EFFICACY AND ECOLOGICAL EFFECTS OF MECHANICAL FUEL TREATMENTS IN PINE FLATWOODS ECOSYSTEMS OF FLORIDA, USA

By

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A DISSERTATION PRESENTED TO THE GRADUATE SCHOOL
OF THE UNIVERSITY OF FLORIDA IN PARTIAL FULFILLMENT
OF THE REQUIREMENTS FOR THE DEGREE OF
DOCTOR OF PHILOSOPHY

UNIVERSITY OF FLORIDA

2012

To our son Raleigh (The "Skootcher")

ACKNOWLEDGMENTS

Funding for this project was provided by the Joint Fire Science Program, the USDA Forest Service, and the American Recovery and Reinvestment Act of 2009. I thank my major advisor, Leda Kobziar, who's continued support and motivation helped me to strive for success and who's professional resolve provides a template for my future endeavors . I thank my committee members, Wendell Cropper, Alan Long, Michelle Mack, and Timothy Martin, for all of their advice and comments. I also thank Wayne Zipperer, who's advice and support for this project was very helpful. I owe much gratitude to Mike Camp, who made this project a success through all of his hard work, in some of the harshest conditions. I thank the many others that worked on this project including Nick Bowman, Shannon McGee, Eric Carvalho, Liz Ramirez, Dawn McKinstry. I thank David Godwin for his help, especially during prescribed burning. I am very thankful for the support of all of the staff of the Osceola National Forest. I especially thank Peter Myers, Shawn Kinghorn, Byron Hart, and the rest of the Osceola fire crew for the many hours of work they provided to implement our research treatments. I thank Morgan Varner who instilled in me an excitement of scientific inquiry and to continually strive to ask questions, follow them to their resolve, and allow them to reveal new ones. I thank my aunt, Melissa Hennessey, for her inspiration as a firefighter with the USDA Forest Service for so many years. I thank my Mom for her much needed help while I worked on this dissertation and for her many years of support, and the rest of my family who have supported my endeavors. I thank the many friends who have encouraged me to achieve my goals. Lastly, and most importantly, I would like to thank my wife Melissa, for 15 years of supporting my dreams, and our newborn Raleigh, who inspires me to be a better person.

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of the University of Florida in Partial Fulfillment of the
Requirements for the Degree of Doctor of Philosophy

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August 2012

Chair: Leda N. Kobziar
Major: Forest Resources and Conservation

Mechanical fuels treatments are being widely used in fire prone ecosystems where fuel loading poses a hazard, yet little research comprehensively examining fuel dynamics, fire behavior, and ecological effects exists, especially in the southeastern US. In order to broaden our understanding of these treatments, effects of mechanical mastication ("mowing") were examined in a common pine ecosystem of the southeastern US Coastal Plain, where the post-mastication fuel environment is unique among ecosystems where mastication is being employed. Foliar litter dominates surface fuels after understory mastication in palmetto/gallberry pine flatwoods, however rapid recovery of shrubs quickly regains control over fire behavior. Treatments were effective at reducing flame heights during post-treatment burning in these sites, however compact surface fuels were observed to cause long-duration heating during laboratory burning. Overstory tree mortality observed following summer burning in these treatments may have resulted from combustion of the compact surface fuels beneath the shrub layer. Although temperature and humidity at the shrub level were little influenced by treatments, drier surface fuels existed in masticated sites where shrub cover was reduced, potentially exacerbating combustibility of the surface fuel layer.

Treatments had little impact on understory vegetation communities or soil nutrients, however reduction in saw palmetto evidenced in this study may alter future groundcover vegetation as slight increases in grass cover were observed here. The fast recovery of understory vegetation and generally low impact to ecosystem attributes suggest resiliency of these pine flatwoods to mechanical treatments, however their effectiveness at reducing fire hazard is likely short-lived. 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 surface litter consumption, while minimizing potential impacts to the overstory and meeting overall management goals.

CHAPTER 1
INTRODUCTION

Fire is a dominant ecological process in many ecosystems worldwide, however maintaining natural fire regimes through active management is often difficult. Ecosystems vary in frequency, intensity, extent, and predictability of their historical fire regime (Agee 1993). While some ecosystems may go several decades or even centuries without fire, some have developed in the face of frequent fires that burn with relatively low intensity. Infrequently burned ecosystems will often burn with high intensity fire behavior that results in substantial alterations of ecosystem structure and composition due to years of fuel buildup. Fuel accumulation may occur as trees, understory and midstory vegetation, and surface debris. When high intensity fire burns in such an ecosystem, it may take decades or centuries to return to pre-disturbance structure and composition. In frequently burned ecosystems, however, fuel tends to accumulate as understory vegetation (e.g. grasses or shrubs) and surface debris (vegetative detritus) but are burned often enough that large quantities are not accumulated between successive fires. The plants that occur in these ecosystems are typically adapted to such a disturbance regime and may even depend on fire for their perpetuation. Therefore, fire adapted species tend to recover quickly following disturbance and thus maintain dominance in these ecosystems. When ecosystems typified by frequent low intensity fire regimes are subjected to years of fire absence, fire-adapted species may be overtaken by fire-sensitive species, but also fuel biomass can build to levels where high intensity fire behavior results when fire does occur.

Prescribed burning is utilized as a management tool to maintain short interval fire frequencies in fire adapted ecosystems and reduce fuel buildup to decrease fire hazard for health and safety of human populations. It is often difficult, however, to maintain frequent enough fire cycles over large areas due to logistics and management constraints, especially in the wildland-urban-interface (WUI) where human population is in close proximity to managed ecosystems. In areas where high fuel buildup has occurred, it is hazardous to return fire into forest and shrublands where expected fire behavior could pose a risk to the public or cause detrimental damage to the ecosystem. Returning fire to long unburned ecosystems is desirable to mitigate long-term fire hazard, but also for ecological restoration purposes. In forest ecosystems where fire frequency has declined through years of fire suppression, and fuel buildup is too hazardous to burn, fuel management techniques are often used to alter fuel structure prior to reintroduction of fire or as a stand-alone treatment option where burning is difficult. In areas where substantial buildup of mid-story trees has occurred, treatments are often silvicultural. Thinning may be used to reduce overstory or midstory density and increase average crown base height, reducing the potential for vertical movement of surface fire into forest canopies. Other treatments may target understory shrub fuels by reducing them through mechanical methods, which may be used in concert with silvicultural treatments. The goals of such treatments include reducing potential fire intensity, lowering the risk of crown or canopy fires, and enhancing ecosystem resistance to future fires (Agee and Skinner 2005).

Mastication of understory shrubs and small trees is a fuels treatment method that has become increasingly used across the United States (US) (Glitzenstein et al. 2006, Kane et al. 2009, Kobziar et al. 2009, Battaglia et al. 2010, Menges and Gordon 2010) and elsewhere (Molina et al. 2009, Castro et al. 2010). Mastication is a process in which shrubs and small trees are chipped, shredded, or mowed using front end or boom mounted machinery attached to ground-based equipment, usually rubber tired or tracked. Mastication machinery typically consist of a mastication head with either rotating blades or a rotating cylinder with fixed or flailing cutters. Mastication heads are hydraulically controlled by the operator and thus allow for manipulation of vegetation with little impact to the ground surface. This is different than methods, such as roller-chopping (Watts and Tanner 2006), that use weighted drums pulled behind ground equipment to push over and chop understory vegetation, however causing soil damage in the process. Mastication largely impacts understory vegetation with little impact to ground fuels or overstory trees.

Mastication treatments are being used in several shrub and forest ecosystems across the US, yet much of the research addressing their ecological impact, their fuel characteristics, or their effectiveness at reducing fire hazard has been conducted in the western US (Busse et al. 2005, Bradley et al. 2006, Hood and Wu 2006, Kane et al. 2009, Kobziar et al. 2009, Vailant et al. 2009, Battaglia et al. 2010, Kreye et al. 2011, Rhoades et al. 2012, Kreye et al. 2012). Much of this research has indicated potential consequences of burning in post-treatment surface debris (Busse et al. 2005, Bradley et al. 2006, Knapp et al. 2011, Kreye et al. 2011) as heavy surface fuel loadings result from treatments where fuel loading is not reduced, but only rearranged into compact woody-dominated surface fuelbeds (Kane et al. 2009, Kobziar et al. 2009, Battaglia et al. 2010). Reduction in fire behavior from these treatments may come at the cost of unforeseen ecological impacts.

Mastication is being widely employed in the southeastern US also and has gained some research attention, however widespread use of these treatments are occurring with little understanding of their effectiveness or impacts. A few studies have begun to compare mastication (mowing) treatments with other fuel treatments such as prescribed burning or roller chopping (Menges and Gordon 2010), however no studies have fully described post-treatment fuel characteristics, evaluated fuel dynamics over time, and determined treatment effectiveness at reducing fire hazard.

Pine flatwoods are a common ecosystem in the Coastal Plain of the southeastern US. They are typified by an overstory of pines (*Pinus palustris* Mill., *P. elliottii* Engelm., *P. taeda* L.) with a shrub understory. In the lower Coastal Plain, flatwoods are dominated by fire resistant *P. palustris* and *P. elliottii* in the overstory and by saw palmetto (*Serenoa repens* (Bartr.) Small) and gallberry (*Ilex glabra* L. (Gray)) shrubs in the understory. These flatwoods have a frequent fire regime, burning every 3-10 years, with shrubs that recovery quickly following burning being the dominant fuel driving fire behavior. Fire management in this ecosystem requires burning at least every five years, or sooner, to maintain desired fuel characteristics to minimize hazardous fire behavior. Mastication (mowing) treatments are being employed in areas that have gone as little as five years without burning, but are being prioritized in flatwoods stands that have gone even longer without fire. While mastication is largely being used as a means to alter fuel structure prior to reintroducing fire, their effectiveness at mitigating fire hazard is unknown. And their potential ecological impacts, with or without follow-up burning, has not been assessed. The uniqueness of this ecosystem regarding its fuel environment (Hough and Albini 1978, McNab et al. 1978) is likely to result in a unique fuel environment when masticated.

Mastication has become such a widespread fuels treatment method that fully understanding its effectiveness, as well as impacts, across the many ecosystems in which it is being employed is necessary to evaluate its use. Assessing impacts of such treatments on the fuel environment, elucidating fire behavior in their resulting fuelbeds, determining their efficacy at fire hazard reduction, and evaluating their ecological impacts will provide a more holistic determination of their effectiveness as a management tool. In order to more fully understand mastication as a fuels treatment option in palmetto/gallberry pine flatwoods of the southeastern US, the research presented here aimed to evaluate the effects of mastication on the fuel environment, fire behavior, and ecological attributes. The objectives of these studies were to 1) describe fuelbed characteristics in masticated stands and evaluate fuel dynamics over time; 2) quantify fuelbed-level effects on fire behavior in masticated residues; 3) determine the effect of mastication on fire behavior and effects at the stand scale; and 4) evaluate the effects of mastication and mastication in conjunction with burning on vegetation dynamics, micro-climate, fuel moisture regimes, and soil nutrients. Addressing these issues should provide insight into the effectiveness and impacts of mastication in palmetto/gallberry pine flatwoods and improve our understanding of mastication as a fuels treatment option as a whole.

CHAPTER 2
FUELBED CHARACTERISTICS FOLLOWING MECHANICAL TREATMENTS OF UNDERSTORY FUEL STRATA IN PINE FLATWOODS ECOSYSTEMS OF FLORIDA, USA

Background

Altering fuel structure in forest and shrub ecosystems has become a common method to mitigate fire hazard in long unburned ecosystems. Mechanical mastication (mowing, shredding, chipping, etc.) of understory fuels rearranges shrubs and small trees into compact surface fuels (Hood and Wu 2006, Kane et al. 2009, Kobziar et al. 2009) with the intent to reduce subsequent fire behavior. In order to develop fuel models to aid in the prediction of fire behavior in these treatments, characterizing fuelbeds following mastication across different ecosystems will be important.

While recent research has started to describe the post-mastication fuel environment, much of this work has been conducted in the western US and has primarily revealed a woody-dominated surface fuelbed following treatment (Hood and Wu 2006, Kane et al. 2009, Kobziar et al. 2009, Battaglia et al. 2010). Pine flatwoods of the southeastern US with understories dominated by saw palmetto (*Serenoa repens* (Bartr.) Small) and gallberry (*Ilex glabra* L. (Gray)) shrubs are unique in regard their fuel characteristics (Mcnab et al. 1978). Saw palmetto is a shrub palm that grows from horizontal stems and reaches approximately 2 m in height . Historically, fires were frequent in this ecosystem and understory shrubs typically recover quickly following burning. Mastication in this fuel complex will likely result in unique post-treatment fuelbeds that may deserve special attention for fire behavior prediction. Characterizing post-mastication fuelbeds in palmetto/gallberry understories will support the creation of fuel models and provide a range of fuelbed characteristics not likely to occur following mastication in other ecosystems.

Mastication, or "mowing", of palmetto/gallberry understories in pine flatwoods is being conducted in large scale applications in northern Florida, USA to reduce fire hazard during post-treatment prescribed burning. Mowing is also being used as a stand-alone treatment where burning is difficult in the wildland-urban interface, but where altering fuel structure is intended to reduce potential fire behavior during a wildfire. While many shrub species in this ecosystem sprout following aboveground damage and saw palmetto will continue to produce new frond growth following burning, it will be important to understand fuelbed dynamics following treatments to better predict future fire behavior and understand treatment efficacy on mitigating fire hazard.

The objectives of this study were to 1) characterize surface fuelbeds following the mowing of palmetto/gallberry dominated pine flatwoods and 2) quantify changes in fuels for up to two years following treatment in three stand types: mature, mature/recently burned, and plantation.

Methods

Study Site

Fuel characteristics were measured in mechanically treated sites on the Osceola National Forest (ONF) in northern peninsular Florida, USA. The ONF encompasses 81,000 ha that occur in parts of Columbia, Baker, Bradford, and Hamilton counties. The terrain is generally flat with underlying marine deposited sandy soils. Climate is characterized by hot humid summers with mild winters and most precipitation occurring during summer months from thunderstorms. Dominant vegetation communities on the ONF include mesic and hydric pine flatwoods and cypress-hardwood swamps.

Mechanical fuels treatments on the ONF were conducted primarily in pine flatwoods communities that have gone unburned for several years and where fuel accumulations pose a hazard within the wildland urban interface (WUI). Pine flatwoods in this region are dominated by slash pine (*Pinus elliottii* var. *elliottii* (Engelm.)) and/or longleaf pine (*Pinus palustris* Mill.) with an understory comprised primarily of saw palmetto and gallberry . Because these systems recover to pre-burn fire hazard levels in less than five years (Davis and Cooper 1963), management goals are to burn pinelands on an average three-year rotation, although many pine flatwoods areas have not burned in over five years. Challenges to management on the ONF include very large burn units, extensive WUI including major interstate highways, wilderness areas isolated by wetlands, and a history of fire exclusion or excessively long fire return intervals in many locations. Thus, mechanical mowing treatments are being used to create firebreaks, reduce the height of understory fuels for re-introduction of prescribed fire, and to reduce fire hazard in areas abutting communities, highways, or large private pine plantations.

For this study, fuels were sampled within two mowing treatments in the southwestern portion of the ONF. One, a large contiguous area (500 ha) adjacent to Interstate 10 is referred here as the 'areal' treatment, and the other, a 100 m wide, 6 km long buffer treatment (60 ha) is adjacent to privately owned pine plantations. Each treatment occurred within pine flatwoods ecosystems, however, the areal treatment site was in mature pine (ca. 80 yrs old) flatwoods, while the buffer treatment occurred across three different pine flatwoods stand types: mature (ca. 80 yrs old), mature/burned (ca. 80 yrs old, burned 5 yrs prior to mowing), and a younger pine plantation (27 yrs old).

Areal Treatment

To characterize fuelbed properties following mowing in pine flatwoods, fuels and vegetation were sampled from 16 plot locations within the 500 ha areal treatment (Figure 2-1). Plots were allocated using a systematic grid randomly located onto an aerial map of the treatment zone. A grid format was used such that the distance between all grid line intersections was 400 m. Relative plot locations were systematically located using a grid pattern to better facilitate repeated sampling, however, of all possible grid intersections, 16 were randomly selected as sample locations. In addition, sampling locations were only used that occurred within mature pine stands, i.e. if a randomly selected grid intersection occurred within a wetland, it was not used. Plots were established and vegetation and fuels sampled in January 2010, just prior to mowing to evaluate pre-treatment vegetation and fuel loading. Vegetation and fuels were subsequently measured following treatment.

At each plot location, all trees were measured within a 201 m^2 (8 m radius) circular plot (Figure 2-2). Tree diameter at breast height (DBH: measured at 1.37 m above the ground), tree height, and the height to live crown base was measured for all trees ≥2.5 cm DBH, by species and by tree status (live or dead).

Shrubs ≥0.5 m in height were sub-sampled within two 4 m^2 rectangular belt transects (1×8 m) located at 4 m N and S of plot center, respectively, each extending to the 8 m plot radius (Figure 2.2). Height and basal diameter were measured for all shrubs. For individual saw palmetto (*Serenoa repens*), fronds were tallied for each individual and an average sized frond was selected for measurement of basal rachis diameter and frond (palm blade and rachis) length. Biomass of shrub woody stems and foliage were estimated, separately, for the dominant shrub species using published allometric equations (Smith and Brand 1983, Schafer 2010), except for saw palmetto. Saw palmetto biomass was estimated from an allometric equation developed in this study from 40 fronds, each collected from 40 different palmetto individuals in an adjacent stand, and regressed against basal rachis diameter and frond length. Gallberry (*Ilex glabra*) and saw palmetto were the most dominant shrub species in this study (Ch 5), however lesser occurrences of *Ilex coriacea*, *Vaccinium stamineum*, *V. myrsinites*, *Lyonia lucida*, *L. ferruginea*, and *Myrica cerifera* were also present, however species specific allometric equations were not available for all of these species. Allometric equations for *I. glabra* (Smith and Brand 1993) were used for *I. glabra* and *I. coriaceae*, equations for *Vaccinium* spp. (Smith and Brand 1993) were used for *V. stamineum*, equations for *Myrica pensylvanica* (Smith and Brand 1993) were used for *M. cerifera*, and equations for *Vaccinium scoparium*, a small statured shrub, were used for *V. myrsinites*, a shrub with similar habit. Because these shrub species were not as abundant in this ecosystem and the respective species used as surrogates were similar in form, biomass estimates across sites are probably reasonable for fuels analysis. Specific allometric equations for *Lyonia lucida* and *L. ferruginea* were from Schafer (2010). Herbs, grasses, and vines are a minor component regarding the fuel complex and were not quantified for evaluation of fuel dynamics in this study. However, they were assessed in a more complete vegetation analysis in an ecological assessment of treatments in the buffer treatment (Ch 5).

Surface fuels were quantified using a non-destructive planer intercept method (Brown 1974). To estimate coarse (CWD) and fine woody debris (FWD), woody fuels were tallied, by timelag diameter classes, along four 10 m transects extending from 4 m N, S, E, and W, respectively, from plot center, and each oriented at a random azimuth (Figure 2.1). FWD include the 1h (<0.635 cm), 10h (0.635 - 2.54 cm), and 100h (2.54 - 7.62 cm) timelag fuel classes. 1h and 10h fuels were tallied within the last meter of each transect, away from plot center, and 100h fuels were tallied within the last 2 m. CWD (>7.62 cm) was tallied, and diameter measured, along the entire 10 m transect. CWD was further categorized into two decomposition classes: sound and rotten. Woody fuel loading ($Mg \cdot ha^{-1}$) was estimated from tallies using Brown's (1974) equations and fuel characteristics of palmetto/gallberry pine flatwoods from Hough and Albini (1978). Litter depth and duff depth were measured along each planer intercept transect at the transect origin and at 8 m. Litter mass was then estimated from litter depth measurements using reported bulk density ($16.1\ mg \cdot cm^{3}$) of a 20-yr rough flatwoods site in the longleaf pine (LLP 09) photo series for quantifying natural fuels (Ottmar and Vihnanek 2000). Because duff mass was assumed to not change following mowing, pre-treatment duff mass was estimated from bulk density values measured from destructive sampling following mowing (described below).

Following mowing treatment (ca. 2 months), all plots were re-sampled using the above methods. To fully describe post-mowing fuelbed characteristics, however, surface fuels (FWD, litter, and duff) were destructively sampled, transported to the laboratory, sorted, oven-dried, and weighed. 1×1 m quadrats were allocated 1m from the end of two randomly selected fuels transects in each plot (Figure 2-2). All FWD and litter was collected from the entire quadrat and duff collected from a 0.25 x 0.25 m nested quadrat. Woody fuel depth and litter depth were measured at four locations within the quadrat and duff depths were measured at four locations within each nested quadrat, prior to the removal of material (Figure 2-2). Litter and FWD were separated in the laboratory. FWD was subsequently sorted into timelag classes (1,10, and 100h) and further into fractured and non-fractured particles. Fractured particles were those in which a minimum of 50% of the length was physically altered from mowing. Litter, FWD, and duff were all oven dried at 65˚C for 72 h. Preliminary analysis of duff samples 'floated' in water for 24 h indicated very little mineral soil content (<5% by weight). The transition from duff to mineral soil is quite distinct, therefore mineral soil was not removed from duff samples collected from quadrats. At the quadrat level, the relationship between litter mass and average litter depth, as well as the relationship between duff mass and average duff depth, were evaluated using linear regression. The resulting linear regression equations were then used to estimating litter and duff mass from depth measurements using non-destructive planer intercept methods for post-masticated sites in the rest of the study. Average bulk density was calculated for FWD, litter, and duff. It was assumed that duff biomass was not altered during mowing, but that bulk density may have increase from machine operations. And since destructive sampling was not conducted prior to treatment, pre-treatment bulk density was calculated using average pre-treatment duff depth, post-treatment duff depth, and post-treatment bulk density, assuming duff mass had not changed.

One year following mowing treatment (spring 2011), plots were re-sampled using the destructive sampling to determine changes in surface fuel loading and whether litter or duff bulk density changed as surface fuels settled over the first year following treatment. One 25×25 cm quadrat was randomly located at each plot. Litter and duff depths were measured and debris collected, oven dried, and weighed as was conducted above. Linear regression was also used to determine if the relationship between litter depth and litter mass, and duff depth and duff mass had changed.

Data Analysis

Mean, range, and standard deviation were reported for all fuelbed characteristics measured from destructive sampling. Linear regression was used to evaluate the relationships between litter depth and litter mass, as well as duff depths and duff mass, for both post- and one year post-treatment, from destructive sampling. From non-destructive sampling, overstory characteristics (tree density, basal area (BA), quadratic mean diameter (QMD), tree height, and tree crown base height (CBH)), shrub characteristics (density, height, biomass), biomass of surface fuels (1h, 10h, 100h, 1000h, litter, duff), and fuel depths (FWD, litter, duff) were each compared between pre- and post-treatment using a repeated measures analysis of variance (ANOVA) with plot as the subject. Tests for differences amongst the means were conducted at the α=0.05 level. Assumptions of normality and equal variance were tested with the Shipiro-Wilk and Modified-Levene Tests, respectively. As mentioned above, saw palmetto frond biomass was regressed against frond length and frond basal rachis diameter, separately, using linear regression to establish an allometric equation to estimate biomass from non-destructive sampling.

Buffer Treatment Zone

A 100 m wide, 6 km buffer zone was masticated along the southwestern boundary of the ONF adjacent to private pine plantations during the summer of 2009. Shrub vegetation and surface fuels were sampled immediately prior to treatment, and at 2, 8, 16, and 24 months following treatment using the same non-destructive sampling methods described above for the areal treatment. Trees were sampled using the same methods as in the areal treatment, but were only measured prior to treatment, post-treatment, and two years following treatment. The 8-mos sampling period was conducted at the beginning of the growing season (Mar, 2010), 16-mos sampling after the growing season (Oct, 2010), and 24-mos in Aug, 2011. Pre-treatment sampling plots were systematically located within the linear buffer and subsequently re-sampled following treatment. Allocation of plots within stand types (mature N=12, mature/burned N=9, plantation N=6) were weighted based on the linear distance of stand types along the buffer. Plots were allocated so that the total number of plots within any one stand type was divisible by three. Plots were spatially arranged in triplets at 15, 45, and 75 m from the buffer edge, but arranged at a 45˚ angle between plots in reference to the edge of the buffer (Figure 2-3). They were spatially established by locating the center of the stand type unit, to reduce edge influence from adjacent stand types, and were arranged so that an equal number of plots were located on either side of the center of the unit.

Shrub biomass was estimated using the same methods described in the areal treatment. Pre-treatment litter and duff mass were estimated from depth measurements using the same procedures as the areal pre-treatment estimations. Two and eight month post-treatment litter and duff mass were estimated from depth measurements using the regression equations developed from destructive sampling in the areal treatment just after treatment, while litter and duff mass at 16 and 24 months following treatment were estimated from depth measurements using the regression equations developed from destructive sampling at one year following treatment in the areal site.

Data Analysis

Overstory tree characteristics (density, BA, QMD, height, CBH) were compared across stand types (mature, mature-burned, plantation) and time since treatment using analysis of variance (ANOVA). Shrub biomass (woody stems and foliage), surface fuel biomass (litter, 1h, 10h, and 100h woody), and total fuel biomass (shrub and surface fuel) were compared across stand types and time since treatment using ANOVA. Duff and 1000h fuels were not considered as surface fuel in this particular analysis, but were evaluated separately since they contribute to smoldering combustion and not flaming combustion at the fire's front. Shrub characteristics (shrub stem biomass, shrub foliar biomass, shrub height, and shrub density) were each compared across stand types and time since treatment using ANOVA. And biomass of all surface fuels, including duff and 1000h fuels, were each compared across stand type and time since treatment using ANOVA. For all ANOVA analyses, statistical significance was test at the $\alpha=0.05$ level, and the Tukey-Kramer post-hoc comparison of the means test was used to determine differences amongst groups. Each ANOVA was conducted as a within-subjects (repeated measures) analysis with time since treatment as the within-subject variable and each plot as the subject. When model assumptions were not met, data were log or square-root transformed to meet assumptions.

