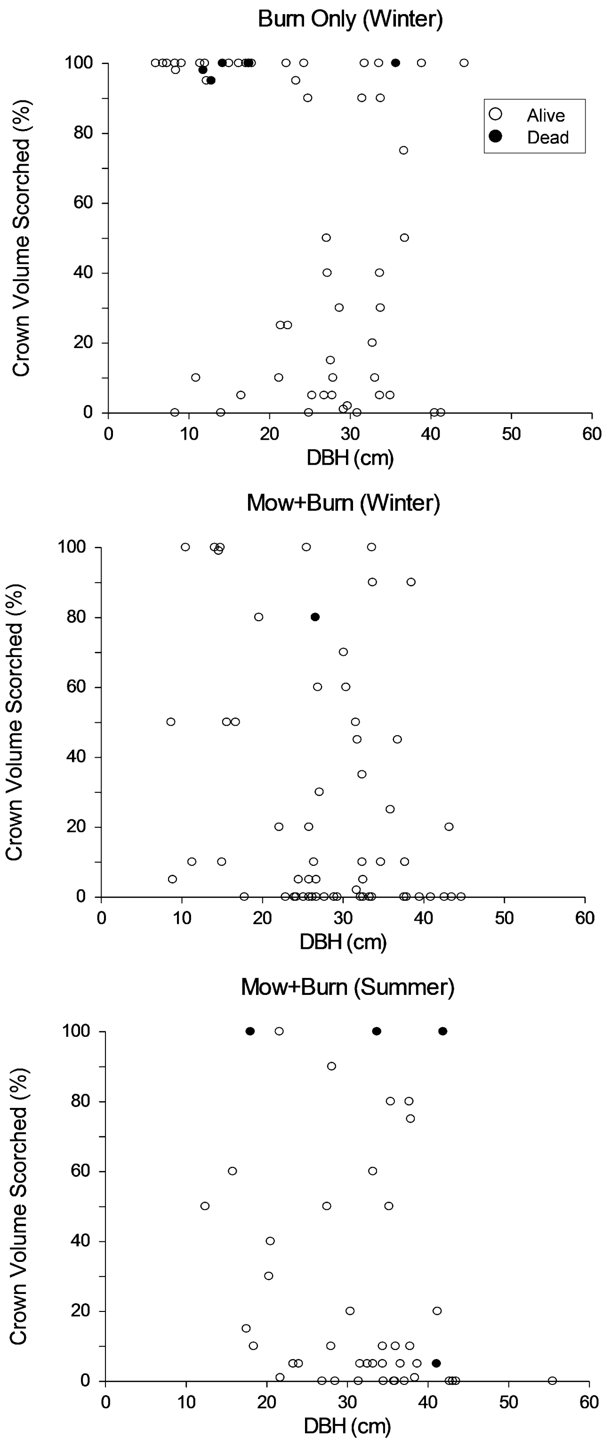


Figure 5. Crown volume scorched (%) versus tree diameter (DBH) and tree mortality following burning in unmowed (top) and mowed (middle) treatments burned in the winter (Feb) and mowed treatments burned in the summer (July, bottom).