Results

Areal Treatment

From destructive sampling of surface fuels following treatment, surface fuel loading ranged from 9.6 to 35.6 Mg·ha^{-1} with foliar litter accounting for over two-thirds of mass, on average (Table 2-1). 1h, 10h, and 100h woody fuels accounted for only 18±7, 11±7, and 2±6 %, respectively. Average litter depth was 5.4±2.4 cm and litter mass, 12.6±5.5 Mg·ha^{-1}, while average duff depth was 3.6±2.0 cm, and duff mass 41.9±21.3 Mg·ha^{-1}. Of the fine woody fuels collected, only 20±8% of the 3.1±1.2 Mg·ha^{-}1 of 1h fuels, and only 25±20% of the 2.1±1.5 Mg·ha^{-1} of 10h fuels, were fractured following mowing. Only 2 plots had 100h fuels within sampling quadrats, one plot with a fractured particle and one with an unfractured particle, resulting in a 50% average fracturing of these rare larger fuels.

Post-mowing litter mass was correlated with litter depth measurements (R^2=0.93, p<0.001) and a regression equation was developed to estimate mass from depth measurements (Figure 2-4). One year following treatment, litter mass per unit depth was slightly higher than post-treatment, however less variation was explained by the regression model (R^2=0.74, p<0.001; Figure 2-4). Duff mass was well explained by duff depth following-treatment (R^2=0.94, p<0.001) and at one year post-treatment (R^2=0.97, p<0.001), however regression models indicate an almost 20% increase in bulk density one year following treatment (Figure 2-4). From the 40 saw palmetto fronds collected for allometry, frond mass was best predicted by total frond length (R^2=0.92, p<0.001) and a regression equation was developed to estimate biomass from non-destructive measurements (Figure 2-5).

Pre-treatment overstory in the areal treatment consisted of 358±39 trees per ha (tph), 18.8±2.3 m^2 per ha of basal area (BA), and a quadratic mean diameter (QMD) of 25.8±1.0 cm. Average tree height was 16.7±0.9 m and crown base height (CBH) was 12.0±0.8 m (Table 2-2). Following mowing, tree density was reduced to 277±38 tph ($p=0.002$), QMD increased to 29.8±1.2 cm ($p=0.002$), average tree height increased to 20.7±0.9 m ($p=0.004$), and CBH increased to 14.7±0.7 m ($p=0.002$). Since only small trees were removed during treatment, BA did not statistically differ following treatment ($p=0.577$), averaging 18.6±2.4 m^2. Shrub density (>0.5 m in height) was reduced from 4.2±0.5 individuals$\cdot m^{-2}$ to 0.6±0.2 individuals$\cdot m^{-2}$ ($p<0.001$) following mowing, and average height from 1.12±0.02 to 0.75±0.14 m ($p=0.015$). Shrub biomass was 3.68±0.49 Mg$\cdot ha^{-1}$ prior to mowing and only 0.24±0.08 Mg$\cdot ha^{-1}$ afterwards ($p<0.001$). From non-destructive sampling (planer intercept method) of surface fuels, biomass of 1h woody fuels increased from 1.7±0.3 to 2.7±0.5 Mg$\cdot ha^{-1}$ ($p=0.022$) and 10h fuels increased from 1.4±0.1 to 3.1±0.5 Mg$\cdot ha^{-1}$ ($p<0.001$) following mowing, however 100h and 1000h fuels did not change. Litter depth was reduced from 7.8±0.8 to 6.0±0.5 cm ($p=0.005$), but litter mass increased from 9.0±0.9 to 13.4±1.2 Mg$\cdot ha^{-1}$ ($p<0.001$). Duff depth was also reduced following treatment ($p<0.001$), from 5.8±0.5 to 3.8±0.4 cm, but duff mass did not change ($p=0.982$), averaging 42.0 Mg$\cdot ha^{-1}$,however duff mass calculations were developed based on the assumption that it would not be altered by treatment. Average depth of fine woody debris (1h,10h, and 100h) was 7.3 cm and did not change following treatment ($p=0.361$).

Buffer Treatment

Mowing in the buffer treatments reduced overstory tree density in all stand types (mature, mature-burned, plantation), but only significantly reduced basal area in the mature stands (Table 2-3). While density did not statistically differ between pre- and post-mowing in the plantation stands, density was lower 2 years following mowing. Quadratic mean diameter (QMD) in mature and mature-burned stands significantly increased, however QMD was not affected by mowing in the plantation. Average tree height increased in both mature stand types following mowing, but not in the plantation, however height did statistically increase in plantation stands two years later. In both mature and mature-burned stands, CBH was increased after treatment, but CBH increased again two years later in the recently burned stands. CBH only differed two years following treatment.

Shrub biomass was reduced following treatment in all stand types, but had increased by 16 months (Figure 2-6, Table 2-4). An interaction between time since treatment (TST) and stand type suggested that changes in shrub biomass following treatments differed amongst stand types. Plantations appeared to have less initial shrub biomass than both mature stands, while mature/burned stands appeared to recover to greater biomass after 16 months than both unburned stand types. Surface fuels increased by about 10 $Mg \cdot ha^{-1}$ in unburned mature stands and plantations, but only increased by 4 $Mg \cdot ha^{-1}$ in the recently burned stands. Total fuel loading (shrubs and surface fuels) did not change in mature/burned stands, however there was evidence of increases in total fuel in the unburned mature stands and especially in plantations. Regarding specific shrub characteristics, shrub foliage, which should translate into surface litter following mowing, was reduced by 2.0, 3.0, and 1.1 $Mg \cdot ha^{-1}$ in mature, mature/burned, and plantation stands, respectively (Figure 2-7, Table 2-5), while litter increased by 2.2, 2.9, and 5.9 $Mg \cdot ha^{-1}$ (Figure 2-8, Table 2-6). Shrub foliage increased across all stands by 16 months (Table 2-5). Shrub stems, which should translate into 1 or 10h woody surface fuels (shrub basal diameters were <1.0 cm), were reduced by 3.1, 1.6, and 0.3 $Mg \cdot ha^{-1}$, following treatment (Figure 2-7, Table 2-5), while 1h woody fuels increased by 2.8, 1.9, and 2.5 $Mg \cdot ha^{-1}$, and 10h fuels increased by 4.2, 0.4, and 2.9 $Mg \cdot ha^{-1}$ in mature, mature/burned, and plantation stands, respectively (Figure 2-8, Table 2-6). Therefore, shrub foliage reduction in both mature stand types were similar to litter increases, however more litter was added to surface fuels in plantations than what had occurred in shrub foliage. And while 1h and 10h woody fuel additions to mature/burned stands were close to shrub stem biomass masticated, woody fuel increases in the unburned mature stands and plantation were much higher than accounted for as shrub stem biomass masticated, especially in plantations. Average shrub heights did not differ following treatment across all stands, however shrub density was substantially reduced and recovered to pre-treatment densities after 16 months in unburned stands (mature and plantations), but recovery was not as high, by 16 months, in mature/burned stands.

As mentioned above, 1h and 10h surface fuels increased following treatments in all stand types, but 1h fuels were higher than pre-treatment values 16 months later (Figure 2-8, Table 2-6). 10h woody fuels were also higher than pre-treatment loading by 16 months, but only in unburned mature and plantation stands. 100h surface fuels were not as abundant as 1h and 10h fuels across planer intercepts and did not statistically differ across time since treatment ($p=0.500$), however these larger fuels were greater in biomass in the unburned mature and plantation stands compared to the recently burned mature stands. Surface litter increased following treatment, as mentioned above, however mowing in unburned plantation stands resulted in greater litter mass than unburned mature stands (p=0.006).

1000 h surface fuels, that contribute to smoldering combustion, were rare prior to treatment in all stand types. But, while 1000h sound fuels increased following mowing in all stand types, 1000h rotten fuels did not (Figure 2-9, Table 2-7). 1000h sound fuels increased more in unburned mature stands than in mature-burned stands, and increased even more in plantation stands. While 1000h sound fuels were observed in mature/burned stands after treatment, but not before, they were very rare. Duff, which also contributes to smoldering combustion, was not changed just after treatment in both unburned and recently burned mature stands, however duff mass increased following treatment in plantation stands. Duff mass was reduced after 8 months in plantations, while it increased in mature-burned stands.

Discussion

Surface fuelbeds following mowing in these palmetto/gallberry pine flatwoods were dominated by foliar litter, with less proportions of fine woody fuels. This is in contrast to many other post-masticated sites that have been studied, where fine woody fuels dominate (Glitzenstein et al. 2006, Kane et al. 2009, Kobziar et al. 2009, Battaglia et al. 2010). Few studies have addressed mastication in shrub or forest ecosystems of the southeastern US, especially in pine flatwoods (Menges and Gordon 2010). Of those studies, none fully describe fuelbed characteristics following treatment, but typically address a treatment effect on other attributes. Since pine flatwoods are typically burned on a frequent interval, stands that are in need of mechanical treatment from lack of fire may have not burned in as little as five years. Small trees are not abundant, shrubs are not very old, and saw palmetto, a dominant shrub, is primarily foliar. Therefore, litter dominated surface fuels following mastication is much different than in other ecosystems where treatments occur in older shrublands and forests with substantial under- and mid-story tree density.

Evidence of increased bulk density of litter and duff one year following treatment may be critical to post treatment burning objectives where surface fuel accumulation is desired. Compaction may result in increased moisture retention (Kreye et al. 2012), but also long duration heating when burned (Busse et al. 2005, Kreye et al. 2011). Meeting management goals when burning in these fuelbeds may require special attention to moisture dynamics in these fuels to ensure desired fuel consumption while minimizing potential effects. Long duration heating in compact surface fuels (Kreye et al. 2011) may result in ignition of duff and potential overstory mortality if conditions are dry (Varner et al. 2007). If surface fuels are slow to lose moisture (Kreye et al. 2012), however, desired fuel consumption may not occur even if flammability of shrubs is high enough to carry fire (Gagnon et al. 2010). Effective burning regimes in these novel fuelbeds may require additional knowledge to ensure that management objectives are likely to be met.

While shrubs were reduced following mowing in the three stand types studied in the buffer treatment they were recovering quickly as little as 16 months later. Treatment effectiveness in this system may be short-lived due to fast recovery of shrub biomass on top of the accumulation of surface fuels as a result of treatment. Even shortly after treatments occurred, total fuel that would contribute to flaming combustion (shrubs, litter, and fine woody fuels) was greater in the unburned mature and plantation stands in this study. While shrubs masticated during treatment translate to surface fuels, even higher total fuel loads in the unburned stands likely result from the smaller trees that were masticated during treatment, but not accounted for as pre-treatment fuels. Understory trees in this study were not considered combustible fuel since they are not primary drivers of fire behavior in this shrub dominated ecosystem (Hough and Albini 1978). Although, when masticated they will likely contribute to surface fire behavior as dead woody fuels and leaves are incorporated onto the forest floor. There were less understory trees in the mature stands that had been recently burned and total fuel loading was not increased by mowing. This is likely why pre-treatment shrub stem biomass in the burned stands translated to increases in 1h and 10h woody surface fuels, but more fine woody surface fuels were added to both unburned stand types than what was accounted for in pre-treatment shrub stems. Although a window of opportunity likely exists to conduct post-treatment burning prior to shrub recovery, the addition of surface fuels may be an important consideration in evaluating potential ecological consequences when these dense surface fuels burn.

Surface litter increases following treatment were much larger in plantation stands compared to pre-treatment shrub foliage, while they matched well with pre-treatment shrub foliage in both the burned and unburned mature stands. While understory trees masticated in both unburned stand types may have added to fine woody debris, they may not have contributed as much to litter compared to the shrubs that were masticated. Shrub density and biomass was higher in the unburned mature stands compared to plantations, and recently burned stands had even more shrubs than both. Saw palmetto is a dominant shrub in this ecosystem and should contribute heavily to surface litter when masticated since they are primarily foliar. Another potential reason for differences in post-treatment litter accumulation is that litter biomass estimates from depth measurements were calculated using the regression equation developed above. Although litter mass was predicted quite well from post-treatment depth measurements, destructive sampling occurred in mature stands, not plantations. If bulk density was lower in plantations, this may account for errors in mass estimation. Mowing equipment was constrained to move linearly in "alleys" between rows of planted pines. Compaction of surface material may have been more spatially restricted than in mature stands with less overstory density.

Large woody fuels (100h) don't contribute to the flaming front, but may result in undesired fire effects from long duration smoldering. Although rare across these stand types, there were some increases in 1000h sound fuels in this study. Most increases in these larger fuels were in unburned mature stands, and especially in the younger pine plantations, where larger understory trees were masticated. Treatments were such that small trees (<20cm DBH) were to be knocked over, but not further masticated after being on the forest floor. Upper portions of downed trees, however, were observed to have been masticated as equipment moved over the surface. This likely attributed to increases in 1h and 10h fuels, while adding to 1000h fuel loading from what remained. Duff is another portion of surface fuels that doesn't contribute to the flaming front, but is an important contributor to smoldering combustion and thus potential fire effects (Varner et al. 2007) and smoke production. It is unlikely that duff mass is affected from mowing even if it is compacted or rearranged. The increase in duff mass just after mowing in the plantation stands may have resulted from error associated with using the duff mass equation developed from the mature stands in the areal treatment above, however duff mass was then reduced at 8 months following treatment. The additional compaction of duff observed at one year following treatment in the areal treatment may have also occurred in the plantation stand, as evidenced by a decrease in mass at 8 months. Nonetheless it is unclear why such differences between stand types occurred and the use of the duff estimation equation in the pine plantation may not be appropriate.

This study revealed that post-mastication surface fuels in pine flatwoods are unique in their high proportion of litter, something not observed with mastication treatments in other ecosystems, and their fast recovery of shrub fuels. While shrubs are reduced following mowing, the effectiveness of treatments at altering fire behavior may be short-lived and follow up prescribed burning to reduce fuel loads or reintroduce fire to long-unburned stands will likely need to occur soon following mowing. The addition of surface fuels, however, especially in unburned pine flatwoods, may present fire managers with potential problems if burning in these compact surface fuels results in damage to fine roots or basal cambial tissue of trees (Varner et al. 2007, O'Brien et al. 2010a). Considerations regarding surface, duff, and soil moisture will need to be taken into account if prescribed burning is utilized as a follow up treatment with the goals of consuming surface fuels created from mowing. While this study provides insight into the dynamics of fuel characteristics following mowing in palmetto/gallberry pine flatwoods of the southeastern US, further research will be needed to elucidate how these fuel treatments burn and what potential ecological consequences may ensue from their use.

Table 2-1. Surface fuel characteristics following mowing in palmetto/gallberry pine flatwoods in northern Florida, USA from destructive sampling.

	Fuel Load ($Mg \cdot ha^{-1}$)		Fuel Depth (*cm*)		Fractured[a] (*%*)		Fuelbed Proportion[b] (*%*)	
	range	mean (sd)	range	mean (sd)	range	mean (sd)	range	mean (sd)
Litter	5.6 - 24.4	12.6 (5.5)	2.4-10.9	5.4 (2.4)	na		40-88	69 (13)
1h	1.4 - 6.0	3.1 (1.2)	-	-	6-33	20 (8)	7-29	18 (7)
10h	0.6 - 6.3	2.1 (1.5)	3.0-12.8[c]	7.4 (3.0)[c]	0-65	25 (20)	4-32	11 (7)
100h	0.0 - 5.9	0.4 (1.5)	-	-	0-100	50 (71)	0-24	2 (6)
Total	9.6-35.6	18.2 (6.6)	3.9-13.2	8.1 (2.8)	na		100	100
Duff	15.0-98.2	41.9 (21.3)	1.0-8.6	3.6 (2.0)	na		na	

[a] Percent of woody fuels (1,10, and 100h), by weight, that has been fractured at least 50% of its particle length,
[b] Proportion, by mass, of the total fuelbed associated with flaming combustion(does not include duff), [c] Depth of all fine woody debris (1h, 10h, and 100h)

Table 2-2. Overstory, understory, and surface fuel characteristics of a 500 ha mowing treatment in palmetto/gallberry pine flatwoods of northern Florida, USA. Surface fuels sampled non-destructively (planer intercept method).

	Trees					Shrubs[a]		
	Density	BA	QMD	Height	CBH	Density	Height	Biomass
	trees·ha^{-1}	*m^{2}·ha^{-1}*	*cm*	*m*	*m*	*ind·m^{-2}*	*m*	*Mg·ha^{-1}*
Pre-Treatment	358 (39)^{A}	18.8 (2.3)^{A}	25.8 (1.0)^{A}	16.7 (0.9)^{A}	12.0 (0.8)^{A}	4.2 (0.5)^{A}	1.12 (0.02)^{A}	3.68 (0.49)^{A}
Post-Treatment	277 (38)^{A}	18.6 (2.4)^{A}	29.8 (1.2)^{B}	20.7 (0.9)^{B}	14.7 (0.7)^{B}	0.6 (0.2)^{B}	0.75 (0.14)^{B}	0.24 (0.08)^{B}
	Surface Fuel Loading							
	1h	10h	100h	1000h-S	1000h-R	Litter	Duff	
	------------------------------------*Mg·ha^{-1}*------------------------------------							
Pre-Treatment	1.7 (0.3)^{A}	1.4 (0.1)^{A}	0.3 (0.1)^{A}	0.3 (0.3)^{A}	0.2 (0.2)^{A}	9.0 (0.9)^{A}	42.0 (3.6)^{A}	
Post-Treatment	2.7 (0.5)^{B}	3.1 (0.5)^{B}	0.6 (0.3)^{A}	0.4 (0.2)^{A}	0.3 (0.2)^{A}	13.4 (1.2)^{B}	42.0 (4.3)^{A}	
	Fuel Depth							
	FWD[b]	Litter	Duff					
	---------------*cm*---------------							
Pre-Treatment	7.2 (1.7)^{A}	7.8 (0.8)^{A}	5.8 (0.5)^{A}					
Post-Treatment	7.3 (0.9)^{A}	6.0 (0.5)^{B}	3.8 (0.4)^{B}					

[a] Shrubs >0.5 m in height, [b] Fine woody debris (1h, 10h, and 100h fuels)

Note: Values sharing letters within columns are not statistically different (α=0.05)

Table 2-3. Overstory characteristics following mowing treatments in three stand types of palmetto/gallberry pine flatwoods of northern Florida, USA.

	Stand Type mature	mature-burned	plantation	Stand Type	TST[a]	Stand Type ×TST
					p value	
Tree Density		*trees·ha^{-1}*		<0.001	<0.001	<0.001
Pre-Treatment	941 (179)^{A}	365 (36)^{A}	1120 (185)^{A}			
Post-Treatment	327 (58)^{B}	216 (30)^{B}	804 (82)^{AB}			
2yrs Post-Treatment	290 (46)^{B}	216 (30)^{B}	713 (71)^{B}			
Basal Area		*m^{2}·ha^{-1}*		0.029	<0.001	0.043
Pre-Treatment	28.3 (3.3)^{A}	17.9 (2.2)^{A}	34.0 (5.9)^{A}			
Post-Treatment	23.2 (2.9)^{B}	17.3 (2.4)^{A}	27.5 (2.2)^{A}			
2yrs Post-Treatment	23.4 (2.8)^{B}	18.2 (2.3)^{A}	26.3 (2.5)^{A}			
QMD		*cm*		0.004	<0.001	<0.001
Pre-Treatment	21.8 (1.7)^{A}	25.6 (2.1)^{A}	20.7 (0.4)^{A}			
Post-Treatment	32.2 (2.0)^{B}	32.8 (2.2)^{B}	21.0 (0.5)^{A}			
2yrs Post-Treatment	33.6 (1.7)^{B}	33.9 (2.2)^{B}	21.8 (0.6)^{A}			
Height		*m*		0.211	<0.001	<0.001
Pre-Treatment	12.9 (0.8)^{A}	16.2 (1.4)^{A}	18.9 (0.4)^{A}			
Post-Treatment	20.3 (1.4)^{B}	21.7 (0.4)^{B}	19.0 (0.2)^{A}			
2yrs Post-Treatment	22.0 (1.1)^{B}	22.8 (0.5)^{B}	21.9 (0.5)^{B}			
CBH		*m*		0.158	<0.001	<0.001
Pre-Treatment	8.3 (0.7)^{A}	10.5 (0.8)^{A}	13.6 (0.5)^{A}			
Post-Treatment	13.3 (1.1)^{B}	13.2 (0.4)^{B}	13.6 (0.3)^{A}			
2yrs Post-Treatment	14.8 (1.1)^{B}	15.7 (0.4)^{C}	15.7 (0.4)^{B}			

[a] Time Since Treatment

Note: Values sharing letters within columns are not statistically different (Tukey-Kramer Test, α=0.05)

Table 2-4. Biomass of shrubs, surface fuels, and total (shrubs and surface fuels) following mechanical mowing of understory shrubs and small trees in pine flatwoods of northern Florida, USA.

	Stand Type					
	Mature	Mature/Burned	Plantation	Stand Type	TST[a]	Stand Type ×TST
	---------------------*Mg·ha^{-1}*----------------------			-------------------------*p value*------------------------		
Shrubs				0.098	<0.001	0.008
Pre-Treatment	5.5 (1.4)^{A}	5.0 (0.9)^{A}	1.6 (0.5)^{A}			
2 months	0.6 (0.3)^{B}	0.5 (0.2)^{B}	0.2 (0.1)^{B}			
8 months	0.4 (0.2)^{B}	0.7 (0.2)^{B}	0.5 (0.3)^{B}			
16 months	0.8 (0.2)^{C}	2.3 (0.7)^{C}	1.1 (0.5)^{C}			
24 months	1.3 (0.3)^{C}	2.1 (0.5)^{C}	0.9 (0.3)^{C}			
Surface Fuels[b]				<0.001	<0.001	0.103
Pre-Treatment	11.1 (1.4)^{A}	13.2 (1.4)^{A}	13.9 (1.1)^{A}			
2 months	20.7 (1.7)^{B}	17.1 (1.7)^{B}	23.1 (2.7)^{B}			
8 months	15.9 (0.9)^{B}	14.0 (0.7)^{B}	22.1 (2.3)^{B}			
16 months	15.8 (1.3)^{B}	17.0 (1.8)^{B}	24.9 (2.8)^{B}			
24 months	16.2 (0.8)^{B}	15.7 (1.6)^{B}	24.1 (1.6)^{B}			
Total Fuel[c]				0.007	0.004	0.009
Pre-Treatment	16.6 (1.6)^{A}	18.2 (1.5)^{A}	15.5 (1.3)^{A}			
2 months	21.1 (1.9)^{B}	17.6 (1.8)^{A}	23.3 (2.8)^{AB}			
8 months	16.1 (0.9)^{A}	14.7 (0.9)^{A}	22.5 (2.3)^{AB}			
16 months	16.7 (1.3)^{AB}	19.3 (2.2)^{A}	26.0 (2.9)^{B}			
24 months	17.4 (0.8)^{AB}	17.8 (1.8)^{A}	25.0 (1.6)^{B}			

[a] Time Since Treatment, [b] includes litter, 1h, 10h, and 100h fuels; [c] shrubs and surface fuels

Note: Values sharing letters within columns are not statistically different (Tukey-Kramer Test, α=0.05)

Table 2-5. Shrub foliage and stem biomass, shrub height, and shrub density following mechanical mowing of understory shrubs and small trees in pine flatwoods of northern Florida, USA.

	Stand Type					
	Mature	Mature/Burned	Plantation	Stand Type	TST[a]	Stand Type ×TST
	---------------------*Mg·ha*$^{-1}$	----------------------		--------------------*p value*	----------------------	
Shrub Foliage				0.049	<0.001	0.306
Pre-Treatment	2.4 (0.5)[A]	3.2 (0.6)[A]	1.2 (0.4)[A]			
2 months	0.4 (0.2)[B]	0.2 (0.1)[B]	0.1 (0.1)[B]			
8 months	0.3 (0.2)[B]	0.4 (0.1)[B]	0.2 (0.1)[B]			
16 months	0.5 (0.2)[C]	1.5 (0.4)[C]	0.6 (0.2)[C]			
24 months	0.9 (0.2)[C]	1.4 (0.4)[C]	0.5 (0.1)[C]			
Shrub Stems				0.308	<0.001	0.002
Pre-Treatment	3.1 (1.1)[A]	1.8 (0.6)[A]	0.4 (0.2)[A]			
2 months	0.2 (0.1)[B]	0.2 (0.2)[B]	0.1 (0.1)[B]			
8 months	0.1 (0.0)[B]	0.3 (0.1)[BC]	0.3 (0.2)[BC]			
16 months	0.3 (0.1)[B]	0.8 (0.3)[C]	0.5 (0.3)[AC]			
24 months	0.4 (0.1)[B]	0.7 (0.2)[C]	0.4 (0.2)[AC]			
Shrub Height	------------------------*m*	-------------------------		0.347	0.078	0.788
Pre-Treatment	0.86 (0.10)[A]	0.79 (0.08)[A]	1.00 (0.08)[A]			
2 months	0.72 (0.08)[A]	0.67 (0.03)[A]	0.81 (0.12)[A]			
8 months	0.62 (0.14)[A]	0.73 (0.04)[A]	0.79 (0.17)[A]			
16 months	0.68 (0.08)[A]	0.78 (0.03)[A]	0.80 (0.02)[A]			
24 months	0.89 (0.08)[A]	0.76 (0.04)[A]	0.86 (0.03)[A]			
Shrub Density	----------------*individuals·m*$^{-2}$	-----------------		0.018	<0.001	0.018
Pre-Treatment	4.9 (0.8)[A]	13.3 (3.4)[AC]	2.3 (0.6)[A]			
2 months	0.5 (0.1)[B]	1.1 (0.3)[B]	0.8 (0.2)[B]			
8 months	0.6 (0.2)[B]	1.5 (0.3)[BC]	0.6 (0.3)[B]			
16 months	3.7 (0.9)[A]	5.2 (0.7[BC]	2.3 (0.5)[A]			
24 months	4.6 (1.1)[A]	7.6 (2.1)[C]	2.7 (0.4)[A]			

[a] Time Since Treatment

Note: Values sharing letters within columns are not statistically different (Tukey-Kramer Test, α=0.05)

Table 2-6. Biomass of litter and fine woody fuels (1h, 10h, 100h) following mechanical mowing of understory shrubs and small trees in pine flatwoods of northern Florida, USA.

	Stand Type Mature	Mature/Burned	Plantation	Stand Type	TST[a]	Stand Type ×TST
	---------------------*Mg·ha*$^{-1}$	----------------------		-------------------------*p value*	---------------------------	
1h woody				0.546	<0.001	0.090
Pre-Treatment	0.4 (0.1)^{A}	0.4 (0.1)^{A}	0.2 (0.0)^{A}			
2 months	3.2 (0.6)^{B}	2.3 (0.3)^{B}	2.7 (0.4)^{B}			
8 months	1.6 (0.4)^{C}	1.5 (0.2)^{C}	1.9 (0.4)^{C}			
16 months	0.8 (0.1)^{D}	0.8 (0.1)^{D}	1.5 (0.2)^{D}			
24 months	0.6 (0.1)^{D}	0.9 (0.1)^{D}	0.8 (0.0)^{D}			
10h woody				<0.001	<0.001	<0.001
Pre-Treatment	1.1 (0.3)^{A}	3.0 (0.7)^{A}	2.5 (0.7)^{A}			
2 months	5.3 (0.9)^{B}	2.6 (0.4)^{A}	5.4 (1.0)^{B}			
8 months	3.0 (0.5)^{A}	1.9 (0.3)^{A}	6.3 (1.4)^{B}			
16 months	2.5 (0.3)^{A}	1.9 (0.3)^{A}	5.6 (0.9)^{B}			
24 months	2.7 (0.4)^{A}	1.9 (0.3)^{A}	5.3 (0.8)^{B}			
100h woody				<0.001	0.500	0.060
Pre-Treatment	1.9 (1.2)	1.0 (0.5)	3.5 (0.9)			
2 months	2.8 (0.8)	0.4 (0.3)	1.3 (0.6)			
8 months	2.0 (0.5)	0.0 (0.0)	2.4 (1.5)			
16 months	2.5 (0.6)	0.0 (0.0)	3.1 (1.5)			
24 months	1.6 (0.5)	1.8 (1.5)	2.7 (0.8)			
Litter				0.006	<0.001	0.201
Pre-Treatment	7.7 (0.5)^{A}	8.9 (0.9)^{A}	7.7 (0.9)^{A}			
2 months	9.5 (0.9)^{BC}	11.8 (1.6)^{BC}	13.6 (2.7)^{BC}			
8 months	8.5 (0.9)^{B}	10.6 (0.7)^{B}	11.4 (0.9)^{B}			
16 months	9.8 (0.6)^{C}	14.3 (1.8)^{C}	14.7 (1.4)^{C}			
24 months	10.9 (0.6)^{C}	11.1 (0.8)^{C}	15.3 (1.0)^{C}			

[a] Time Since Treatment

Note: Values sharing letters within columns are not statistically different (Tukey-Kramer Test, α=0.05)

Table 2-7. Biomass of 1000h (sound and rotten) woody fuels and duff following mechanical mowing of understory shrubs and small trees in pine flatwoods of northern Florida, USA.

	Stand Type					
	Mature	Mature/Burned	Plantation	Stand Type	TST[a]	Stand Type ×TST
	---------------------*Mg·ha⁻¹*		----------------------	--------------------*p value*		----------------------
1000h-Sound				0.002	<0.001	0.138
Pre-Treatment	0.2 (0.2)[A]	0.0 (0.0)[A]	0.0 (0.0)[A]			
2 months	1.9 (0.7)[B]	0.4 (0.3)[B]	4.9 (2.1)[B]			
8 months	2.6 (1.0)[B]	0.4 (0.2)[B]	3.1 (0.8)[B]			
16 months	2.5 (1.2)[B]	0.2 (0.2)[B]	3.4 (1.3)[B]			
24 months	2.7 (1.3)[B]	0.7 (0.6)[B]	6.3 (2.1)[B]			
1000h-Rotten				0.874	0.269	0.755
Pre-Treatment	1.0 (1.0)[A]	0.0 (0.0)[A]	0.7 (0.5)[A]			
2 months	0.0 (0.0)[A]	0.2 (0.2)[A]	0.2 (0.2)[A]			
8 months	0.0 (0.0)[A]	0.0 (0.0)[A]	0.0 (0.0)[A]			
16 months	0.0 (0.0)[A]	0.0 (0.0)[A]	0.1 (0.1)[A]			
24 months	0.0 (0.0)[A]	0.2 (0.2)[A]	0.0 (0.0)[A]			
Duff				0.179	0.048	0.004
Pre-Treatment	62.1 (10.1)[A]	34.3 (5.5)[A]	36.3 (7.2)[A]			
2 months	56.5 (5.8)[A]	37.9 (2.9)[A]	67.3 (7.0)[B]			
8 months	64.3 (9.2)[A]	53.1 (6.6)[B]	50.9 (2.9)[AB]			
16 months	57.6 (8.2)[A]	51.1 (5.1)[B]	57.8 (9.9)[AB]			
24 months	48.5 (6.9)[A]	46.6 (4.4)[AB]	61.2 (3.1)[B]			

[a] Time Since Treatment

Note: Values sharing letters within columns are not statistically different (Tukey-Kramer Test, α=0.05)

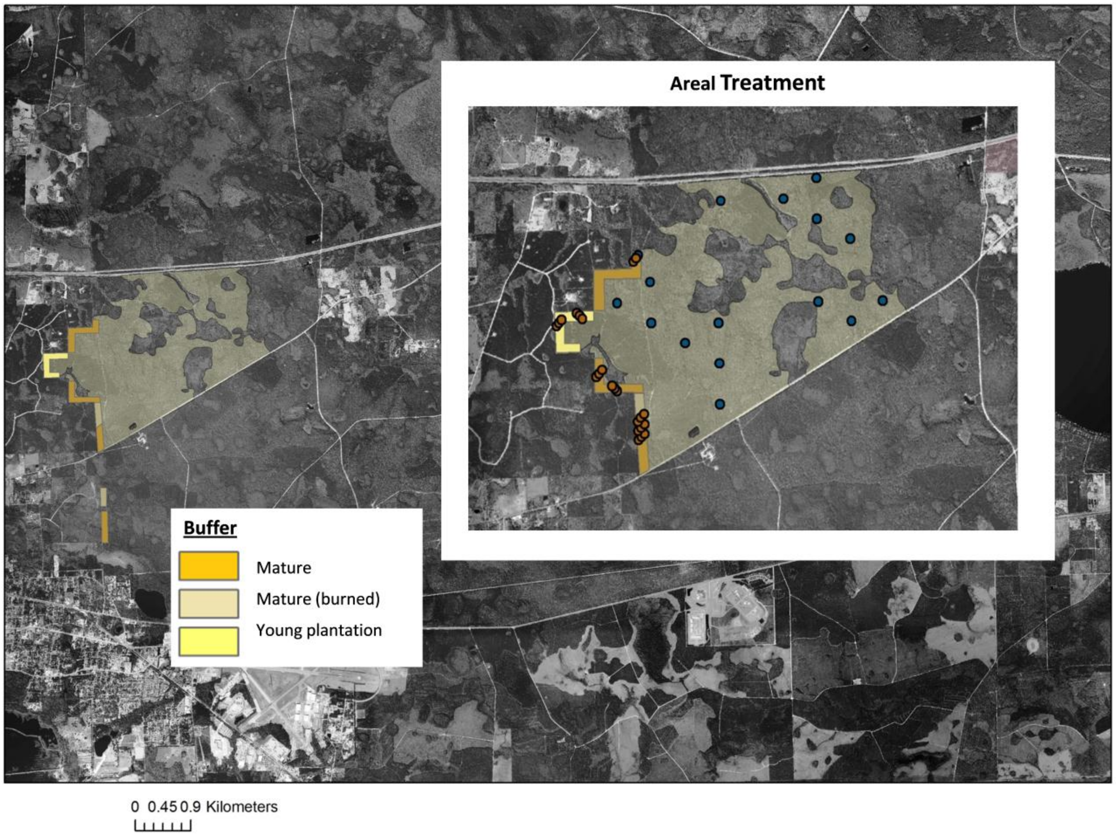

Figure 2-1. Areal (500 ha) and buffer (60 ha) treatments masticated in palmetto/gallberry pine flatwoods in northern Florida, USA.

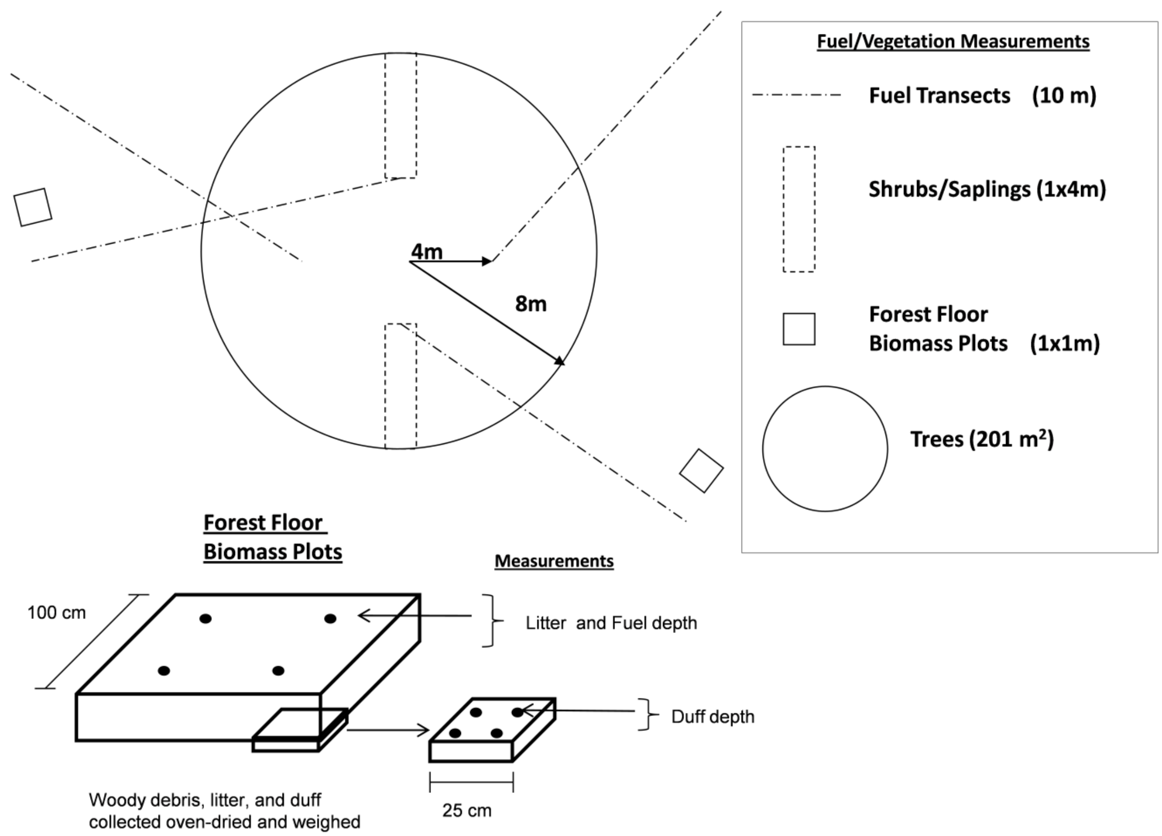

Figure 2-2. Fuels and vegetation sampling in the areal mowing treatment.

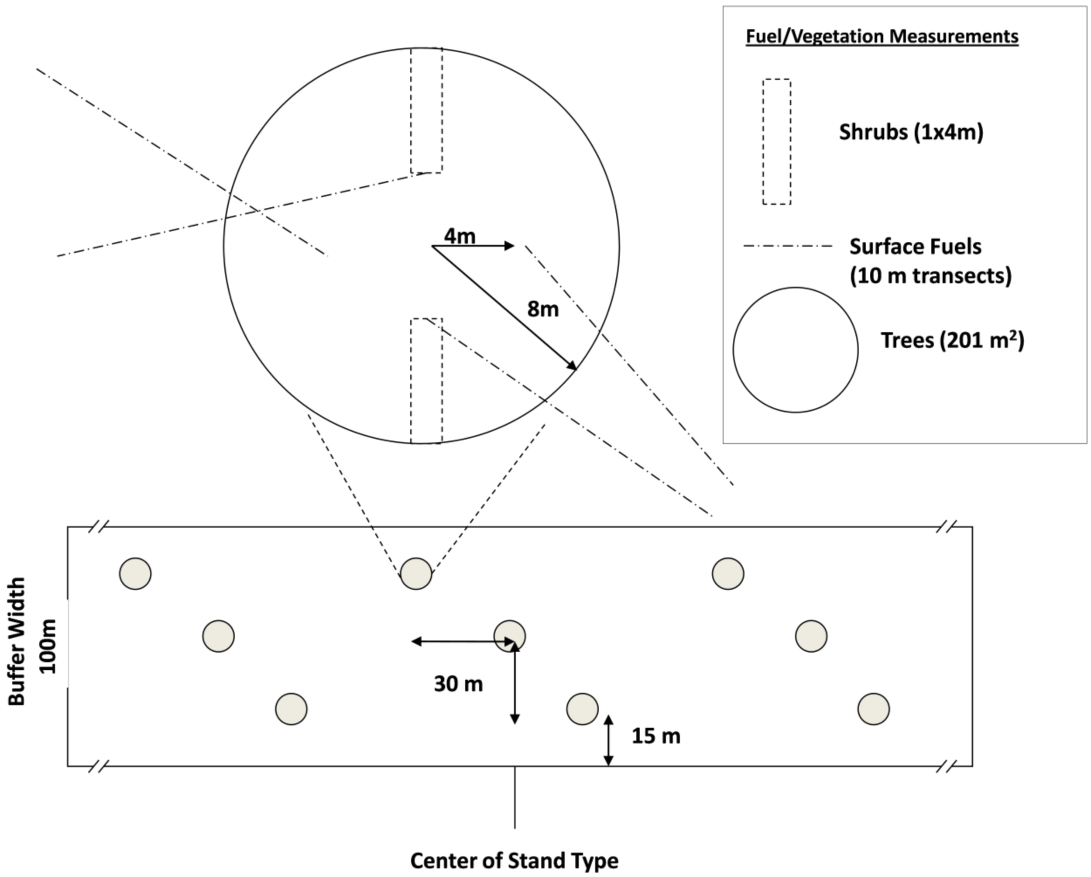

Figure 2-3. Fuels and vegetation sampling in the buffer treatment.

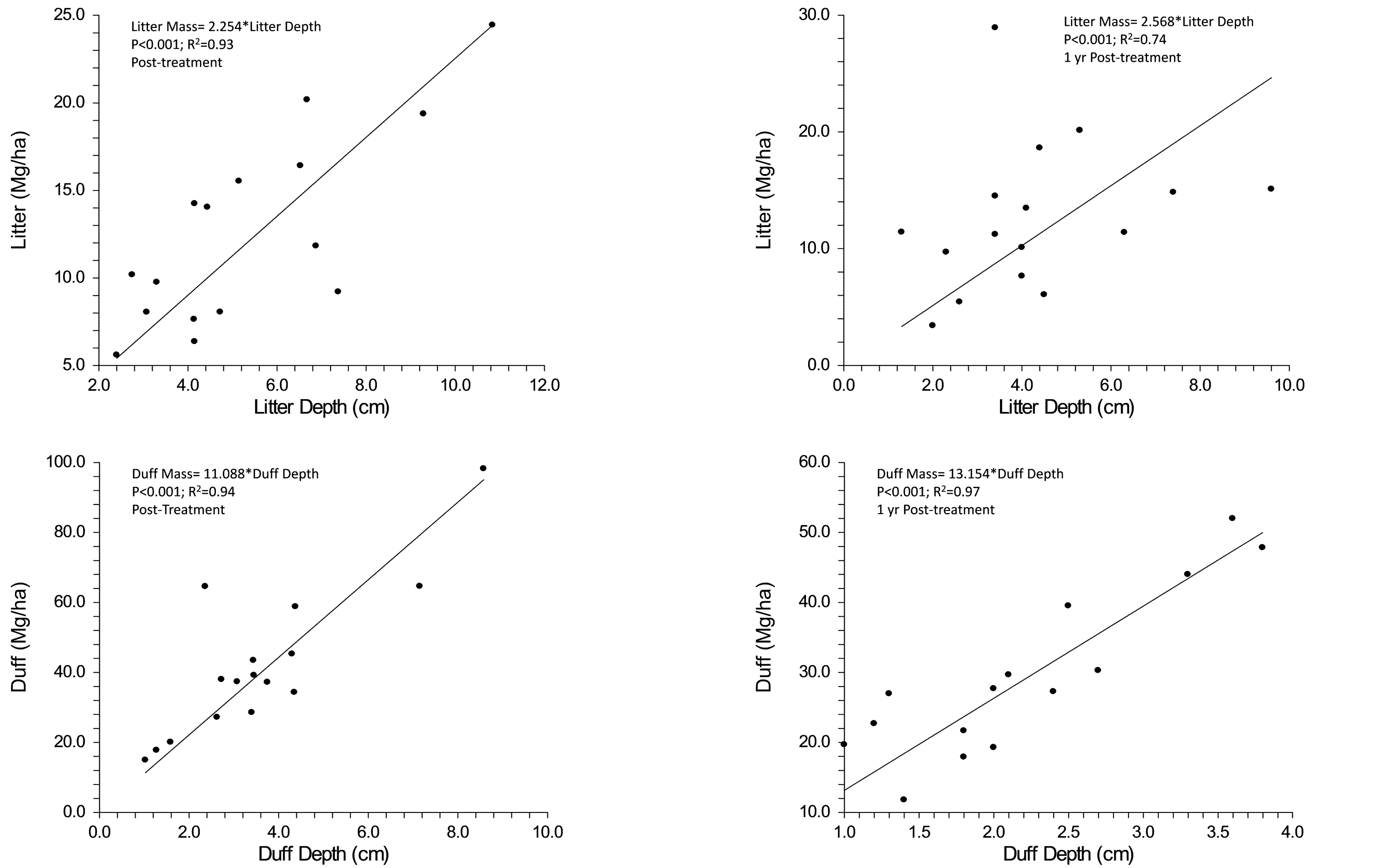

Figure 2-4. Litter (top) and duff (bottom) mass as a function of depth following mowing treatments in palmetto/gallberry pine flatwoods in northern Florida, USA. Measurement taken just after mowing (left) and one year following mowing (right).

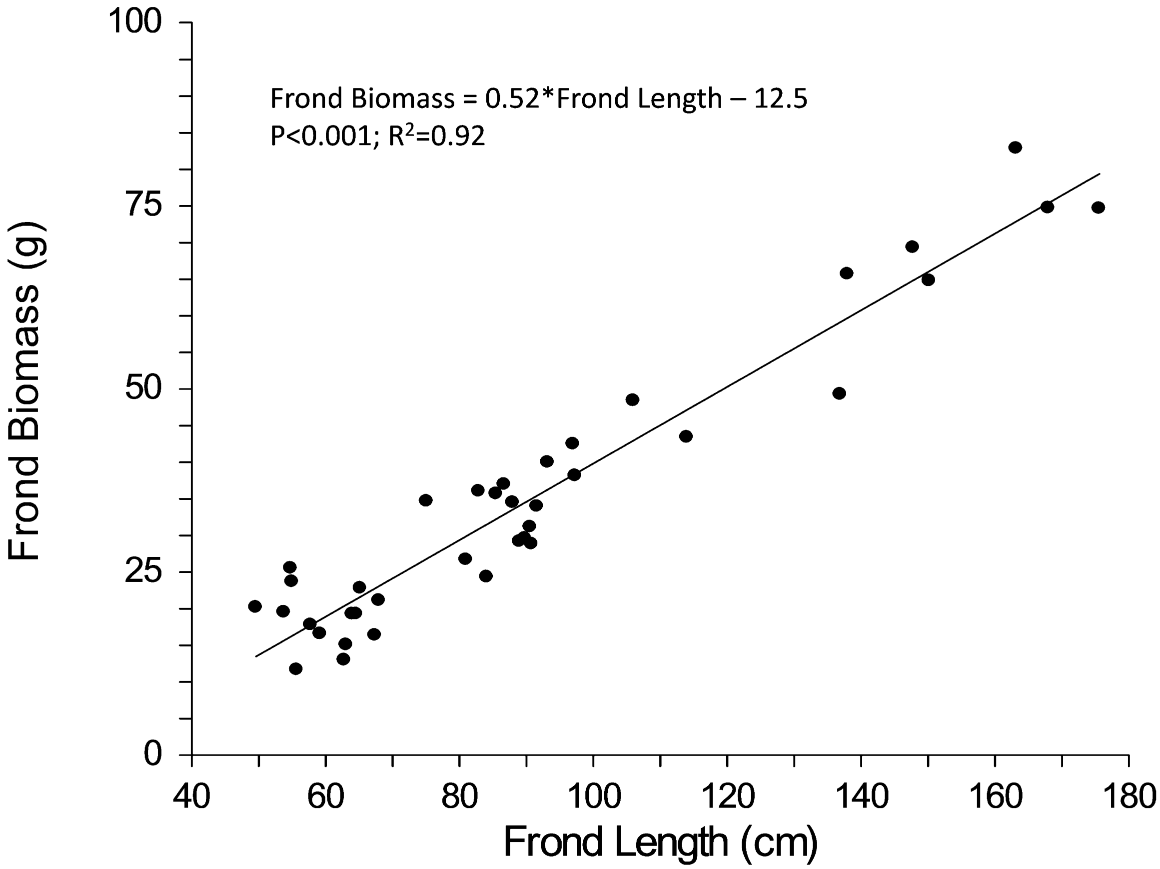

Figure 2-5. Saw palmetto allometry used for estimation of biomass from non-destructive sampling. Frond includes rachis and lamina.

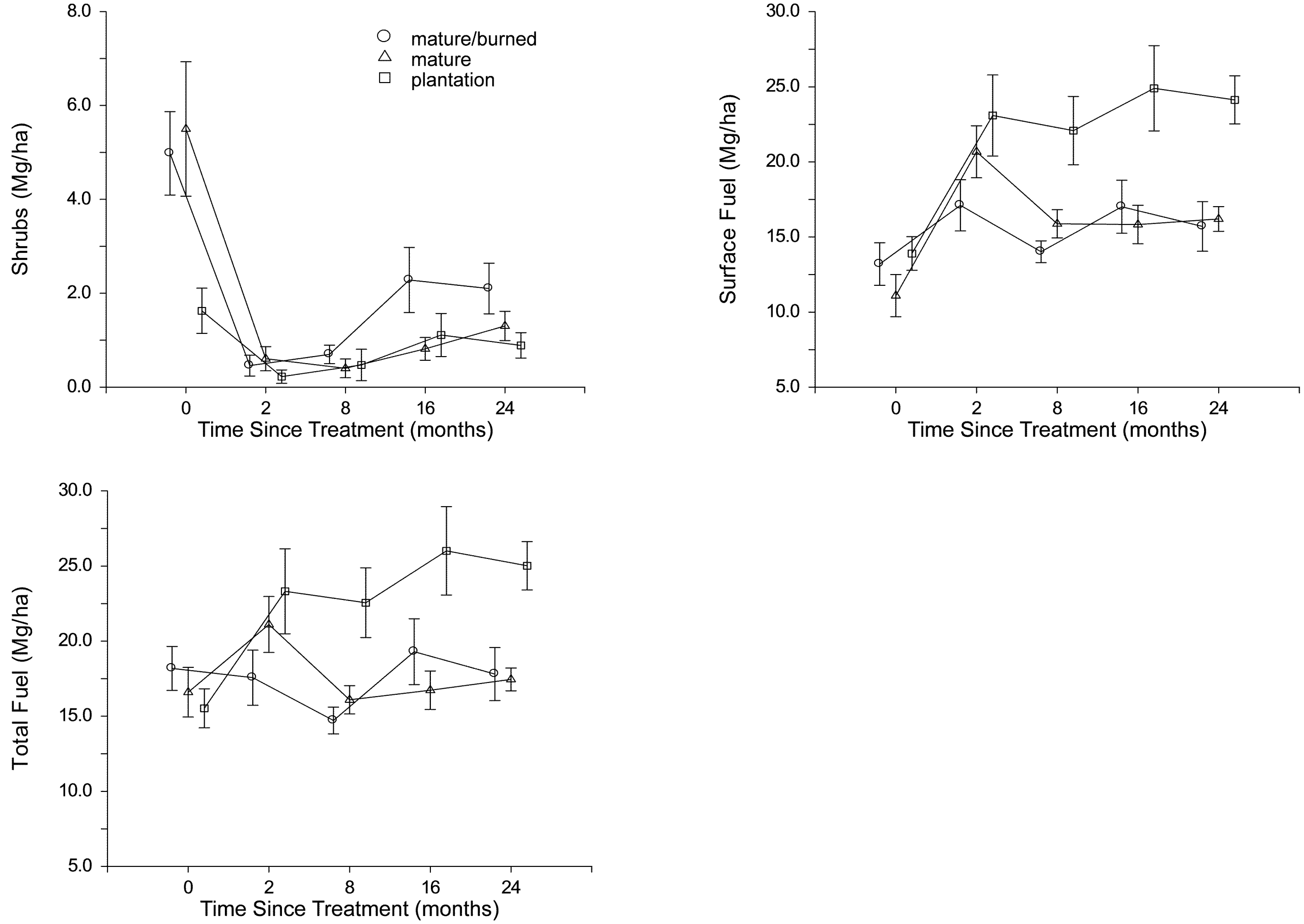

Figure 2-6. Shrubs, surface fuels (litter, 1h,10h, and 100h fuels), and total fuel (shrub + surface) loading ($Mg \cdot ha^{-1}$) following mowing treatment in 3 stand types (mature, mature/burned (burned 5 yrs prior to mowing),plantation) of palmetto/gallberry pine flatwoods in northern Florida, USA. (0 time since treatment= pre-treatment)

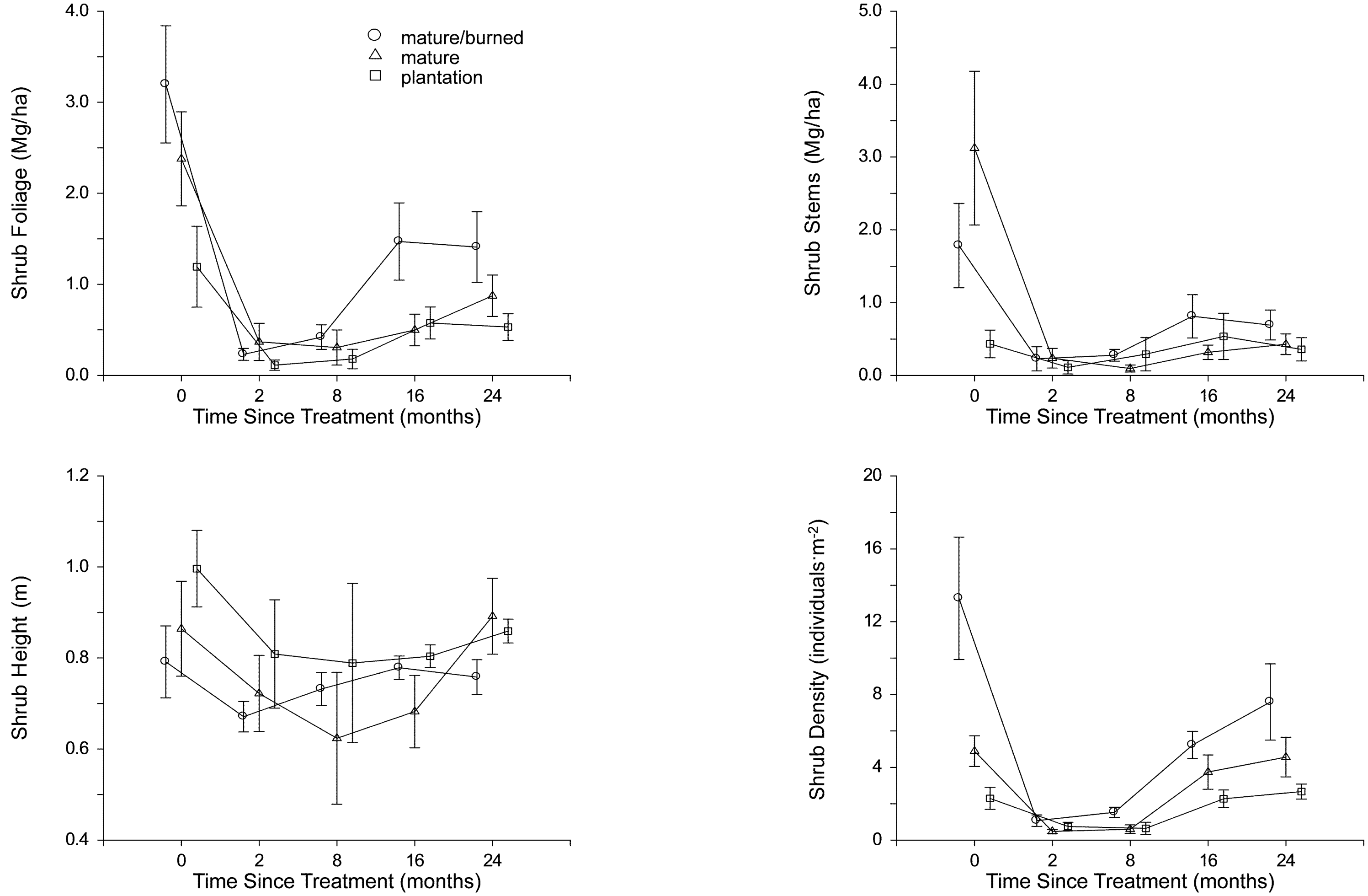

Figure 2-7. Shrub foliage and shrub stem biomass, shrub height, and shrub density following mowing treatment in 3 stand types (mature, mature/burned (burned 5 yrs prior to mowing),plantation) of palmetto/gallberry pine flatwoods in northern Florida, USA. (0 time since treatment= pre-treatment

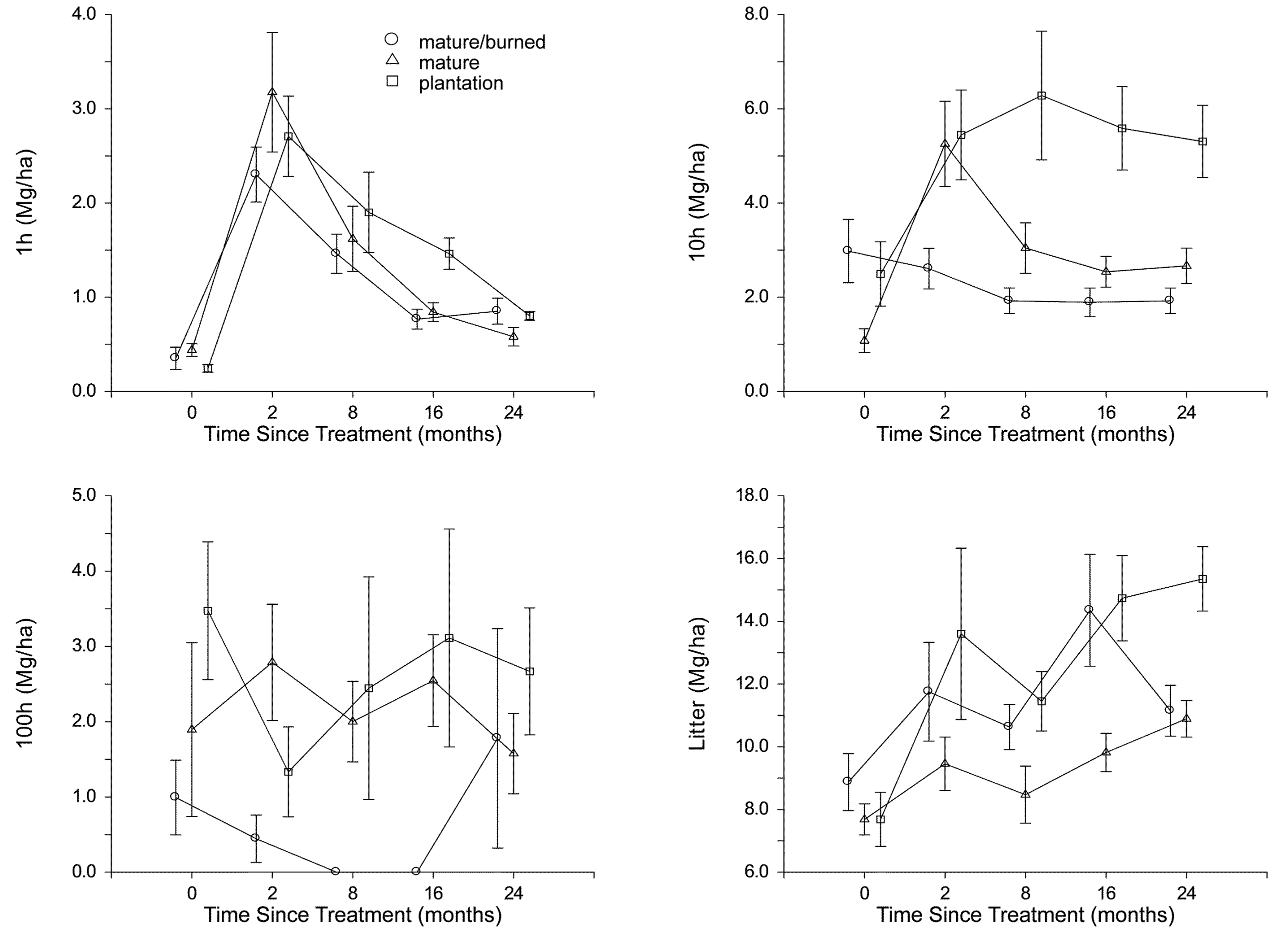

Figure 2-8. Surface fuel components (1h, 10h, 100h, and litter) following mowing treatment in 3 stand types (mature, mature/burned (burned 5 yrs prior to mowing),plantation) of palmetto/gallberry pine flatwoods in northern Florida, USA. (0 time since treatment= pre-treatment)

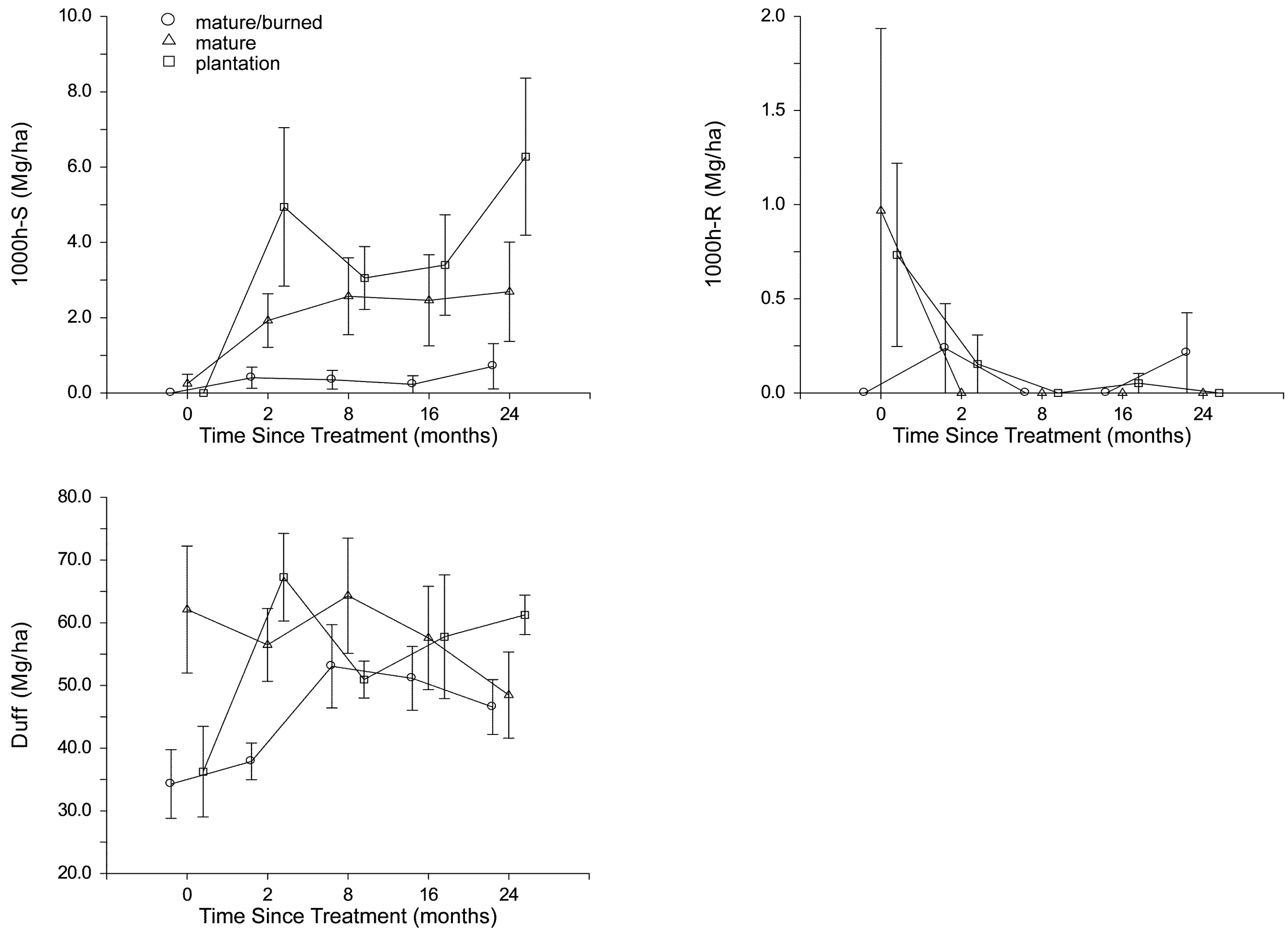

Figure 2-9. Large woody fuels (1000h sound (S) and rotten (R)) and duff biomass following mowing treatment in 3 stand types (mature, mature/burned (burned 5 yrs prior to mowing),plantation) of palmetto/gallberry pine flatwoods in northern Florida, USA. (0 time since treatment= pre-treatment)

CHAPTER 3
EXPERIMENTAL BURNING IN MASTICATED PALMETTO/GALLBERRY: EFFECTS OF FUEL LOADING AND MOISTURE CONTENT ON FIRE BEHAVIOR AND LETHAL HEATING IN COMPACT LITTER-DOMINATED FUELBEDS

Background

Mechanical manipulation of forest and shrubland fuels has become an increasingly common approach to mitigate potential hazards associated with wildfire. Mechanical treatments are frequently utilized within the wildland urban interface (WUI) where risk to life and property are greatest, but are also employed as a restoration tool in fire-dependant ecosystems where historical fire regimes have been altered. Such treatments play the role of a fire surrogate in areas where prescribed burn implementation is difficult. Mastication differs from other fuels reduction methods, such as roller chopping, because ground fuels and soils are not impacted (Glitzenstein et al. 2006). As such treatments are increasingly being implemented, it is important to fully understand their impacts on potential fire behavior and fire effects.

Fuels treatments may be used in concert with prescribed burning or as a stand-alone management option. In conjunction with prescribed burning, mastication is used to alter fuel structure prior to implementing fire. The mastication of shrub and small tree understories is intended to reduce flame lengths, thus reducing potential overstory tree mortality and increasing control during burning operations. The conversion of live shrubs and small trees into dead surface fuels can reduce the vertical continuity of fuel strata and the overall fuelbed depth, but increases fuelbed bulk density. If left on site, fuels are only rearranged, with no immediate reduction in total fuel loading (Kobziar et al. 2009, Vaillant et al. 2009). Surface fuel loading is increased, especially in the small diameter classes (Kane et al. 2009, Kobziar et al. 2009). Fire behavior in densely compacted fuelbeds following mastication has been shown to result in aboveground (Kreye et al. 2011) and belowground (Busse et al. 2005) heating that may conflict with management objectives and have unforeseen ecological consequences.

Studies have begun to describe fuel conditions following mastication and to quantify fire behavior in treated sites (Glitzenstein et al. 2005, Bradley et al. 2006, Knapp et al. 2006, Kane et al. 2009, Kobziar et al. 2009). Negative effects on both tree mortality (Bradley et al. 2006) and crown damage (Knapp et al. 2006) have been documented after burning in masticated sites. Laboratory studies have also reported that burning of masticated fuelbeds may result in long-duration heating both within the soil (Busse et al. 2005) and above the ground (Kreye et al. 2011). Most of the existing mastication research has been conducted in the western US.

Mastication ("mowing") treatments are being increasingly employed in the flatwoods forests of the southern Coastal Plain, but their effects have not been examined. Flatwoods forests are a fire dependant ecosystem typified by a historical high frequency, low intensity fire regime (Abrahamson and Hartnett 1990). The understory component is comprised mostly of gallberry (*Ilex glabra* (Bartr.) Small) and saw palmetto (*Serenoa repens* (L.) Gray) and when masticated, results in high concentrations of litter and fine woody fuels (≤7.62 cm diameter) at the surface of the forest floor. While previous research has found moderate to high proportions, by weight, of fine woody particles in surface fuels of mastication treatments (89%, Glitzenstein et al. 2006; 87%, Kane et al. 2009; 51%, Kobziar et al. 2009), fuelbeds resulting from mastication in gallberry/palmetto flatwoods are composed of both foliar litter and wood particles with foliar litter being dominant (66%: Kreye unpublished data).

This study had two objectives: 1) to evaluate the effects of fuel loading and fuel moisture content (FMC) on fire behavior characteristics from the burning of fuelbeds created from masticated understories in southeastern pine flatwoods and 2) to evaluate the effects of fuel loading and fuel moisture content (FMC) on above and below ground heating during the burning of these fuels. To address our first objective we tested the hypotheses that maximum flame length, forward rate of spread (ROS) of the flaming front, percent fuel consumption, and fireline intensity would differ across three fuel load (10, 20, and 30 Mg/ha) and two fuel moisture content (FMC) treatments (low and moderate). We expected flame length and fireline intensity to increase with higher fuel loads, due to higher potential energy available for combustion. We expected the same results in drier fuelbeds, due to a faster rate of combustion as measured by ROS. We also determined the relationship between fireline intensity and flame length and compared it with Byram's (1959) fireline intensity equation. To address above and belowground heating, we tested the hypotheses that maximum temperature and duration of lethal temperatures would differ in relation to fuel load and FMC. We expected maximum temperatures and duration of lethal heating to increase with higher fuel loading, due to our expected increase in fireline intensity, but that all heating would decrease with soil depth.

Methods

Masticated fuels were collected from a pine flatwoods site in the Osceola National Forest in north-central Florida. The site was dominated by longleaf pine (*Pinus palustris* Mill.) and slash pine (*Pinus elliottii* Engelm.) in the overstory, and by saw palmetto and gallberry in the understory prior to mowing conducted in April 2010. Understory shrubs and small trees (<20cm) were masticated using a front-end mounted masticator attached to a Gyrotrack. Surface fuels were collected approximately 2-3 weeks following mowing and were oven dried at 50˚C for 7-10 days.

To conduct experimental burning, 18 fuelbeds were created from the collected fuel and subsequently burned in May 2010 at the University of Florida Austin Cary Memorial Forest approximately 16 km northeast of Gainesville, FL, USA. Burns were conducted during the typical wildfire season and under warm (28-34˚C), moderately dry (46-63% relative humidity), and light wind (0.3-1.8 $m \cdot s^{-1}$) conditions. Fuelbeds were burned under three fuel loading treatments (10, 20, and 30 $Mg \cdot ha^{-1}$) and two fuel moisture content (FMC) treatments (low and moderate) in a 3x2 factorial experimental design, replicated three times. To create two FMC treatments, half of the fuel remained in the drying oven, while the other half was stored in a greenhouse until burning experiments were conducted. Temperature and humidity were not precisely controlled in the greenhouse, but conditions were cooler and wetter than the oven. Three fuel samples were taken from each fuelbed to estimate FMC prior to ignition using the oven-dry method.

Fuelbeds were created within 4 m diameter circular rings, constructed of 15 cm aluminum flashing, located in a treeless opening within a pine flatwoods forest, similar to methods used by Zipperer et al. (2007). Surface vegetation (primarily grass) was removed prior to loading. Soils on which fuelbeds were created were somewhat poorly drained Grossarenic Paleudults of marine origin with fine sands in the upper 20 cm. The 4 m diameter rings were loaded with 12.6, 25.1, or 37.7 kg of masticated fuel to create 10, 20, and 30 $Mg \cdot ha^{-1}$ fuel loading treatments, respectively. For low FMC treatments, fuel from the oven was taken to the site and kept in a covered truck bed until loading of each ring plot directly prior to burning. To create each fuelbed, fuel was placed within the ring and spread out to reach uniform loading. Fuel was tamped down to mimic compact fuelbeds observed in the field as a result of mowing machinery. Low FMC treatments were burned immediately following loading and sensor setup. Each replicate was loaded and then subsequently burned prior to loading the next replicate burn so that fuelbeds would remain as dry as possible prior to each burn. For moderate FMC treatments, fuel that had been stored in a greenhouse for several days were used to create each of nine fuelbeds across the three fuel loading treatments. Fuelbeds were setup, water was applied with a hose, and subsequently covered with plastic for adsorption of moisture into fuel particles for approximately 18 hrs prior to burning. Individual fuelbeds (burn replicates) remained covered until prepared for burning.

Thermocouples were located within ring plots to record temperatures above and below ground during combustion. At the center of each ring plot, three 30-AWG Type K PFA insulated thermocouple wires (Omega Engineering, Stamford, CT, USA) were buried to depths of 2, 5, and 8 cm below the soil surface. Wires were buried horizontally in orientation and exposed junctions were inserted approximately 10 cm into an exposed vertical soil profile, approximately 10 cm deep, to reduce soil disturbance at the location of temperature measurement. The cavity created for soil thermocouples was then backfilled. At the fuelbed surface, three high temperature Type K Thermocouple probes (Omega Eng., Stamford, CT, USA) were placed at 1, 2, and 3 m from the ring plot edge, and perpendicular to the anticipated flame front, to record surface temperatures during burning. All thermocouples were connected to an OMB-DAQ-55 datalogger (Omega Engineering, Stamford, CT, USA) and temperatures were recorded every 3 seconds. Six poles, with alternating 20 cm black and white measurement markings, were placed at 1.0, 1.5, 2.0, 2.5, 3.0, and 3.5 m from the ignition edge of the ring plots and perpendicular to the anticipated flame front to estimate flame heights and to estimate the fire's rate of spread. Litter pins (4 ea) were placed at the four cardinal directions, and 1.0 m from the ring's edge, with the top of the litter pin placed at the fuelbed surface to measure pre- and post-burn fuelbed depth. Wind speed, air temperature, and relative humidity were measured prior to ignition for each burn.

To ignite each fuelbed, a line of fire was initiated perpendicular to the anticipated spread of the fire at 0.5 m from the edge of the ring using a drip torch. All burns were video recorded from a horizontal position 4.0 m from each ring plot and at 1.5 m above the ground. Maximum flame height was visually estimated at each height pole as the flaming front passed and the time of arrival of the flaming front from ignition was recorded. Maximum flame height was measured as the height of flame that was continuous from the fuel surface, i.e. not including flickering flames detached from the main flaming front. Flame length was determined by dividing observed flame heights by the sine of the average flame angle (Rothermel and Deeming 1980).

Following combustion, depth of fuel consumed was measured at the four litter pins. Proportion consumed was calculated as the depth of fuel consumed divided by pre-burn fuelbed depth. Rate of spread (ROS) was calculated as the average ROS between each height pole. Fireline intensity was also determined by multiplying the forward rate of spread ($m \cdot s^{-1}$) of each burn by the proportion of fuel consumed, the fuel load ($kg \cdot m^{-2}$), and fuel heat content ($kJ \cdot kg^{-1}$) (Van Wagner 1973). A heat content value of 19,678 kJ/kg was used from of composite of low heat content values, assuming latent heat of vaporization as a loss, of saw palmetto, gallberry, and a mixture of other pine flatwoods shrubs (Hough and Albini 1978) and adjusted for a 20% nominal energy loss due to radiation (Nelson and Adkins 1986).

To evaluate the effects of fuel load and FMC on the burning of masticated fuelbeds, maximum flame height, ROS, consumption, and fireline intensity were compared across both fuel loading and FMC treatments using a GLM analysis of variance. Both main effects and their interaction were tested at the 0.05 alpha level. Model assumptions of normality and equal variance were validated using the Shipiro-Wilk Test and the Modified-Levene Equal Variance Test, respectively. Where a significant effect of fuel load was detected, the Tukey-Kramer Test was used to determine differences amongst treatment means. The relationship between flame length and fireline intensity was modeled using non-linear regression assuming an exponential increase in fireline intensity with flame length (Byram 1959).

To evaluate above ground heating at the fuelbed surface, where the potential for basal damage to trees is most likely in these compact fuelbeds, we tested the effects of fuel loading and FMC treatments on both maximum surface temperatures and the duration of lethal heating using general linear model procedures (SAS version 9.2, SAS Institute Inc., Cary, NC, USA). Maximum temperatures were compared across low and moderate FMC and the three fuel loadings (10, 20, and 30 $Mg \cdot ha^{-1}$), and their interaction, to determine how FMC and fuel load influence heating near the fuelbed surface. Duration (min) of temperatures ≥60˚C were also compared across FMC and fuel loading and their interactions. Thermocouple locations within burns were treated as subsamples and were nested within treatments when testing for main effects. Effects were tested at the 0.05 alpha level and GLM model assumptions were validated as described above.

To evaluate soil heating we tested the effects of fuel loading and FMC treatments on soil temperatures across the three soil depths (2, 5, and 8cm) using a GLM analysis of variance. Temperatures were compared across soil depth, FMC, and fuel loading as well as all interactions to determine how FMC and fuel load influence heating at shallow soil depths. Pre-burn soil temperatures were used as covariates in analysis. Effects were tested at the 0.05 alpha level and GLM model assumptions were validated as above.

Results

The manipulation of fuelbeds resulted in a low (8.9±0.6%) and a moderate (12.9±2.0%) fuel moisture content (FMC) treatment. One fuelbed was burned with a FMC of 35.6% and was therefore excluded from analysis. Air temperature ranged from 27.8 to 33.9 ˚C and relative humidity (RH) ranged from 46 to 63%. Temperature and RH did not differ across FMC or fuel load treatments and were not significant covariates in any analysis. Wind speed during burning was light (0.3 to 1.8 $m \cdot s^{-1}$) and did not differ across treatments nor was it a significant covariate in any analysis.

Both fuel moisture content (FMC) and fuel loading were significant factors affecting flame lengths and fireline intensity during the burning of fuelbeds created from masticated pine flatwoods understory (Table 3-1). Flame lengths increased approx. two-thirds under the drier versus the wetter (111 cm and 67 cm, respectively) FMC treatment ($P=0.001$). Flame lengths also increased directly with fuel loading ($P<0.001$) by approximately 0.5 m per 10 $Mg \cdot ha^{-1}$ increase in load, where the 10, 20, and 30

$Mg \cdot ha^{-1}$ treatments burned with 49, 91, and 140 cm flame lengths respectively. There was no interaction effect (P=0.808) between FMC and fuel loading on flame lengths. Fireline intensity was greater in the drier (593 $kJ \cdot m^{-1} \cdot s^{-1}$) versus the wetter (317 $kJ \cdot m^{-1} \cdot s^{-1}$) FMC treatments (P=0.029) and also differed across fuel loading (P=0.003), but only between the lowest (10 Mg/ha: 183 $kJ \cdot m^{-1} \cdot s^{-1}$) and the highest (30 Mg/ha: 773 $kJ \cdot m^{-1} \cdot s^{-1}$) fuel loading (Table 3-1). There was no interaction effect (P=0.758) between FMC and fuel load on fireline intensity. The relationship between fireline intensity ($kJ \cdot m^{-1} \cdot s^{-1}$) and flame length (m) determined from non-linear regression was

$$I = 498 * FL^{1.34}$$

where *I* is fireline intensity ($kJ \cdot m^{-1} \cdot s^{-1}$) and *FL* is flame length in meters (Figure 3-1, R^2=0.81). Fireline intensity was higher, across our measured flame lengths, than that predicted in Byram's fireline intensity equation (Figure 3-1).

Fire rate of spread (ROS) was faster in the drier (1.17 $m \cdot min^{-1}$) versus the wetter (0.61 $m \cdot min^{-1}$) FMC treatments (P=0.007), but was not affected by fuel loading treatments (P=0.446). Fuel consumption was high across all burns, ranging from 84 to 99%, but did not differ across FMC (P=0.130) or fuel loading treatments (P=0.387) (Table 3-1).

Maximum surface temperatures differed across fuel loading treatments (P=<0.001), but not across FMC (P=0.887). Temperatures at the fuelbed surface reached 274±19 ˚C during the burning of the lowest fuel loading (10$Mg \cdot ha^{-1}$), but reached 429±15 ˚C and 503±16 ˚C from the burning of the 20 and 30 $Mg \cdot ha^{-1}$ fuelbeds, respectively (Figure 3-2). The duration in which lethal heating (≥60˚C) occurred at the fuelbed surface also differed across fuel load (P=0.002), but not between the low and moderate FMC treatments ($P=0.547$). Lethal heating occurred for long durations and increased with fuel loading, with 9.48±0.73 min of lethal heating during burning in low fuel loads (10 $Mg \cdot ha^{-1}$) and 14.25±1.14 and 19.93±0.91 min during burning of the moderate (20 $Mg \cdot ha^{-1}$) and high fuel loads (30 $Mg \cdot ha^{-1}$), respectively (Figure 3-3).

Maximum belowground temperatures differed across the 2, 5, and 8cm soil depths ($P<0.001$), but lethal temperatures (≥60˚C) did not occur. At these three soil depths, heating was influenced both by fuel moisture (Figure 4, $P<0.001$) and fuel loading (Figure 5, $P<0.001$). The dry FMC treatment resulted in greater soil heating compared with the wet FMC treatment and higher fuel loading resulted in greater soil heating ($P<0.001$), but differences were only detected between the lowest (10 Mg/ha) and the two higher fuel loads (20 and 30 $Mg \cdot ha^{-1}$) using the Tukey-Kramer post hoc comparison (Figure 3-5). The highest fuel load (30 Mg/ha) did not result in greater soil temperatures compared with the moderate fuel load (20 $Mg \cdot ha^{-1}$). Initial soil temperature (31.8±3.2˚C) did not differ across soil depth ($P=0.560$), FMC ($P=0.323$), or fuel loading ($P=0.651$), but was a significant covariate ($P=0.006$) in the general linear model. No interaction effects between soil depth, FMC, or fuel loading on soil heating were found to be significant using a GLM analysis of variance.

Discussion

Mechanical based fuels treatments are being increasingly used by land managers to mitigate fire hazard and restore long unburned ecosystems. The ability to predict potential fire behavior and subsequent fire effects is key to evaluating the effectiveness of these treatments. Heterogeneity of understory shrub and small tree biomass across space as well as time since disturbance will likely result in heterogeneity of fuel loading on the forest floor following mowing treatments. Experimental manipulation of fuels allows researchers to address how this heterogeneity influences potential fire behavior and ecological consequences. Here, we have determined the effect that varying fuel loading has on observed fire behavior characteristics as well as on measured aboveground and belowground heating from the burning of masticated palmetto/gallberry dominated pine flatwoods of the southeastern US. This work provides insight into masticated fuelbed fire behavior, and presents results relevant to assessing post-mowing burning effects on soil ecology and residual vegetation.

Although determining the effect of fuel loading across a larger range of moisture conditions would be informative, it was difficult under environmental constraints to do so. Environmental factors such as air temperature, relative humidity, and wind made it difficult to manipulate FMC to a large degree. However, the environmental and FMC conditions in this study would commonly occur during wildfire season in the region, thus providing an indication of the effectiveness of such treatments at mitigating fire hazard in flatwoods forests.

In testing our hypotheses, flame length and fireline intensity both increased with greater fuel loading and under drier FMC treatments, but rate of spread (ROS) only differed between FMC treatments, and consumption did not differ across any treatment. In support of our expectations, maximum surface temperatures increased with fuel loads, but did not differ between FMC treatments. Also as expected, maximum soil temperatures increased with greater fuel loads and under the dry FMC treatments, and decreased with increasing soil depth. The duration of lethal heating (≥60˚C) at the surface increased with fuel load, but did not differ between FMC. Importantly, soil temperatures never reached 60˚C during experimental burning of any of the treatments.

Treatment Effects on Fire Behavior and Above and Belowground Temperatures

Fuel loading and fuel moisture content (FMC) both independently increased flame length and fireline intensity. Even though the disparity of the two FMC treatments was not substantial (~4%), the effect on fire intensity was significant, linked to a near-doubling of ROS in the dry treatment. Since neither ROS nor consumption differed across fuel loading treatments, fireline intensity was increased primarily from the increase in fuel biomass. Although higher fuel loading treatments were also greater in fuelbed bulk density, (to mimic that found in the field), the increased compactness of the fuelbed did not restrict the horizontal propagation of fire. The 10, 20 and 30 $Mg \cdot ha^{-1}$ fuel loading treatments resulted in 6, 9 and 12cm fuel depths and 16.7, 22.2, and 25.0 $kg \cdot m^{-3}$ fuelbed bulk densities, respectively. This range of fuel loading likely captures most understory and forest floor fuel loadings in pine flatwoods forests with a dominant palmetto and gallberry understory that have gone unburned (McNab et al. 1978) and where mowing treatments are most likely to be implemented.

Maximum temperatures reached both at the fuelbed surface and belowground were influenced by fuel loading during the burning of these fuelbeds, yet fuel moisture content only influenced temperatures belowground. While maximum surface temperatures are likely reached instantaneously as the flaming front passes a given point, soil provides an insulation layer in which belowground heating likely depends both on the intensity of energy output and the duration that heat energy is being transferred beneath the soil surface at a given location (Neary et al. 2005). The burning of drier fuelbeds resulted in greater soil heating and although ROS was faster, flame lengths were greater, compared with the wetter fuelbeds. Also, the wetting of fuelbeds for the moderate FMC treatments did not increase soil moisture (P=0.847), averaging 9.9±1.1%, which may have otherwise subdued soil heating. Nonetheless, while maximum temperatures exceeded 500˚C at the fuelbed surface, soil temperatures never exceeded those considered lethal to plant tissues (60˚C).

The insulation capacity of the coarse soils on which these fuelbeds were burned may help mitigate the potential for lethal root heating during burning in these compact fuels. But high temperatures and long-duration heating at the fuelbed surface could cause basal cambial damage to overstory trees. The duration of temperatures exceeding 60˚C at the fuelbed surface increased by about 5 minutes for each 10 $Mg \cdot ha^{-1}$ increase in fuel load. Although ROS differed across FMC but not fuel loading, duration of lethal heating differed across fuel loading, but not FMC. Lethal heating was not exclusively a function of flame residence time or fireline intensity, but was likely influenced by their combination, along with residual combustion following the passage of the flame front. Although total consumption did not differ across fuel load, the intensity and duration of residual combustion was likely greater in the heavier and more densely packed fuelbeds. The consequences of burning masticated fuelbeds are more likely to include damage to residual trees in long-unburned flatwoods forests where fuel loads are high (Varner et al. 2005).

Saw Palmetto/Gallberry and Other Fuelbed Types Compared

While these fuelbeds were primarily composed of saw palmetto litter and some 1-h woody fuels, they were highly compact compared to that of typical pre-mowing fuel strata in pine flatwoods (McNab et al. 1978). While flame lengths observed here were not unlike those of other controlled experiments where compact masticated fuelbeds from western US shrub fuels were burned (Busse et al. 2005, Kreye et al. 2011), maximum surface temperatures were somewhat lower and soil temperatures were much lower (Table 2). Busse et al. (2005) developed an empirical model to predict maximum soil temperatures from fuelbed depth, soil moisture, and soil depth that drastically overestimates soil heating in our fuelbeds, ranging from 43 to 318˚C predicted. Soil temperatures did not reach 60˚C even as shallow as 2.5 cm beneath the soil surface in this study. Although fuel depths across all three studies are comparable, fuel loading in the other two studies were substantially greater than ours (Table 2). Higher woody fuel loading in these other studies likely contribute to the higher surface temperatures and much higher soil temperatures during burning due to higher total energy released per unit area, along with longer combustion times. Although ROS was not measured in the above mentioned experiments, flaming times were observed to be much longer than those in this study. Busse et al. (2005) observed flaming times between 20 and 27 min in small fuelbeds (0.9 x 0.9m) and Kreye et al. (2011) observed 13 to 22 min of flaming from burning even smaller fuelbeds (38 x 26cm). Average flaming times in our study were 7 ± 0.8 and 14 ± 1.4 min in the low and moderate FMC treatments, respectively, over much larger (4 m diameter) fuelbeds. The greater foliar fuel component in the palmetto-gallberry fuelbed is likely responsible for these differences.

Fireline Intensity

An exponential model fit the relationship between fireline intensity and flame length from our study (R^2=0.81), but this relationship differs from that of Byram's fireline intensity equation, which is commonly used in fire behavior/ fire effects prediction software such as Behave Plus (Andrews et. al. 2005). The rate of energy output at the fire front is greater for a given flame length than that observed by Byram (1959). Residual energy release following the passage of the flaming front may account for the different relationship observed in our fuelbeds compared with that observed by Byram (1959). Residual combustion following frontal passage of the flaming front was anecdotally observed in this study, but to what extent it may account for the disparity between our observations and that of Byram (1959) is unknown. Nelson and Adkins (1986) also observed higher fireline intensities across a range of flame lengths (46-144 cm) compared to Byram (1959) during both laboratory and field burning of slash pine (*Pinus elliottii*) needle litter beds with standing live saw palmetto. However, they found that flame lengths were relatively constant over a range of fireline intensities (98-370 $kW \cdot m^{-1}$) when needle litter was burned without palmetto. Catchpole et al. (1993), on the other hand, found that fireline intensity increased with flame lengths according to Byram's (1959) equation when burning either excelsior or 6.35 mm sticks alone, but that flame length did not increase with fireline intensity when burning both excelsior and sticks in a mixed fuelbed. The higher fireline intensity observed in this study compared with Byram (1959) may indicate residual combustion during the burning of these fuels or there may be inconsistency in the relationship of fireline intensity and flame lengths across various types of fuelbeds. Nonetheless, any long term residual combustion during the burning of masticated fuelbeds may ultimately prolong heating at the forest floor and result in unintended ecological consequences such as tree mortality. The use of Byram's fireline intensity equation may therefore be inappropriate for estimating fireline intensity from observed flame lengths in masticated saw palmetto-gallberry fuels, especially if predicting possible fire effects on residual vegetation is of interest.

The results of this study indicate that variation in fuel loading influences fire behavior and lethal heating within masticated pine flatwoods fuelbeds. This variation will be important to managers to understand the effectiveness of these treatments to achieve management objectives, which often include retention of overstory trees. Mechanical fuels treatments will likely occur where either flatwoods have not burned for several years, or in the wildland urban interface where the use of prescribed fire as a primary management tool is restricted. Mowing converts standing live fuels into compact surface fuels, so pre-treatment standing biomass should translate into post-treatment surface biomass. The ability to predict post-mowing fire behavior and potential ecological effects enhances managers' capacity to use mowing treatments.

Further research is needed to explore how other fuels, moisture, and weather conditions affect fire behavior and effects in masticated fuelbeds. Such work would inform the development of additional fuel models to aid in fire prediction following mowing. The majority of existing work has been conducted in compact masticated fuelbeds with low fuelbed depths, but where woody material is the primary fuel component. The gallberry/palmetto pine flatwoods of the southeastern US coastal plain is a widespread forest ecosystem, but with unique fuels compared to other North American fuel complexes. And while singular fuel models are already used to predict fire behavior in untreated flatwoods, this work suggests that the masticated gallberry/palmetto fuel complex also deserves a unique fuel model.

Table 3-1. Fire behavior characteristics from experimental burning of masticated understory vegetation of southeastern pine flatwoods across fuel loading and fuel moisture content treatments. Marginal and cell means are listed along with p-values from GLM ANOVA.

		Flame Length *(cm)*		Rate of Spread *($m\cdot min^{-1}$)*		Consumption *(%)*		Fireline Intensity *($kJ\cdot m^{-1}\cdot s^{-1}$)*	
		mean (SE)	P	mean (SE)	P	mean (SE)	P	mean (SE)	P
FMC[a]	Low	111 (14)	0.001	1.17 (0.12)	0.007	93.6 (1.9)	0.130	593(116)	0.029
	Moderate	67 (14)		0.61 (0.09)		97.0 (0.7)		317 (83)	
Fuel Load[b] ($Mg\cdot ha^{-1}$)	10	49 (10)[A]	<0.001	0.75 (0.19)	0.446	94.2 (2.2)	0.387	183 (47)[A]	0.003
	20	91 (10)[B]		0.98 (0.16)		94.2 (2.2)		487 (81)[AB]	
	30	140 (14)[C]		1.00 (0.19)		97.6 (0.7)		773 (149)[B]	
FMC*Fuel Load	Low/10	69 (7)	0.808	1.08 (0.27)	0.851	90.7 (3.5)	0.343	260 (71)	0.758
	Low/20	106 (16)		1.26 (0.13)		92.0 (4.0)		611 (84)	
	Low/30	159 (6)		1.18 (0.27)		98.0 (0.6)		908 (207)	
	Mod/10	29 (5)		0.41 (0.03)		97.7 (0.3)		105 (8)	
	Mod/20	76 (7)		0.71 (0.19)		96.3 (1.8)		362 (101)	
	Mod/30	114 (25)		0.75 (0.20)		97.0 (2.0)		569 (161)	

[a] Fuel moisture content treatment: low (8.9±0.6%) and moderate (12.9±2.0%)
[b] Where fuel load was significant, similar letters within columns indicate no difference amongst means from the Tukey-Kramer post hoc comparison (α=0.05).

Table 3-2. A comparison of observations from this study conducted in constructed fuelbeds of masticated palmetto/gallberry of southeastern USA pine flatwoods and that of two other studies where burning experiments were conducted with constructed fuelbeds from masticated understory shrub vegetation of western USA forests.

Study	Dominant vegetation masticated	Fuel moisture *(%)*	Soil moisture *(% VMC)*	Fuel depth *(cm)*	Fuel load *($Mg \cdot ha^{-1}$)*	Flame length *(cm)*	Surface temperature *(˚C)*	Soil[b] temperature *(˚C)*
this study	saw palmetto (*Serenoa repens)*	9-13	10	6.0	10	49	274	36-43
	gallberry (*Ilex glabra*)			9.0	20	91	429	45-47
				12.0	30	140	503	43-51
Busse et al. 2005	whiteleaf manzanita (*Arctostaphylos viscida*)	2	4	2.5	34	40	450-600[a]	80-120
				7.5	101	100	500[a]	200-300
				12.5	169	130	450-600[a]	275-350
	common manzanita (*A. manzanita*)	16	25	2.5	34	30	80-440[a]	40-80
				7.5	101	110	275-450[a]	90
				12.5	169	170	350-500[a]	100-130
Kreye et al. 2011	common manzanita (*A. manzanita*) snowbrush (*Ceanothus velutinus*)	2.5-11.0	<5	7.0		69-95	436-771	131-208

[a] Range of peak temperatures were estimated, to the nearest 10, from temperature profile graphs in Busse et al.'s (2005) paper.
[b] Soil temperatures recorded at 2.0cm (this study), 2.5cm (Busse et al. 2005), and 5 cm (Kreye et al. 2011, soil data unpublished) soil depths.

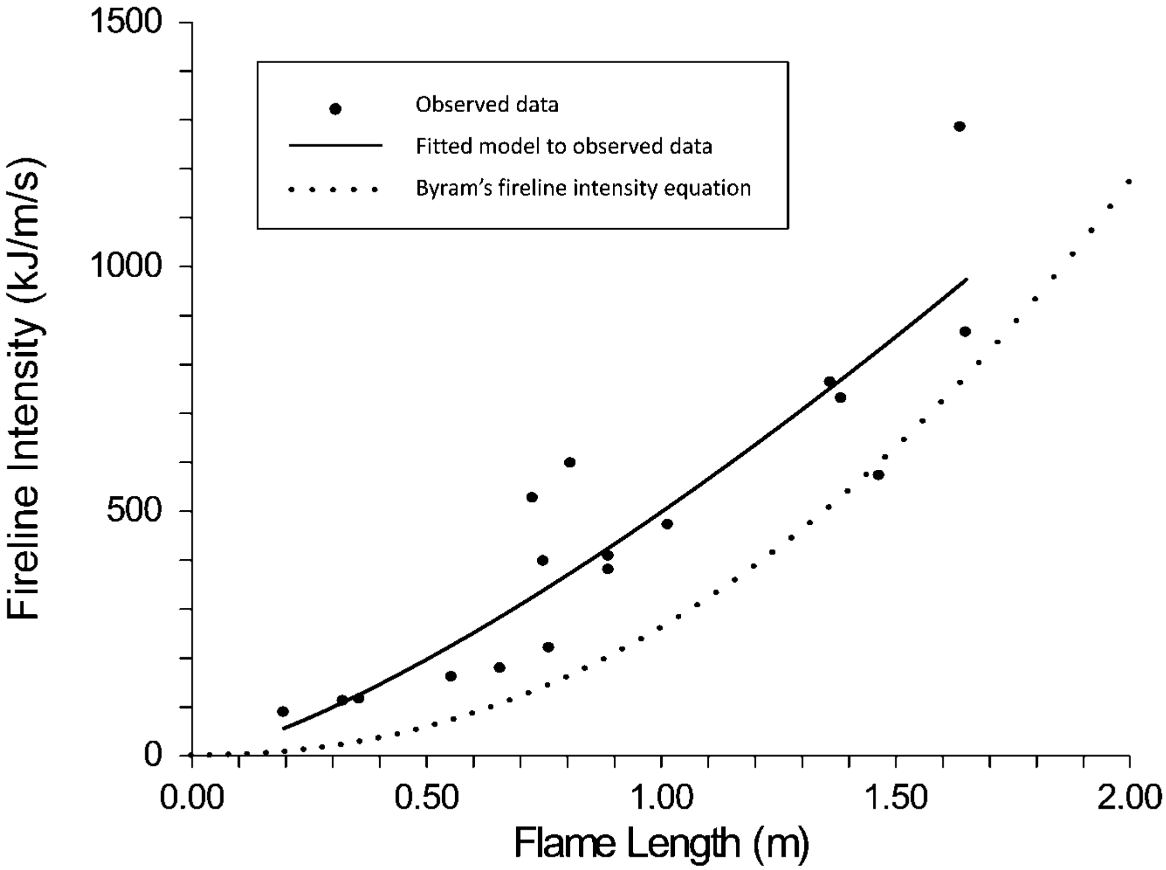

Figure 3-1. The relationship[1] between fireline intensity (kJ·m^{-1}·s^{-1}) and flame length (m) during the burning of fuelbeds created from masticated palmetto/gallberry dominated pine flatwoods understory (solid line, R^2=0.81), compared with Byram's (1959) fireline intensity equation[2] (dotted line).

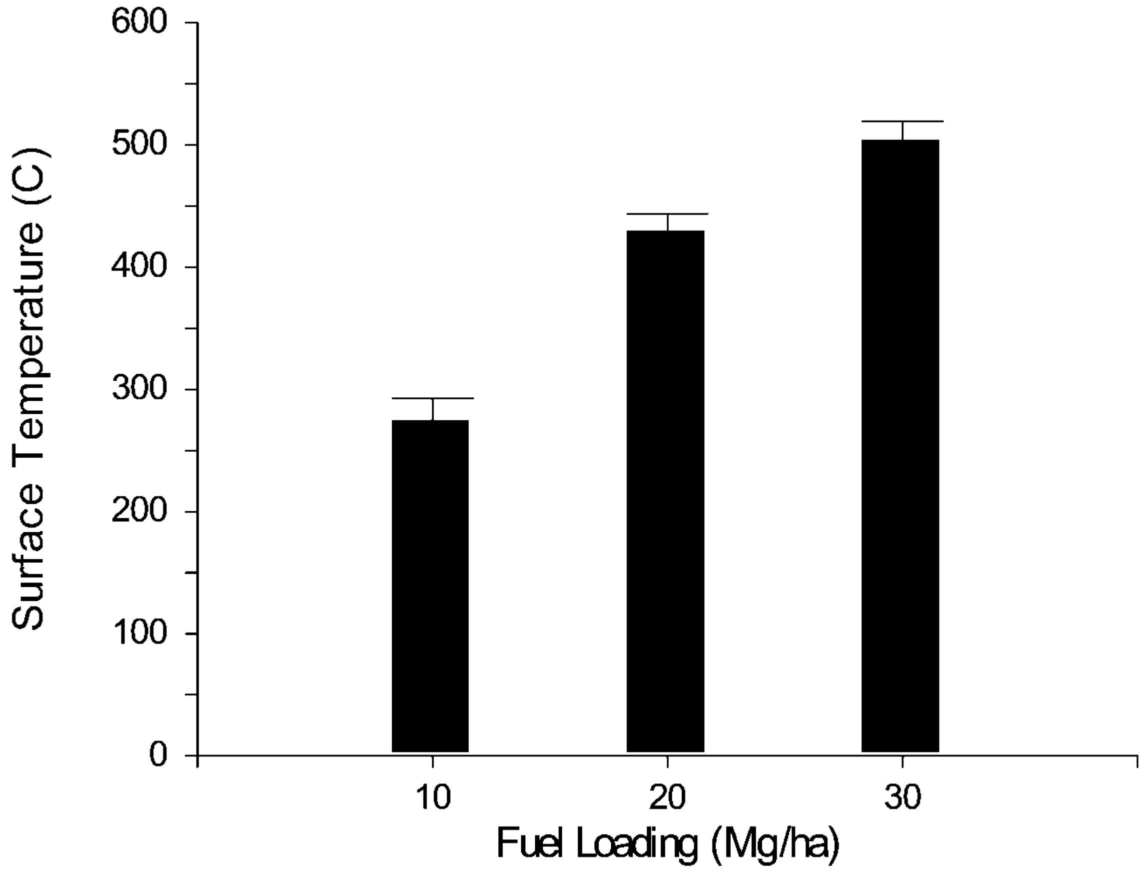

Figure 3-2. The effect of fuel loading on maximum temperatures reached at the fuelbed surface during the burning of fuelbeds created from masticated palmetto/gallberry dominated pine flatwoods understory. Temperatures differed amongst all three fuel loading treatments using the Tukey-Kramer post-hoc comparison of the means.

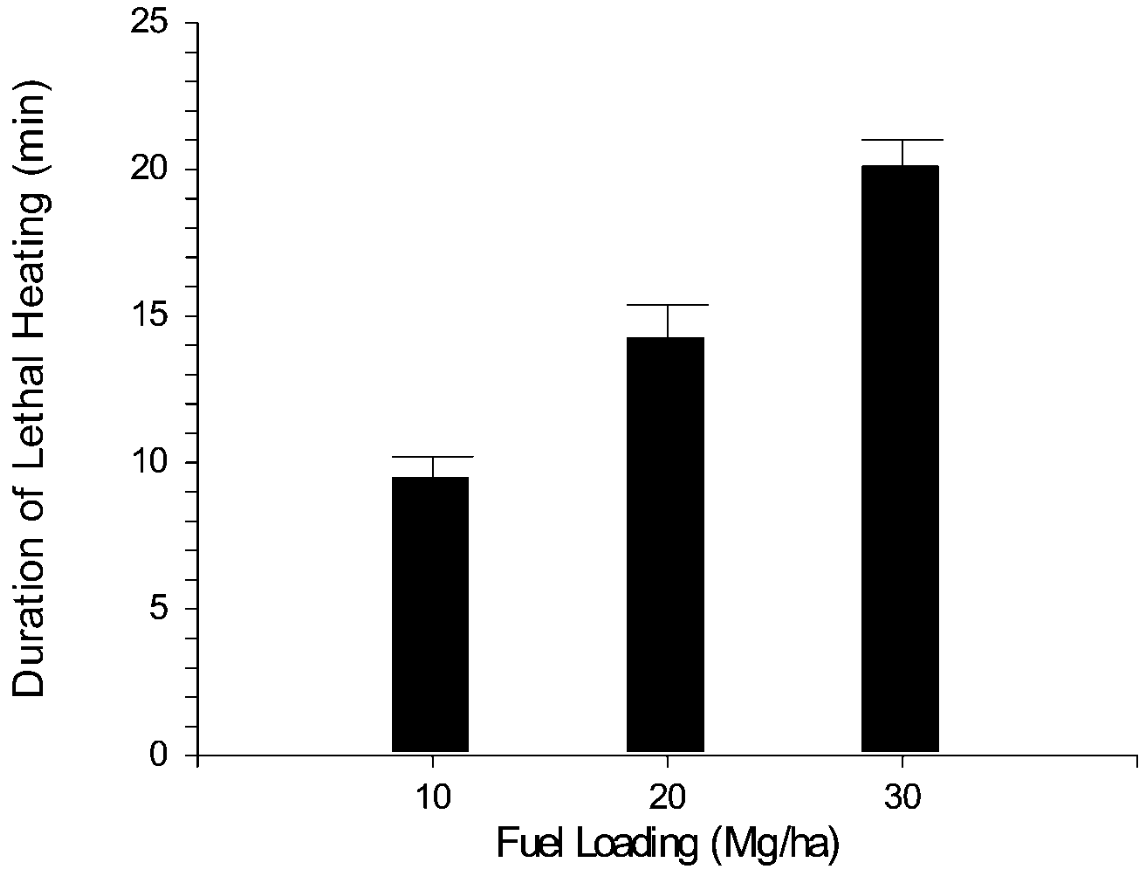

Figure 3-3. The effect of fuel loading on the duration of aboveground surface heating considered lethal to plant tissues (≥60˚C) during the burning of fuelbeds created from masticated palmetto/gallberry dominated pine flatwoods understory. Lethal heating differed amongst the three fuel loading treatments using the Tukey-Kramer post-hoc comparison of the means.

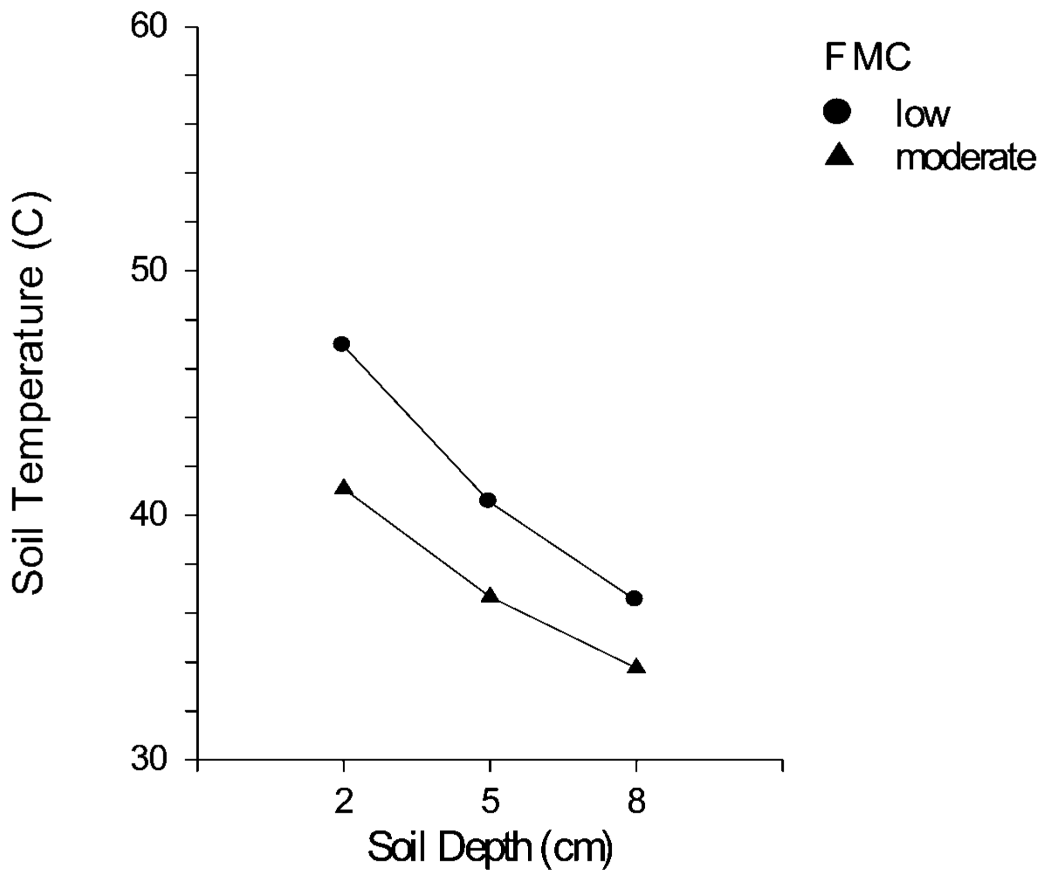

Figure 3-4. The effect of fuel moisture content (FMC) on soil heating (maximum temperatures) at three soil depths during the burning of fuelbeds created from masticated palmetto/gallberry dominated pine flatwoods understory.

note: FMC: low (8.9±0.6%) and moderate (12.9±2.0%).

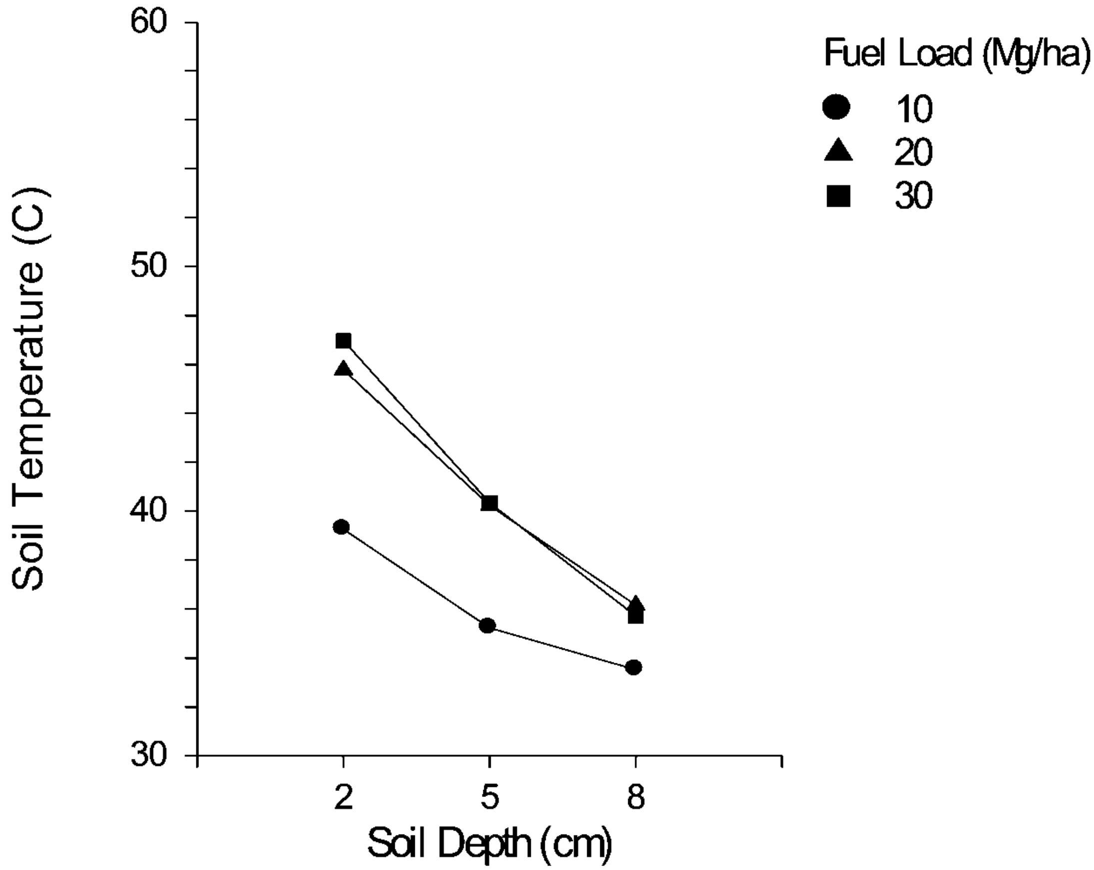

Figure 3-5. The effect of fuel loading on soil heating at three soil depths during the burning of fuelbeds created from masticated palmetto/gallberry dominated pine flatwoods understory.

CHAPTER 4
FIRE BEHAVIOR AND EFFECTS IN MASTICATED PINE FLATWOODS ECOSYSTEMS OF FLORIDA, USA

Background

The use of mechanical fuels treatments to reduce fire hazard in forest and shrub ecosystems has become a common management practice, however there are few empirical studies to elucidate the effectiveness of such treatments by quantifying fire behavior following their implementation. While treatments may be used as a stand-alone option, they are often used as a pre-treatment strategy to reduce fire hazard during follow-up prescribed burning. These types of treatments are being widely implemented across the United States (Glitzenstein et al. 2006, Kane et al. 2009, Kobziar et al. 2009, Brockway 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 with goals of retaining mature overstory trees and enhancing resistance to future fire (Agee and Skinner 2005). Evaluating the effectiveness of mastication type fuels treatments at reducing fire behavior and overstory resistance to post-treatment burning is vital to determine treatment effectiveness.

Mastication is a mechanical treatment that alters fuel structure through mowing, shredding, or chipping understory shrubs and small trees. Front end or boom mounted equipment, attached to ground-based equipment, is used to manipulate understory fuels with little impact to ground fuels or soils. Horizontal and vertical fuel continuity is disrupted, however total fuel loading is not reduced (Kane et al. 2009, Kobziar et al. 2009, others). 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 will likely remain a feasible option to remove masticated surface fuels following treatments.

Current work evaluating fire behavior and effects in masticated fuels is limited and much of it has been 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). Furthermore, while studies have used various approaches to address problems at different scales, empirical studies determining treatment effects on fire behavior at the stand scale are still few. Stand-scale research in a variety of ecosystems will be needed to not only evaluate the effectiveness of mastication at altering fire behavior, but also to determine whether results of fire behavior studies at smaller scales translate to scales in which treatments are being implemented.

Small-scale laboratory experiments have elucidated some understanding of the effects of particle- or fuelbed-scale properties on moisture dynamics (Kreye et al. 2012), fire behavior, and potential fire effects (Busse et al. 2005, Kreye et al. 2011) in masticated fuels. While these studies quantify the influence of fuelbed level properties on fire related metrics, it is unclear if such influences translate to a larger scale. Also, field studies at the larger scale have varied in results regarding the effectiveness of treatments at mitigating fire hazard (Bradley et al. 2006, Glitzenstein et al. 2006, Kobziar et al. 2009, Knapp et al. 2011). Treatment effectiveness will likely vary across ecosystems due to differences in pre-treatment fuel structure. Mastication is being conducted in shrub ecosystems with no overstory, in forest ecosystems with dense understory trees, as well as forest ecosystems that are dominated by shrub understories. More empirical studies that quantify fire behavior and effects in masticated sites across several ecosystems will enhance our understanding of fuel treatment effectiveness, but will also increase our general understanding of fire behavior and effects across masticated fuels that vary in fuelbed structure and properties.

While mastication in forest and shrub ecosystems often results in compact woody dominated fuelbeds (Kane et al. 2009, Battaglia 2010), mastication ("mowing") in pine flatwoods dominated by palmetto and gallberry shrubs in the understory results in fuelbeds comprised mostly of foliar litter with a smaller percentage, by mass, of small diameter woody fuels (Ch 2). Although compact, such fuelbeds will likely result in fire behavior and effects that are unique in comparison to those studied elsewhere. While small scale burning experiments have revealed precise control of surface fuel loading over fire behavior in masticated debris collected from treatments in this ecosystem (Ch 3), it is unclear if surface fuels will control fire behavior at the stand scale in an ecosystem where shrubs recovery quickly (Ch 2 and Ch 5).

The objectives of this study were to 1) determine the effectiveness of mowing at reducing fire behavior at the stand scale in an ecosystem where masticated residues are primarily litter dominated and where shrub recovery is rapid; 2) determine if surface fuels or shrub fuels controlled 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.

Methods

Mechanical fuels treatments were conducted in the Osceola National Forest (ONF) in northern Florida, USA in pine flatwoods communities that had gone unburned for several years and where fuel accumulations posed a hazard within the wildland urban interface (WUI). Pine flatwoods on the ONF are dominated by slash pine (*Pinus elliottii* var. *elliottii* (Engelm.) and/or longleaf pine (*Pinus palustris* Mill.) in the overstory and by saw palmetto (*Serenoa repens* (Bartr.) Small) and gallberry (*Ilex glabra* L. (Gray) shrubs in the understory. Mechanical mastication ("mowing") was used to reduce the height of understory fuels for re-introduction of prescribed fire, and to reduce fire hazard in areas abutting communities, highways, and private pine plantations. Treatments occurred in mature pine flatwoods (ca. 80 yrs old) lacking a mid-story and where the primary fuel strata altered during mowing was understory shrubs, including palmetto.

Field Experimental Burns

For this study, two treatment locations were used to evaluate the influence of mowing on subsequent fire behavior and effects. The first location occurred within a 100 m wide buffer masticated in August 2009 under ONF management plans, and burned in July 2010 for this study. The second location occurred in a block experimental design set up for long-term evaluation of the effects of mowing and mowing in conjunction with prescribed burning on ecological attributes (Ch 5). The experimental block treatments included mowing (mow: M), mowing followed by burning (mow+burn: M+B), burn without prior mowing treatment (burn only: B), and no treatment (control: C). Treatments blocks were approximately 2 ha in size (Figure 4-1) and replicated three times. One replication was burned and used for ecological assessment (Ch 5), however during burning operations two of three control plots were burned when fire escaped from a burn only block and fire behavior could not be assessed during operational control of the escaped fire. Therefore, the third replicate was not used in this study for fire behavior analysis, but was used to assess post-fire tree mortality. M and M+B treatments were masticated in August 2010, just following burning in the buffer location, and subsequently burned in February 2011. While the buffer treatments were located according to the management plan of the ONF, the experimental treatment block locations were selected for this study in sites with similar ecological attributes as those of the buffer units evaluated in this study. Therefore, we were able to evaluate the effects of mowing on subsequent fire behavior and fire effects during dormant season (winter) burning, typical of the management regime, using the experimental block treatments, but also to compare fire behavior and effects between a dormant (winter) season burn and a growing (summer) season burn in masticated treatments.

Nine plots were allocated to each burn treatments (winter B, winter M+B, summer M+B) systematically to better facilitate coordination between ignition operations and fire behavior observations at each plot during burning (Figure 4-2). In the experimental blocks, three plots, per treatment, were allocated to each block. As mentioned above, only six plots pre treatment were used to assess burning behavior, however all nine plots per treatment were used to analyze tree mortality. In the buffer treatment, nine plots were allocated to two locations within the buffer. Of the nine, six were monitored during burning and all nine were evaluated for tree mortality. Burning operations were conducted by the ONF fire management staff using strip head firing techniques (Figure 4-1). Ignition patterns were directed such that strip head fires were located far enough downwind of plot locations whereby a strip head fire ignited 15-20 m upwind of each plot location would burn through plots prior to downwind backing fires nearing plot locations. Observations of upwind strip head fires burning through plot locations were such that a steady-state ROS and intensity appeared to be reached prior to plot ignition.

Because the timing of burns were constrained by weather and ONF resource availability, full vegetation and fuels measurements could not be conducted immediately prior to burning. Comprehensive sampling of vegetation and fuels were conducted four months prior to each burn within all plots, including those not used in fire behavior analysis, but used for tree mortality. Sampling occurred in March 2010 prior to the July 28, 2010 summer burns, and in October 2010 prior to the February 23, 2011 winter burns. Overstory, shrubs, and surface fuels were quantified within each plot (full sampling techniques described in Ch 2) during sampling (Figure 4-2). Tree 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 assessed for each plot. Total shrub biomass and shrub foliar biomass was estimated from shrub measurements in two 1×4 m belt transects. Litter depth, duff depth, as well as litter, duff, and woody (1h, 10, and 100h) fuel biomass was estimated using four 10m fuel transects. It was assumed that surface fuels and overstory trees were relatively unaltered during the four months between full sampling and burning, however shrubs grow relatively quickly in this ecosystem so a quick assessment of shrub characteristics was conducted for each fire behavior monitoring plot on the day of burning. While the same sampling techniques were used four months prior to burning in both locations, sampling on the day of the burns differed between the summer burn in the buffer and the winter burn in the experimental plots. Average shrub height was measured in each plot in both locations on the day of the burn, however shrub cover was also estimated during burning in the experimental block treatments. During summer burning in the mowed buffer, three subsamples of surface litter were collected and pooled, at each plot, to determine surface fuel moisture, on a gravimetric basis. During winter burning in the experimental treatment blocks (B and M+B), fuel moisture samples were taken of surface litter, as in the buffer, but also of live shrubs to compare between masticated and non-masticated sites. Temperature, relative humidity, and wind speed were recorded hourly during all burns and the Keetch Byram Drought Index (KBDI) reported. KBDI is a indication of soil moisture conditions, and thus used as a coarse assessment of fuel conditions, and is reported on a county scale. While duff moisture was not estimated during this study, KBDI is an indication of relative duff moisture differences between summer and winter burning conditions.

Fire behavior was estimated during burning using plot level measurements. At each plot, rebar was used as a measurement device to estimate ROS and flame height. In each plot, three rebar were located 8 m apart and oriented in line with predicted wind direction and perpendicular to the anticipated flame front. Each rebar was exposed 3.0 m above the surface litter and marked in 50 cm increments using fluorescent paint. In the experimental treatment blocks (winter burn treatments), litter and duff pins were also placed at each rebar location prior to burning. Litter and duff pins were put in the ground with the top flush with the litter or duff, respectively to determine pre-burn and post-burn surface fuel loading and to calculate consumption. 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 as the time between the arrivals of the flaming front at successive rebar locations divided by their respective distance. Flame heights were averaged across all three rebar by plot.

Within a week of burning, tree damage was assessed for all trees within each 200 m^2 circular plot, including those not monitored during burning. Bole char was measured in two ways: percent of the bole circumference at DBH charred and maximum char height. Crown damage was assessed by estimating crown volume scorched (CVS). CVS was visually estimated as the proportion of the crown volume that was scorched. Scorch occurs when foliage is desiccated from heating. Foliage is initially retained on branches and is typically reddish in color. Quick assessment was conducted to quantify CVS prior to needle loss. Scorched needles were not observed on the forest floor at the time of damage assessments. Tree mortality was assessed one year following burning. To assess surface fuel consumption in the experimental treatment blocks, litter and duff depth consumed was measured at each litter and duff pin location. Depth consumed was measured as the distance between the top of pins and the fuel surface. Pre-burn depth was measured as the distance between the top of the pin and the bottom of the respective fuel layer. Duff pins were located approximately 5 cm from litter pins so that pre-burn litter depth could be estimated as the difference between the two if all litter was consumed. The percentage consumed was calculated from pre- and post-burn measurements. Litter mass consumed in the B treatments was estimated using bulk density reported across similar pine flatwoods sites in the region (16.2 $mg \cdot cm^{-3}$, Behm et al. 2004), while Litter mass consumed in M+B treatments, as well as duff mass consumed for both B and M+B treatments, were estimated using litter bulk density ($22.54\ mg \cdot cm^{-3}$) and duff bulk density ($110.88\ mg \cdot cm^{-3}$) values determined in a similar masticated site nearby (Ch 2). Within a month of burning, all sites were fully re-sampled for vegetation and surface fuels using the above sampling methods conducted four months prior to burning. Because litter and duff pins were not used during the burning of the buffer locations (summer M+B), the pre-burn and post-burn surface fuel measurements, using the planer intercept method, was used to assess consumption in these locations.

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 respective treatments. Pre-burn vegetation and fuels were compared between the summer M+B and winter M+B treatments to isolate seasonal effects on fire behavior and fuel consumption. Because measurements taken on the day of the burn differed between summer and winter burns, the comparison between summer M+B and winter M+B treatments were conducted using sampling techniques consistent between compared treatments. While litter and duff measurements were compared between the winter B and winter M+B treatments using measurements from litter and duff pins, respectively, litter and duff measurements from fuel transects were used to compare consumption between winter M+B and summer M+B treatments. Therefore, errors associated with sampling methods would be consistent between treatments in respective comparisons. Fire behavior (ROS and flame height), fuel consumption (litter and duff), and overstory effects (CVS, char at DBH, and char height) were compared between burning treatments, again winter B versus winter M+B separately and winter M+B versus summer M+B separately. Plots used for these analyses were only those in which fire behavior was assessed (6 per treatment). All subsamples, within plots, were averaged for analysis. Statistical comparisons were made using a two-sample T-test ($\alpha=0.05$). Model assumptions were evaluated using the Shipiro-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 was controlling fire behavior, linear regression was used to determine the correlation between flame height and shrub cover, shrub height, and litter mass. Linear regression was also used to determine the correlation between ROS and shrub cover, shrub height, and litter mass. Only data from the experimental winter burning blocks were used for this analysis. Shrub cover and shrub height were estimated on the day of the burn, as described above, and litter mass was determined from litter pins, as described above.

To evaluate post-burn tree mortality, three additional plots per treatment were included in analysis where fire behavior could not be monitored. Although fire behavior was not monitored in the extra plots, vegetation and fuels sampling was conducted in the same manner as for those where fire behavior was monitored. Therefore, vegetation structure, fuel loading, fuel consumption, and tree damage characteristics were evaluated for all plots (9 per treatment). Mortality assessments between treatments (winter B, winter M+B, and summer M+B) were conducted with respect to measured tree characteristics (height and DBH) and tree damage characteristics (CVS,char DBH, char height). This allowed us to evaluate whether treatment differences in mortality were linked to treatment differences in damage or treatment effects were isolated from observed damage. While averages of CVS, char at DBH, and char height in the above analysis were compared between treatments, and using only the monitored plots during burning (6 per treatment), tree damage, across all treatment plots (9 per treatment), was evaluated at the individual tree level to evaluate mortality. Frequency distributions of CVS, char at DBH, and char height, were created for all trees separated by treatment. Diameter distributions were created for each treatment, separately, with the number of trees dead, within diameter classes, indicated. Because a low number of trees died in this study, a rigorous statistical analysis of mortality rates could not be conducted. Evaluation of the effects of mowing or season of burning on tree mortality were assessed through simple evaluation of the number of trees dead within each treatment and determining whether tree size or tree damage observations (crown or potential bole damage) were associated with mortality. Pre-burn vegetation and fuels, as well as fuel consumption, were also compared between burning treatments to determine if such differences could have attributed to post-fire tree mortality. Since winter B and M+B treatments were established within an experimental design that included controls (C) and mow only (M) treatments (Chapter 5) with the same level of replication and plot sampling techniques, background mortality was assessed in these C and M treatments also.

Modeled Versus Observed Fire Behavior

Modeled fire behavior predications were 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 fuel loading, fuel moisture, and weather conditions, as measured above. Modeling was conducted in the BEHAVE PLUS Fire Modeling System (Andrews et al. 2008, version 4.0) and fuel parameters input from measurements 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, and a value recommended in BEHAVE PLUS when moisture is unknown (Andrews et al. 2008). 10h woody fuels accounted for a small proportion of surface fuels compared to the finer fuels and their moisture content was much higher than finer fuels during the winter burns, thus they did not likely contribute to flaming front combustion. 100h fuels were rare. Also, 10h and 100h woody fuel consumption was difficult to measure in this study due to increases in these larger fuels following burning, likely due to input from tree damage above or exposure during surface combustion. Post-burning consumption values are used to estimate fireline intensity during burning. Therefore, only litter and 1h fuels were used as inputs into the prediction model and their consumption used to calculate fireline intensity during observed burning. Fuelbed depth was input as average shrub height and live woody fuel loading as total shrub foliar biomass, the portion of shrubs involved in flaming combustion during burning.

Modeled outputs, by plot, were compared with the ROS, flame length, and fireline intensity observed during field burns. Flame lengths predicted in the model are measured from the top of the fuelbed to the flame tip along the flame axis, even if bent. Flames observed in the field were measured by vertical flame height and flame angle could not be observed from behind the flaming front. Observed flame length was calculated assuming a 30˚ flame tilt, a value that seemed reasonable under the light wind conditions. Observed fireline intensity was calculated as fuel mass consumed ($kg \cdot m^2$) multiplied by energy content (18.622 kJ·kg, Hough and Albini 1978) and by ROS ($m \cdot min^{-1}$). Fuel mass consumed included surface litter, 1h woody fuels, and shrub foliage. Because nearly all shrub foliage was observed to have been consumed during burning, measured pre-burn shrub foliar mass was assumed to have been consumed. Observed and predicted values were compared using linear regression.

Results

Winter M+B versus Winter B Treatments

Regarding differences between winter B and M+B treatments, overstory vegetation did not differ between treatments, however shrubs were much reduced in M+B treatments compared to B treatments (Table 4-1). 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. Shrub cover ($p<0.001$), shrub height ($p<0.001$), shrub biomass ($p<0.001$),and shrub foliar biomass ($p<0.001$) all were lower in M+B versus B treatments before burning. In M+B treatments, shrub cover, height, total biomass, and foliar biomass averaged 33 %, 58 cm, 0.6 $Mg \cdot ha^{-1}$, and 0.4 $Mg \cdot ha^{-1}$, respectively. While in B treatments, cover, height, total biomass, and foliar biomass averaged 78 %, 145 cm, 4.4 Mg·ha^{-1}, and 4.1 Mg·ha^{-1}, respectively. Litter depth was lower in the M+B treatments (5.7 cm) compared with B treatments (7.6 cm) (p=0.005, however litter mass, averaging 12.8 Mg·ha^{-1}, was higher than the 8.8 Mg·ha^{-1} in the burn only sites (p=0.002). Duff depth (p=0.116), averaging 3.8 cm, and duff mass (p=0.116), averaging 41.6 Mg·ha^{-1}, did not differ between treatments. 1h woody fuel mass was higher in the M+B treatments (1.1 Mg·ha^{-1}) compared to B treatments (0.5 Mg·ha^{-1}) (p=0.015), but 10h, averaging 1.6 Mg·ha^{-1} did not differ (p=0.105). 100h fuels, averaging 0.9 Mg·ha^{-1}, also did not differ (p=0.534). Live fuel moisture did not differ between treatments (p=0.140), averaging 114 %, nor did 10h woody fuel moisture (p=0.465), averaging 24.4 %, however litter moisture in M+B treatments (12.1%) was lower than in B treatments (17.8%) (p=0.047). KBDI during burning was 107.

Temperature on the day of winter burning ranged from 17 to 24 ˚C, relative humidity from 47 to 62%, and wind speed from 1.6 to 4.8 km·hr^{-1}. While treatments could not be burned simultaneously to avoid any potential differences in weather conditions, treatments were burned from between 11:00 to 14:30 to avoid drastic differences in weather conditions. Flame heights during burning in M+B treatments (1.1 m) were one-third of those observed in B treatments (3.3 m) (p=0.003), however ROS (3.4-7.1 m·min^{-1}) did not differ (p=0.150) (Table 4-2). Litter mass consumed was higher in M+B treatments (10.6 Mg·ha^{-1}) compared to B treatments (7.6 Mg·ha^{-1}) (p=0.026), however the proportion of litter and duff consumption, averaging 85% and 2%,respectively, did not differ (p=0.819, p=0.341), nor total duff mass consumed (0.6 Mg·ha^{-1} ,p=0.341) (p=0.997). Crown scorch averaged 45% across treatments and did not differ (p=0.158). Bole char at DBH and maximum bole char height, however, were marginally different (p=0.99 for both). Percent of bole circumference charred at DBH was 86±6% in M+B treatments and 97±2% in B treatments, and char height was 5.5±0.6 and 7.4±0.9 m in M+B and B treatments, respectively. While shrub consumption was not quantified, nearly 100% of the understory area was burned and almost all shrub foliage consumed during burning (Figure 4-3).

Flame heights, across all treatment plots pooled, were controlled by both shrub cover (R^2=0.80, p<0.001) and shrub height (R^2=0.63, p=0.002), but not by litter mass (p=0.962) (Figure 4-4). Shrub cover and height were also correlated (r=0.862). There was also some evidence that rate of spread was controlled by shrub cover (R^2=0.31, p=0.058) and shrub height (R^2=0.27, p=0.084), but not by litter mass (R^2=0.000, 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 slight 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 a significant factor on flame heights in either treatments. Using multiple regression techniques revealed that only shrub cover was significantly related to flame heights and that all others were not significant with shrub cover in the model. ROS was not related to any quantified fuel characteristic within treatments.

Winter Versus Summer M+B Treatments

In regard to winter M+B versus summer M+B treatments, Overstory conditions did not differ between treatments, however average tree height was slightly higher in the buffer M+B treatments burned in the summer (23.3±0.9 m) compared to the experimental M+B treatments burning in the winter (21.0±0.7), but differences were marginal ($p=0.054$) (Table 4-3). Tree density, BA, QMD, and CBH averaged 299 tph, 21 m^2 per ha, 29.9 cm, and 12.3 m, respectively. Four months prior to burning, shrub height, averaging 64 cm, did not differ between treatments ($p=0.467$). While shrub cover was not quantified on the day of summer burning, 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) did not differ between treatments, nor did 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±1.0 $Mg \cdot ha^{-1}$ in summer M+B treatments, higher ($p=0.016$) than the 1.1±0.2 $Mg \cdot ha^{-1}$ in the winter M+B treatments. 100h fuels did not differ ($p=0.301$), averaging 1.8 $Mg \cdot ha^{-1}$, and were sparse.

While temperature, RH, and wind speed ranged from 17 to 24 ˚C, 47 to 62%, and 1.6 to 4.8 $km \cdot hr^{-1}$, respectively, during winter burning, temperature (31-34 ˚C) and RH (61-76%) were both higher during summer burning and wind speeds, while still mild, varied a bit more, ranging from 1.6 to 7.2 $km \cdot hr^{-1}$ (Table 4-3). 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 during winter burns, KBDI was 425 during summer burns, indicating drier soil conditions during the day of the summer burn. Quantified fire behavior did not differ between the summer and winter burns (Table 4-4). Average flame heights were 1.5±0.1 m during summer burns and 1.1±0.3 m during winter burns, but did not differ (p=0.267). Rate of spread (ROS) was 5.9±1.8 $m \cdot min^{-1}$ during summer burning and 3.4±1.0 $m \cdot min^{-1}$ during winter burning and did not differ (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 $Mg \cdot ha^{-1}$) compared to winter (9.6±0.9 $Mg \cdot ha^{-1}$) burns. Duff consumption, however, was greater in average proportion consumed during summer burns (32±11%) compared to winter burns (5±3%), but variation was high and differences were marginal (p=0.067). Average duff mass consumed was also higher in summer (23.1±10.1 $Mg \cdot ha^{-1}$) versus winter (2.6±1.9 $Mg \cdot ha^{-1}$) burns, with high variation and marginal differences (p=0.098). Crown scorch, averaging 31%, did not differ between treatments (p=0.406) and maximum char height, averaging 5.1 m, did not differ (p=0.319). Percent of bole circumference charred at DBH was 64±9% following summer burns and 86±6% during winter burns, but were only marginally different (p=0.069). The proportion of understory area burned was almost 100% during summer burns as was observed during winter burns.

Modeled versus Observed

Using the Rothermel (1972) fire spread model, within the BEHAVE PLUS fire modeling system (Andrews et al. 2008, version 4.0), there was much variation with observed and predicted values of fire behavior when modeling across all treatment burns, at the plot level (Figure 4-5). Observed flame lengths were generally over-predicted in the mowed treatments, while under-predicted in the non-mowed (B) treatments. ROS was over-predicted across all plots burned, even in the non-mowed treatment, however the relationship between observed and predicted ROS in the B plots appears better. Although there was variation in predictability, with more values over- than under-predicted, observed fireline intensity appeared to better fit predicted values than the other metrics. As observed with ROS, there was a wider range of variation around the relationship between predicted and observed fireline intensity in the mowed sites compared to the un-mowed (B) sites.

Tree Mortality

Across all treatment plots (winter B, winter M+B, and summer M+B), 165 trees were assessed for mortality, all of which were alive prior to burning. Of 65 trees assessed in winter B treatments, 2 trees were dead one year later (Table 4-5, Figure 4-6); both were longleaf pines <20cm in DBH (Figures 4-6 and 4-7). Of 61 trees assessed in winter M+B treatments, all were alive one year following burning, however of 47 trees assessed following summer M+B burns, 7 were dead one year later (Table 4-5, Figure 4-6). As a reference for background mortality, 1 out of 61 trees assessed in controls died during the study (longleaf pine, 9 cm DBH) and 0 out of 52 trees assessed in unburned mowed sites died. Of the 7 dead trees in the summer M+B treatment, 2 were small diameter hardwoods, while the others were all longleaf pines with only one being <20cm DBH (Figure 4-7). Across all treatments, dead trees spanned the entire range of tree sizes across sites (Figure 4-7), however only following summer burns did trees >20cm DBH and >20 m in height die. Also, while all but two of the trees that died had almost 100% crown scorch, the two trees with <20% crown scorch that died following summer M+B burning were relatively large trees (Figure 4-7). More trees in the winter B sites had >90% scorch compared to both winter and summer M+B sites (Figures 4-6 and 4-8), however there were also more smaller trees (<20 cm DBH) in the B treatments (Figure 4-6). Most of the small trees were 100% scorched in B treatments, however there were still more larger trees (>20 cm DBH) in the B treatments with >90% scorch than in either the winter or summer M+B treatments (Figure 4-8). Distribution of maximum char heights across trees were relatively similar between treatments, except that there were more trees in B treatments with char >8 m than in both M+B burn sites (Figure 4-8). Percent of bole circumference charred at DBH was high across all treatments, however M+B sites burned in the summer had less trees with >90% char (Figure 4-8).

Discussion

While mechanical fuels treatments are being widely implemented to mitigate fire hazard, it is difficult to conduct field level experiments to gather empirical data evaluating their effectiveness. This study determined the effectiveness of understory mowing at reducing fire behavior in a common forest ecosystem of the southeastern US, but also determined shrub control over fire behavior following these treatments, evaluated model predictability, and evidenced a seasonal effect on tree mortality.

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 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 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 (Ch 2), 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 began controlling fire behavior as soon 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 (Ch 3), which was not evidenced in this study. Shrubs were much reduced in the treated sites, however their quick recovery resulted in a shrub-type fuel model (Scott and Burgen 2005) soon after treatment as evidenced by their control over fire behavior. While mastication in many shrub and forest ecosystems may result in a surface fuel-type for some time, mastication in areas where shrubs resprout vigorously will likely return to a shrub fuel-type quickly and treatment efficacy on fire behavior 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.

Although shrubs controlled 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). More trees were 100% scorched in the winter burn only treatments compared to both winter and summer burning in mowed sites, however more tree mortality was evidenced following summer burning in mowed sites and even two large trees with little crown scorch died. Litter consumption during winter burns was high, but little duff was consumed. During summer burns, less litter consumption was observed, but there was some evidence of greater duff consumption, even though there was a lot of variation. While litter consumption in the summer burns were lower, on average, long duration heating from litter combustion (Ch 3) may have been enough to ignite duff during summer burns where 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 (Busse et al. 2005, Kreye et al. 2011, Ch 3) in conjunction with duff accumulation in long-unburned sites (Varner et al. 2005) may result in fine root or bole damage (O'Brien et al. 2010a). While southern pines are capable of recovering from substantial crown damage (Waldrop and Van Lear 1984, Johansen and Wade 1987), effects of fine root or bole damage may result in delayed mortality (O'Brien et al. 2010a), and trees that survived one year following burning in this study could potentially still die. Although few trees that we assessed for mortality died in this study, there was evidence that summer burning resulted in greater tree death and that tree damage typically attributed to greater flame lengths (crown scorch and bole char) didn't explain differences in mortality across burning treatments. Larger sized plots or transects would have been needed to incorporate more trees into our study, allowing a more thorough statistical analysis of tree mortality. The effectiveness of mastication in reducing fire behavior may be important for restoration of long-unburned sites, but timing of prescribed burns should be taken into consideration regarding potential ecological effects.

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. While litter consumption was quite high in these burns, the mulching effect of moisture retention in masticated fuelbeds (Kreye et al. 2012) may mean that attaining desired fuel consumption may be difficult under wetter surface conditions. Although KBDI was higher during summer burning in this study, indicating drier soil conditions, there was some evidence of higher litter moisture during summer burns. In contrast, shrub reduction following mowing in this ecosystem may result in drier surface fuels (Ch 5), potentially due to increased solar radiation or surface winds. Litter moistures, during winter burns, were lower in mowed treatments versus un-mowed treatments. In long-unburned forests, where mowing is likely to occur, duff accumulation may be heavy and burning under drier conditions could result in high tree mortality (Varner et al. 2007). 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 with regard to the fire metric. Flame lengths were over-predicted in mowed sites and ROS over-predicted for both mowed and un-mowed sites. Flame lengths were adjusted for an assumed flame tilt of 30˚ under the light wind conditions. It is difficult, however, to quantify actual flame length during burning, especially in shrub fuels. From observations in the field, a 30˚ tilt is likely a liberal estimate, however the adjustment from vertical flame height is only an increase of 15%. One additional point is that flame heights measured during burning extended 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 being average shrub height. If estimated flame lengths from field burning were adjusted to include only the flaming portion above the average shrub height, model performance would be even poorer with drastic over-estimations of flame length. Flame length above the forest floor is likely a more important metric as a tool to assess fire suppression tactics or controllability during prescribed burning. Fireline intensity appeared to be better predicted in un-mowed sites, compared to the mowed sites. Fireline intensity is calculated from fuel consumption and ROS, and also should be related to flame lengths (Byram 1959). A tighter relationship between observed and predicted ROS in B plots likely attributed to the tighter relationship of observed and predicted fireline intensity in B plots, however intensity was much closer to observed values. One major shortcoming of the Rothermel (1972) model is that is assumes a homogenous fuelbed. In these shrub fuels there is a vertically oriented shrub fuel layer above a denser horizontally oriented surface layer, even when un-mowed. The model is quite sensitive to fuelbed bulk density and the heterogeneous nature of these fuels is exacerbating following mowing, where higher surface fuel loads are even more compact, but under a quickly recovering shrub layer. In chapter 3, fireline intensity in these masticated surface fuels was observed to be greater per unit flame length than Byram's (1959) relationship, which is used to predict flame lengths in the model. The relationship between flame lengths and fireline intensity may not be as clear in such fuel scenarios, especially in a heterogeneous fuelbed 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). There was much variation regarding the accuracy of model predictions and observations of fire behavior at the plot level in the study, however average predictions across sites may be sufficient to predict fire behavior at the stand scale, at least in regard to fireline intensity. Models are generally used as a prediction tool across a site 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 in the model. Spatial variation in fuel structure likely attributes to spatial variation in fire behavior, which may not be fully captured, even at our plot level, when average fuel characteristics are input to the model. Mismatches between observed and predicted outputs may occur for several reasons. Whether mismatches occurred because the model has fundamental errors, if fuel or weather inputs were inaccurate at our scale, if model parameters are inappropriate for these kinds of fuelbeds, if the uncertainty of the model does incorporate the variation we observed, or if our methods of observation were inaccurate, is unknown. But, even if models may be sufficient to predict fire intensity, their use as a predictor of fire effects may be limited where dense surface fuels, beneath a burning shrub layer, may be generating localized heat for long durations. One of the model assumption is fuelbed homogeneity, which does not accurately represent a dense masticated fuelbed beneath a shrub layer. 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.

Table 4-1. Weather, overstory, and fuel conditions during experimental burning of masticated (mow+burn) and untreated (burn) stands of palmetto/gallberry pine flatwoods in northern Florida, USA.

Burning Conditions

	Burn Date	Temp	RH	Windspeed	Litter	Live	10h	KBDI
		˚C	*%*	*$km \cdot hr^{-1}$*	-----------*% moisture*------------			
Mow+Burn	23 Feb 2011	17-24	47-62	1.6-4.8	12.1 (0.6)^{A}	117 (3)^{A}	20.9 (6.6)^{A}	107
Burn Only					17.8 (2.4)^{B}	110 (3)^{A}	27.8 (5.6)^{A}	107

Overstory

	Tree Density	Basal Area	QMD	Height	CBH
	$trees \cdot ha^{-1}$	*$m^2 \cdot ha^{-1}$*	*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}

Understory Fuels

	Shrub Cover[1]	Shrub Height[1]	Shrubs	Shrub Foliage
	%	*cm*	--------------------*$Mg \cdot ha^{-1}$*-----------------	
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*----------		--------------------------------*$Mg \cdot ha^{-1}$*-----------------------------				
Mow+Burn	5.7 (0.4)^{A}	3.0 (0.5)^{A}	12.8 (1.0)^{A}	33.6 (5.5)^{A}	1.1 (0.2)^{A}	2.1 (0.3)^{A}	1.1 (0.6)^{A}
Burn Only	7.6 (0.2)^{B}	4.5 (0.7)^{A}	8.8 (0.3)^{B}	49.5 (7.4)^{A}	0.5 (0.1)^{B}	1.1 (0.4)^{A}	0.7 (0.3)^{A}

Note: Values sharing letters within columns are not statistically different (Tukey-Kramer Test, $\alpha=0.05$).

Table 4-2. Fire behavior and effects from burning of masticated (mow+burn) and unmasticated (burn only) palmetto/gallberry pine flatwoods.

	Fire Behavior		Consumption				Overstory Fire Effects		
	Flame Ht	ROS	Litter	Duff	Litter	Duff	Scorch	Char	Char Height
	m	$m \cdot min^{-1}$	-------$Mg \cdot ha^{-1}$---------		-------%-------		%	%	*m*
Mow+Burn	1.1 (0.3)^{A}	3.4 (1.0)^{A}	10.6 (0.8)^{A}	0.0 (0.0)^{A}	83 (4)^{A}	0 (0)^{A}	37 (8)^{A}	86 (6)^{A‡}	5.5 (0.6)^{A‡}
Burn Only	3.3 (0.5)^{B}	7.1 (2.1)^{A}	7.6 (0.8)^{B}	1.1 (1.1)^{A}	86 (8)^{A}	3 (3)^{A}	53 (6)^{A}	97 (2)^{A}	7.4 (0.9)^{A}

Note: Values sharing letters within columns are not statistically different (Tukey-Kramer Test, α=0.05), ‡ indicates marginal differences (p<0.10)

‡ Marginal difference (p<0.100)

Table 4-3. Comparison of burning conditions (weather, overstory, and fuels) between a summer and winter burn in masticated palmetto/gallberry pine flatwoods of northern Florida, USA.

Burning Conditions

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

Overstory

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

Understory Fuels

	Shrub Height[1]	Shrubs	Shrub Foliage
	cm	------------------------*Mg·ha^{-1}*-----------------	
Summer	69 (7)^{A}	0.9 (0.5)^{A}	0.5 (0.2)^{A}
Winter	58 (13)^{A}	0.6 (0.3)^{A}	0.4 (0.2)^{A}

Surface Fuels

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

Note: Values sharing letters within columns are not statistically different (Tukey-Kramer Test, α=0.05)

‡ Marginal difference (p<0.10)

Table 4-4. Fire behavior and effects between summer (July) and winter (Feb) burning of masticated palmetto/gallberry pine flatwoods.

	Fire Behavior		Consumption				Overstory Fire Effects		
	Flame Ht	ROS	Litter	Duff	Litter	Duff	Scorch	Char	Char Height
	m	$m \cdot min^{-1}$	--------$Mg \cdot ha^{-1}$--------		--------%--------		*%*	*%*	*m*
Summer	1.5 (0.1)^{A}	5.9 (1.8)^{A}	5.5 (1.3)^{A}	23.1 (10.1)^{A}ǂ	48 (7)^{A}	32 (11)^{A}ǂ	25 (11)^{a}	64 (9)^{A}ǂ	4.7 (0.6)^{A}
Winter	1.1 (0.3)^{A}	3.4 (1.0)^{A}	9.6 (0.9)^{B}	2.6 (1.9)^{A}	71 (4)^{B}	5 (3)^{A}	37 (8)^{a}	86 (6)^{A}	5.5 (0.6)^{A}

Note: Values sharing letters within columns are not statistically different (Tukey-Kramer Test, $\alpha=0.05$)
ǂ Marginal differences ($p<0.10$)

Table 4-5. Number of trees dead or alive across three treatments at one year following burning in palmetto/gallberry pine flatwoods.

	Burn Only[a] (winter)	Mow+Burn[b] (winter)	Mow+Burn[c] (summer)	Total
Dead	2	0	7	9
Alive	55	61	40	156
Total	57	61	47	165

Note: All trees were alive prior to burning.
[a] Non-masticated, burned Feb, 2011
[b] Masticated Aug, 2010, burned Feb, 2011
[c] Masticated Aug 2009, burned Jul, 2010

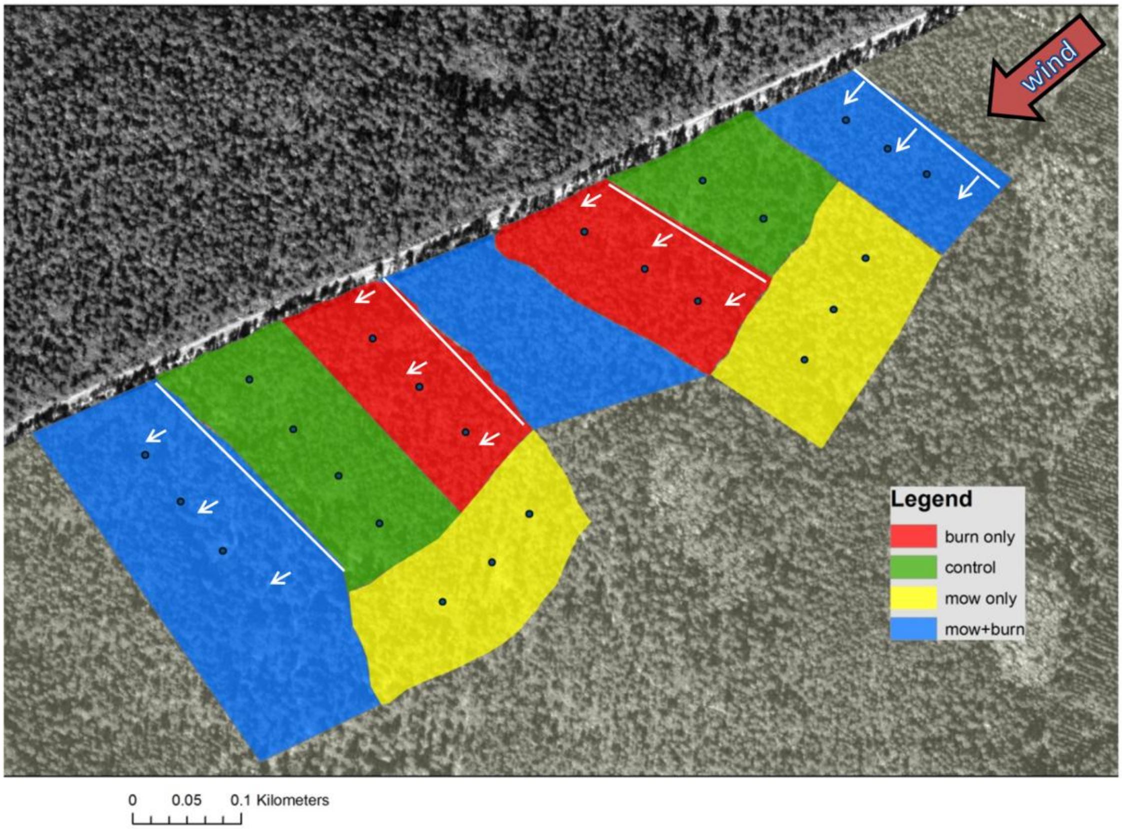

Figure 4-1. Experimental mowing and burning treatments in pine flatwoods in northern Florida, USA (Osceola National Forest). Systematic plot locations are indicated. Burn only and mow+burn treatments burned with strip head firing techniques (white arrows indicate fire movement).

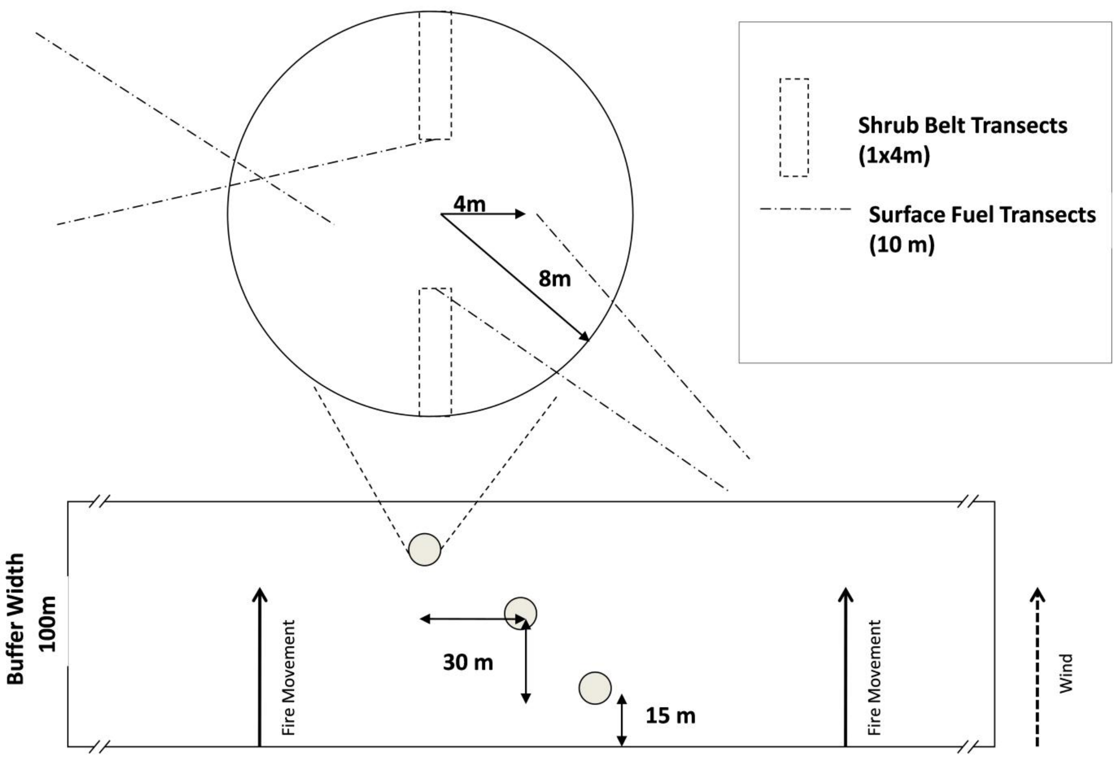

Figure 4-2. Example of plot locations within the buffer treatments. Sampling within plots were the same for both buffer and experimental block treatments. All trees (≥2.5 cm DBH) were measured within the entire 8m radius plot. Surface fuel transects were randomly oriented.

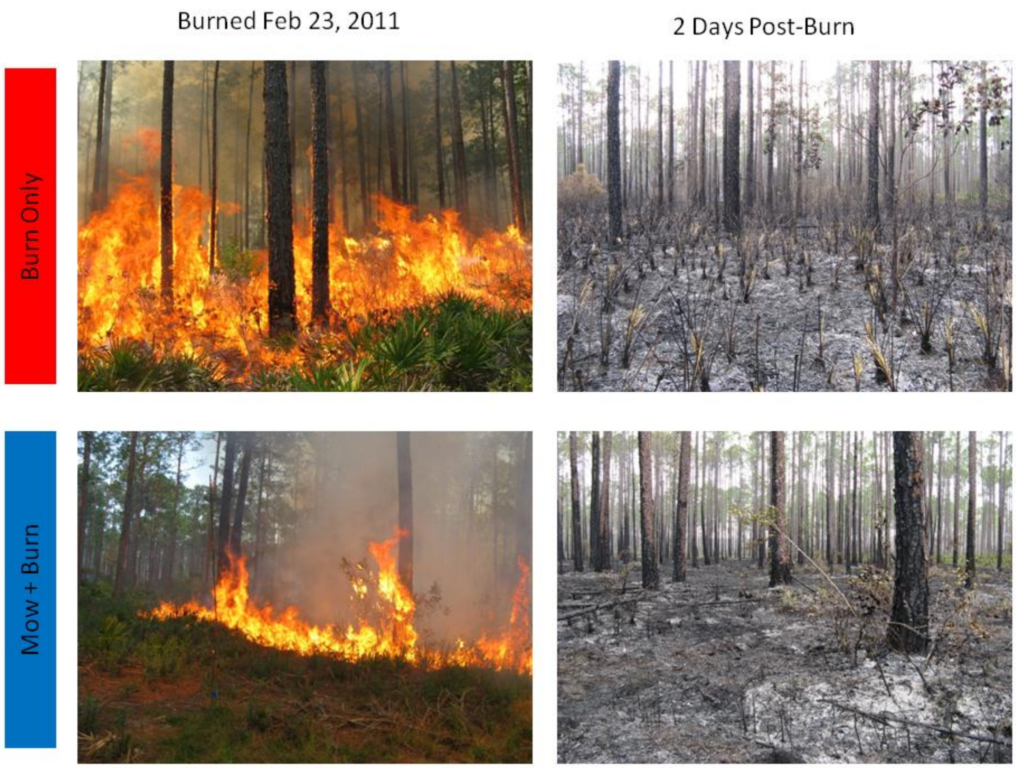

Figure 4-3. Fire behavior in experimental mowing and burning treatments in pine flatwoods of northern FL, USA. Burn only treatments were not masticated, mow+burn treatments were masticated 6 months prior to burning.

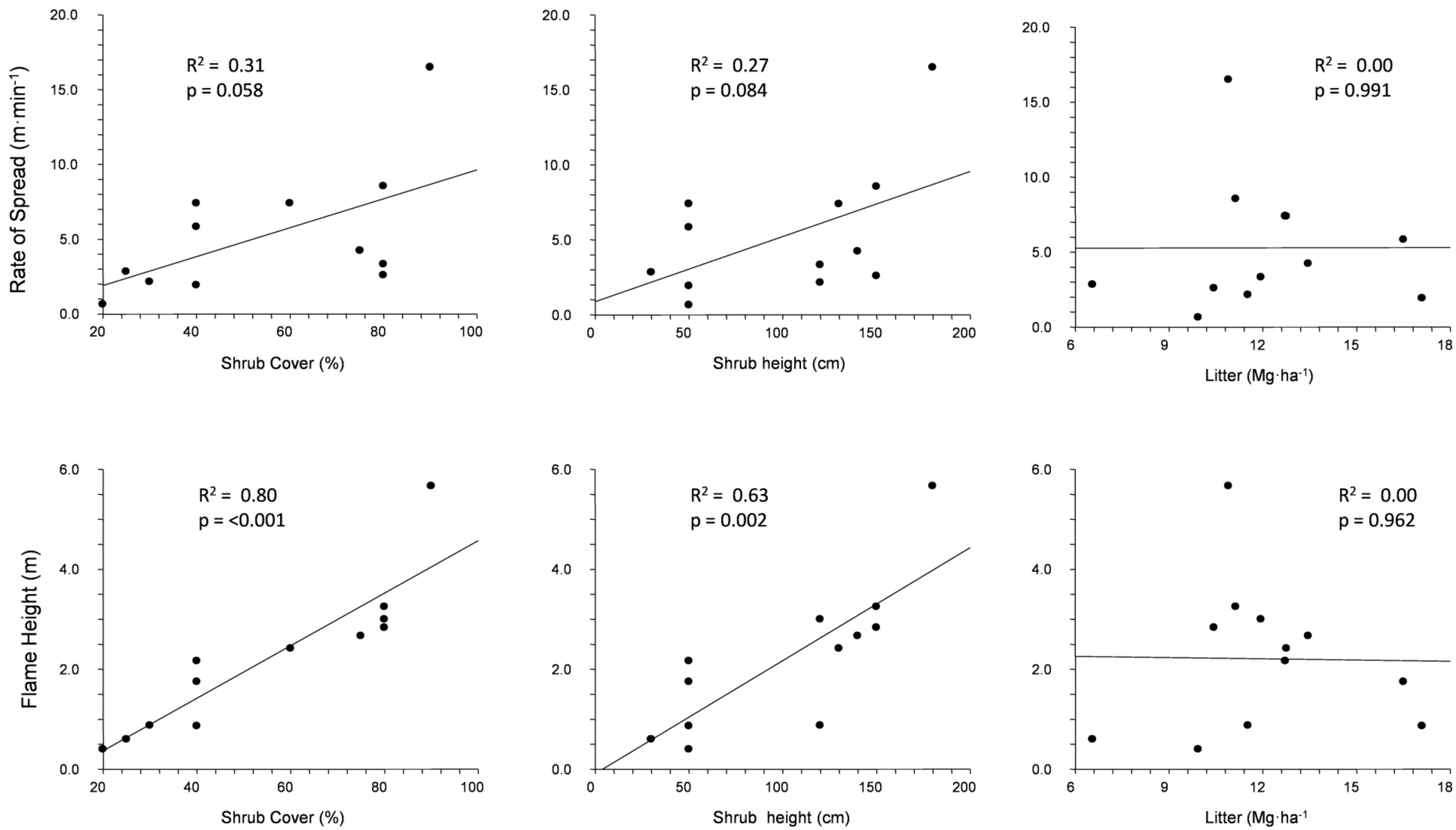

Figure 4-4. Fire behavior measurements (rate of spread, above; flame height, below) as a function of shrub cover (left), shrub height (middle), and litter mass (right) during the burning of mowed and un-mowed experimental treatments in pine flatwoods.

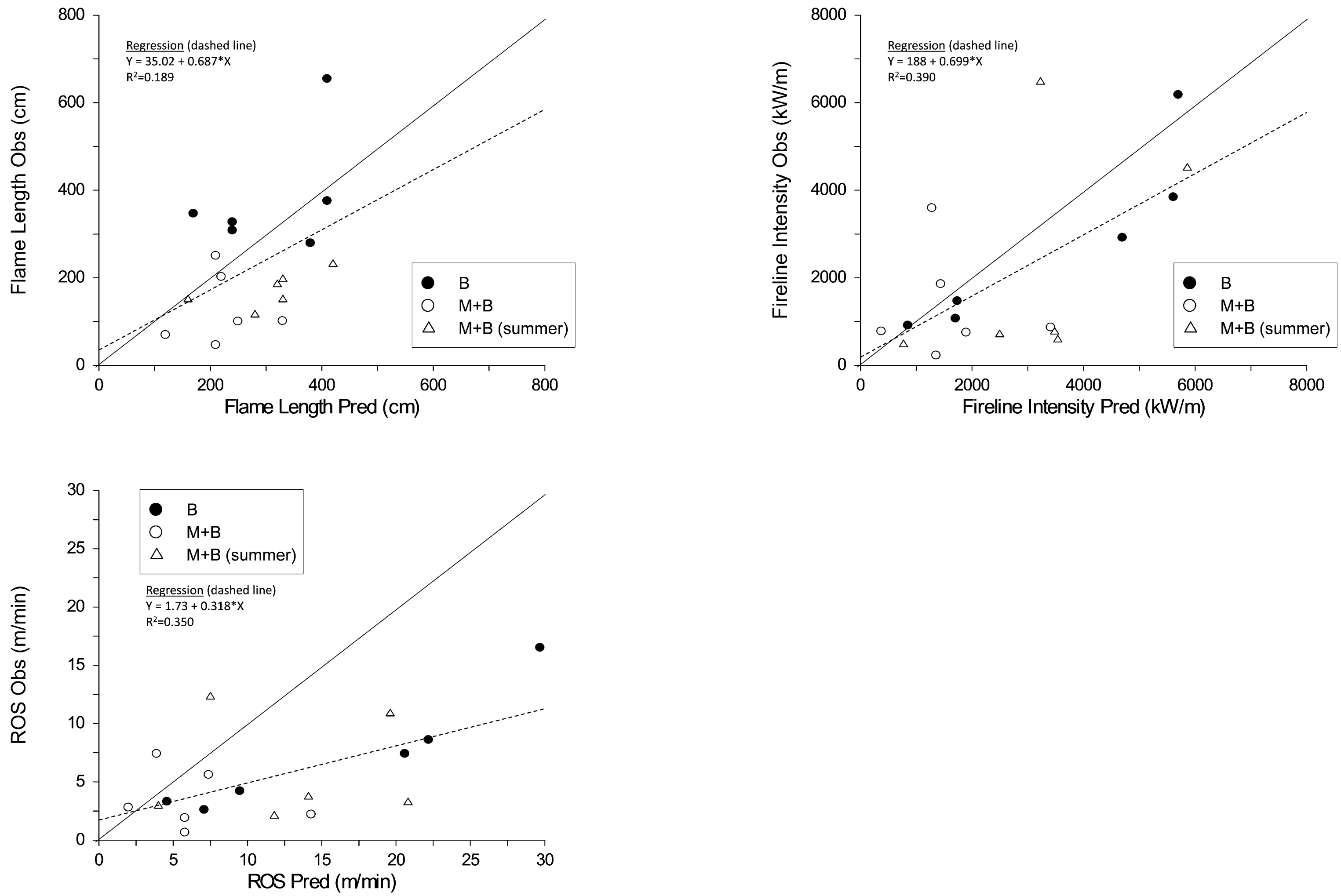

Figure 4-5. Observed versus predicted fire behavior across burning treatments within mowed (M+B) and un-mowed (B) palmetto/gallberry pine flatwoods burned in the winter (Feb) and mowed treatments burned in the summer (M+B summer). Solid line, 1:1 ratio; Dashed line, linear regression.

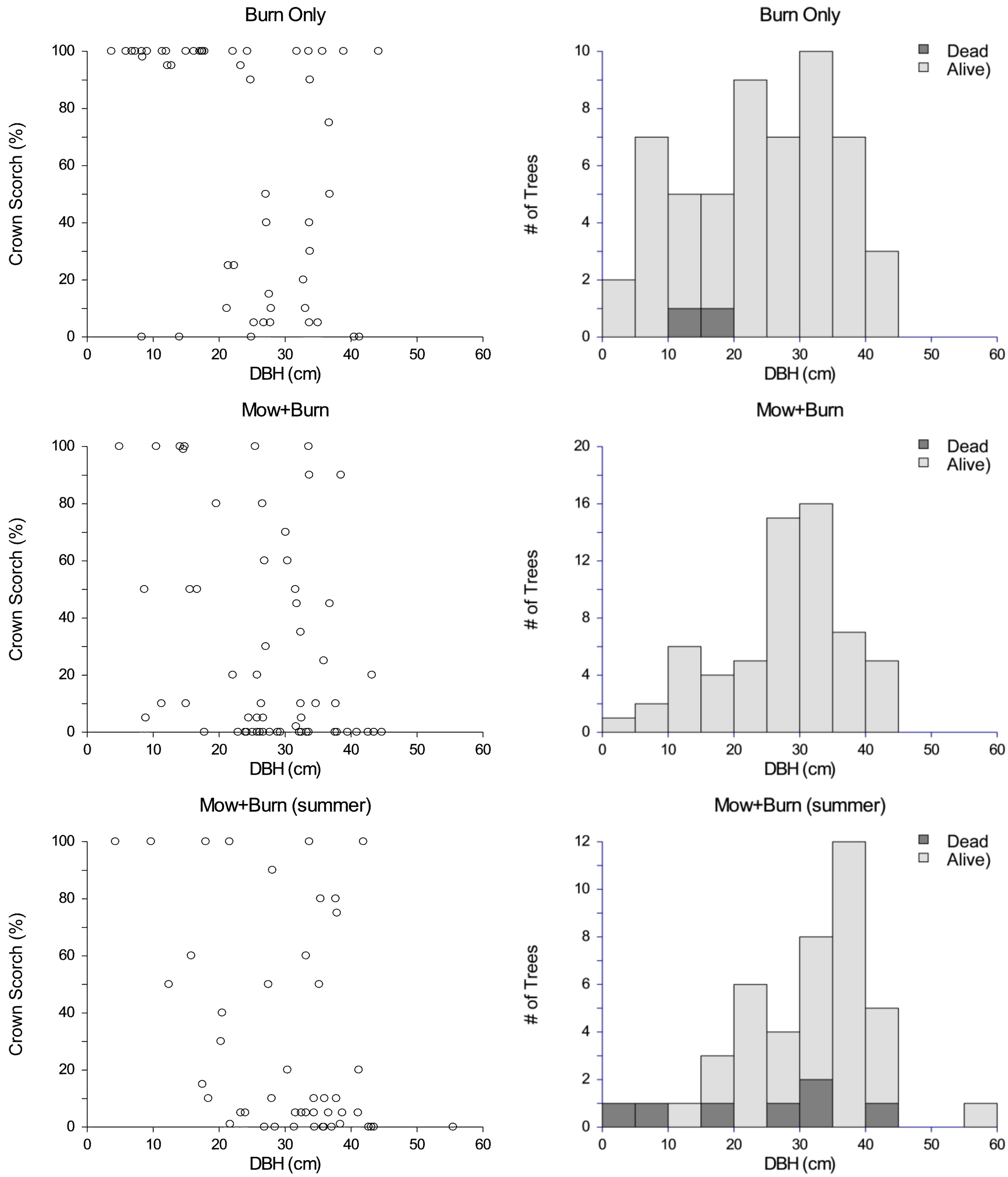

Figure 4-6. Crown scorch (%) versus tree diameter (DBH) (left) and tree mortality within diameter distributions (right) across burn only (top) and mow+burn (middle) treatments burned in the winter (Feb) and mow+burn treatments burned in the summer (July) (bottom).

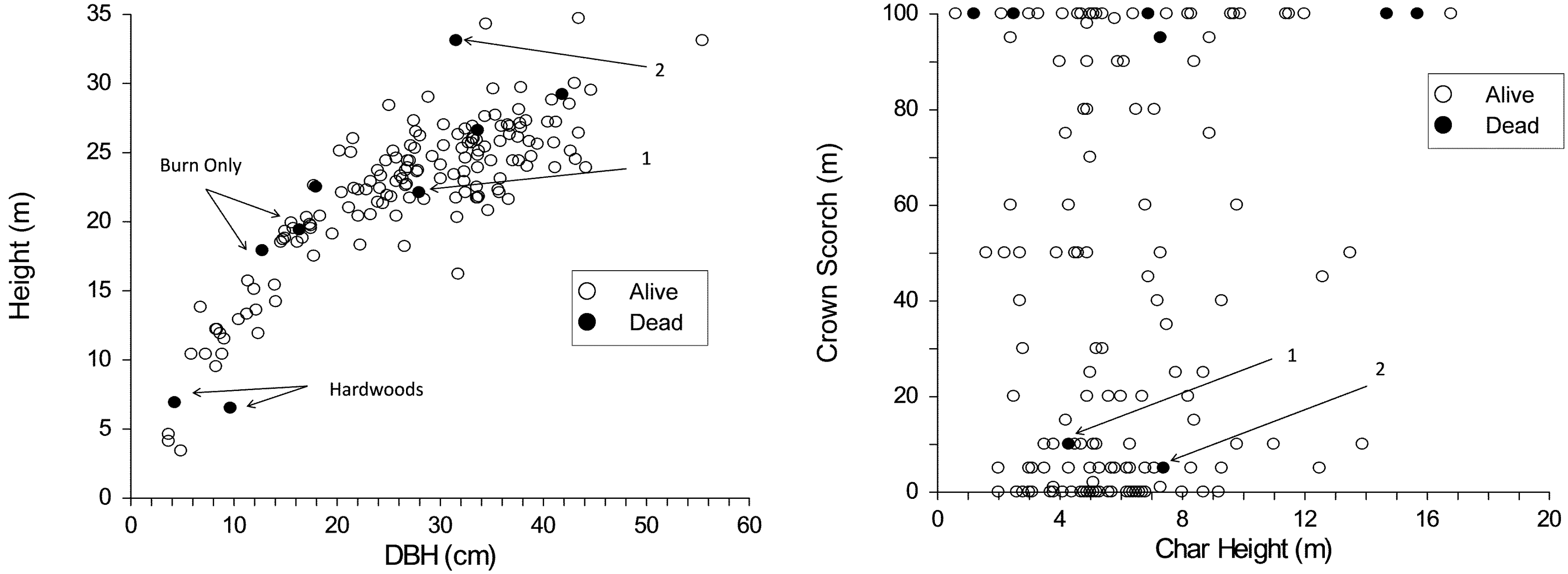

Figure 4-7. Tree mortality across individual tree characteristics (height and DBH) and tree damage (crown scorch and bole char height) following burning in masticated and non-masticated treatments in palmetto/gallberry pine flatwoods. The height vs DBH graph indicates the only 2 hardwoods in the study (both died) and the only 2 trees that died in the burn only treatment, all other dead trees occurred in the masticated treatment burned in the summer. Trees 1 and 2 are indicated in both graphs and were both large trees with little crown scorch that died following summer burning following mowing.

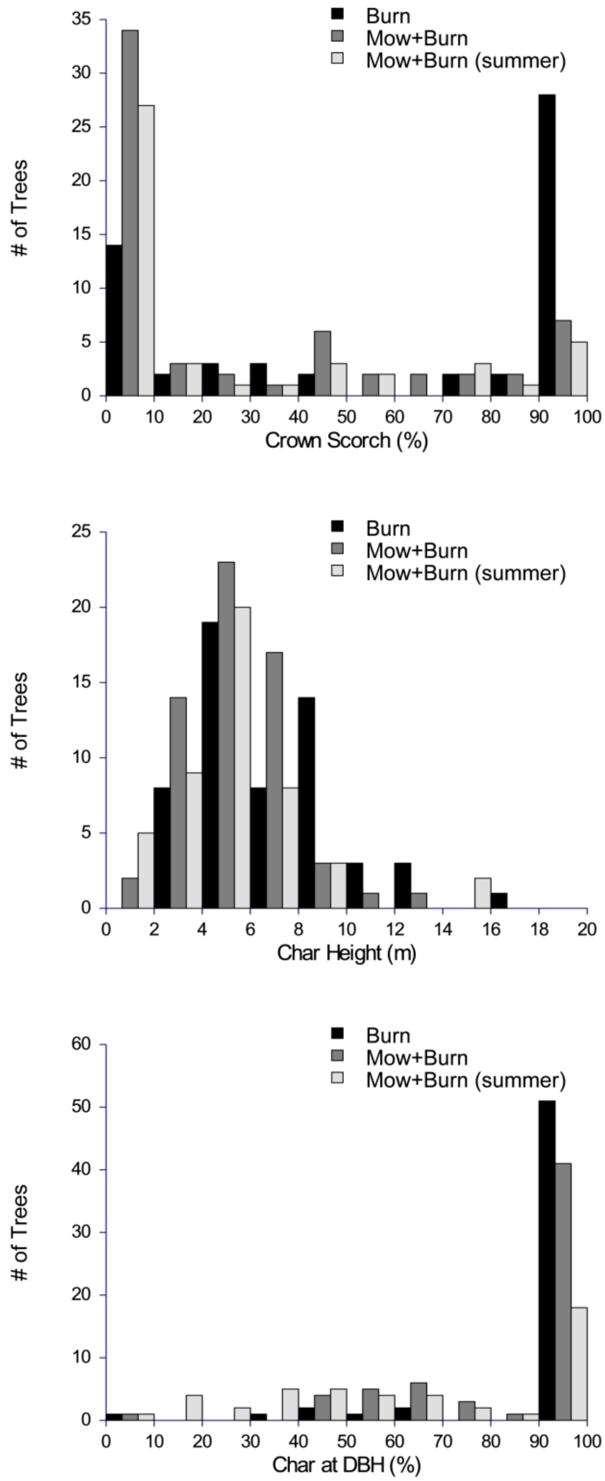

Figure 4-8. Distribution of crown scorch (top), bole char height (middle), and percent bole circumference charred at DBH (bottom) across burn only and mow+burn treatments burning in the winter (Feb) and mow+burn treatments burned in the summer (July).

CHAPTER 5
EFFECTS OF MECHANICAL FUEL TREATMENTS AND PRESCRIBED BURNING ON VEGETATION, MICROCLIMATE, AND SOILS IN PINE FLATWOODS ECOSYSTEMS OF FLORIDA, USA

Background

Fire is a critical ecological process in many ecosystems worldwide. In many ecosystems, however, fire exclusion has resulted in increased accumulation of fuel, often leading to increased wildfire hazard. The use of prescribed burning as a management tool to reduce fuel loads is often difficult due to the increased fuel biomass, and the challenges of the wildland urban interface, where human development is interspersed with wildlands. In addition, factors associated with climate change may likely result in increased risk of wildfire occurrence and the extent of areas burned (Westerling 2006). The use of mechanical treatments to reduce fuel biomass or to alter fuel structure as a means to mitigate such hazards has become widespread. Treatments may also be used for restoration where fire sensitive species have invaded as a result of fire exclusion. Treatments are used as a stand-alone management tool or in conjunction with prescribed burning to consume treatment residues or restore a managed fire regime to the ecosystem. The ecological consequences of these treatments are poorly understood.

Mechanical mastication has become widespread in recent decades, and is used to alter fuel structure in both forest and shrub-dominated ecosystems (Hood and Wu 2006, Glitzenstein et al. 2006, Kane et al. 2009, Kobziar et al. 2006, Battaglia et al. 2010). Understory shrubs or small trees are masticated (chipped, mowed, etc.) via front end or boom mounted mastication heads attached to various types of mobile machinery (Gyrotracks, skidders, etc.). Immediate results of such treatments include a reduction in fuel height and a compaction of the fuelbed, however no reduction in fuel loading occurs. Mastication's immediate effects consist only of the rearrangement of fuel structure(Kobziar et al. 2009, Kane et al. 2009). Current research has focused on mastication of shrubs and small trees in western US ecosystems where the resulting fuelbed is primarily composed of small diameter woody material fractured through the mastication process (Kane et al. 2009, Kobziar et al. 2009, Battaglia et al. 2010, Kreye et al. 2011). Initial research in these fuels indicates that while fire intensity may be reduced immediately following treatments, compact fuelbeds may lead to long durations of burning (Kreye et al. 2011) with sufficient heat to cause ecological change, such impacts to soils (Busse et al. 2005, Kobziar and Stephens 2006) or overstory trees (Knapp et al. 2011). Long duration heating of fuelbed surfaces and underlying soils has been observed during laboratory burning in collected fuels from western sites (Busse et al. 2005, Kreye et al. 2011) as well as impacts to soil respiration in the field (Kobziar and Stephens 2006). Higher than expected fire intensity (Bradley et al. 2006, Kobziar 2009) and overstory mortality (Knapp et al. 2011) have been observed from post-mastication burning in field experiments as well as increases in both native and non-native understory species(Kane et al. 2010).

Although laboratory experiments have indicated that compact woody fuelbeds following mastication enhances moisture retention (Kreye et al. 2012), field assessments of treatment impacts on moisture dynamics or micrometeorology have not been explored. Furthermore, impacts on soil nutrients and decomposition of surface litter have been given little attention in masticated sites, especially where sites are burned following treatment.

While some research on the ecological impacts of mastication have been conducted in the western US, where resulting fuelbeds are primarily woody debris (Kane et al. 2010, Knapp et al. 2011, Rhoades et al. 2012) mastication ("mowing") is being widely employed in palmetto/gallberry pine flatwoods of the southeastern US, where surface fuels following treatments are largely composed of foliar litter and, to a lesser extent, very small diameter woody debris (Ch 2). In the sub-tropical climate of the southeastern US, humidity and regrowth rates are higher, species composition and flammability differ, and consequences of fuels treatments to soil characteristics are unknown when compared with the western US. Understanding these treatment effects is key to evaluating the usefulness of mechanical treatments in this region.

Pine flatwoods represent the most widespread and prevalent forested ecosystem in the coastal plain of the southeastern US. Flatwoods occur on sandy soils of marine origin. In areas where seasonal inundation of water due to poor drainage occur, nutrient poor Spodosols are common, and understory shrubs, dominated by saw palmetto (*Serenoa repens* (Bartr.) Small) and gallberry (*Ilex glabra* (L.) Gray), occur under a canopy of longleaf (*Pinus palustris* Mill.) or slash pine (*P. elliottii* Engelm.) with varying densities. While fires were historically frequent (return interval <10 yrs) in these ecosystems, sites that have gone unburned for over ten years are being treated using mastication ("mowing") to reduce fire hazard on many public lands, especially in the wildland urban interface. Although soils are nutrient poor in these sites, understory vegetation resprouts vigorously following disturbance. The quick response of understory vegetation to disturbance makes this a unique ecosystem where the ecological effects of mastication have been inadequately addressed.

Existing work on mastication type fuels treatments in the southeast have focused on treatments in the more xeric scrub and sandhill ecosystems (Brockway et al. 2009, Menges and Gordon 2010,). These studies have shown that mechanical treatments alone are not as effective as burning for attaining restoration goals that typically include reduction of woody plant cover and promotion of herbaceous species. Initial reductions in tree density following mowing has been observed, but with a quick recovery of hardwoods and with substantial increases in understory plant cover, but without desired gains in grasses and forbs (Brockway et al,. 2009). Little work exists in the primary literature regarding mastication in the wetter palmetto/gallberry dominated flatwoods ecosystems. The few studies addressing ecological effects of understory fuels treatments in this ecosystem have focused on roller chopping (Schwilk et al. 2009), a treatment that differs from mastication in that a rolling drum, filled with water, is pulled across the ground resulting in greater soil disturbance than mastication (O'Brien et al. 2010b). Effects of roller chopping to understory plants have been found to be minimal in both flatwoods (Schwilk et al. 2009) and dry prairies (Watts and Tanner 2006), an ecosystem floristically similar to that of flatwoods, but without an overstory (Abrahamson and Hartnett 1990). When in combination with burning, however, these treatments may reduce shrubs and enhance herbaceous layers, the common restoration goals, better than either roller chopping or burning alone (Watts and Tanner 2006, Schwilk et al. 2009). Whether mastication treatments, where soil disturbance is less likely, would have similar effects in this commonly targeted ecosystem is unknown.

To evaluate ecological impacts from mastication fuels treatments in pine flatwoods ecosystems, vegetation dynamics, microclimate, understory moisture dynamics, litter decomposition, and soil nutrients were determined following mowing treatments in northern Florida, US. The objectives of this study were to 1) determine changes in overstory, understory, and groundcover up to two years following mechanical mowing treatments in three stand types of pine flatwoods; 2) measure decomposition rates of litter created by mechanical treatment; and 3) compare the effects of mowing and mowing followed by prescribed burning on vegetation (overstory, understory, and ground cover), microclimate (air temperature and relative humidity), shrub and litter moisture, soil temperature and soil nutrients.

Methods

Mechanical fuels treatments were conducted in the Osceola National Forest (ONF) in northern Florida, US in pine flatwoods communities that had gone unburned for several years and where fuel accumulations pose a hazard within the wildland urban interface (WUI). Mesic pine flatwoods on the ONF are dominated by slash pine and/or longleaf pine in the overstory and by saw palmetto and gallberry shrubs in the understory. Mature pine stands with moderate tree densities and open-canopied structures are common, but many younger pine plantations also exist. Shrubs tend to dominate the understory, but grasses, mainly wiregrass (*Aristida* spp.), may be common as well as other herbaceous plants. Climate is hot in the summer, averaging 33˚C, and mild, but variable, in the winter, with 17 to 19˚C highs and lows as cold as -10˚C (Chen and Gerber 1991). Summer months are the wettest with precipitation occurring from frequent thunderstorms. Topography is flat and soils are primarily Spodosols of coarse-textured marine deposits that are poorly drained. Mowing, a regional term for mastication, was used to reduce the height of understory fuels for re-introduction of prescribed fire, and to reduce fire hazard in areas abutting communities, highways, and private pine plantations. Treatments occurred in mature pine flatwoods (ca. 80 yrs old) and a younger plantation (28 yrs old), both lacking a mid-story and where the primary fuel strata altered during mowing was a continuous understory of saw palmetto and gallberry shrubs.

Treatments used in this study occurred in two locations (Figure 5-1), 1) a 100 m wide and 6 km long buffer, mowed in 2009, that included mature pine, mature pine that was recently burned (5 yr since fire), and young pine plantation; and 2) three experimental blocks (8 ha ea) in mature pine that were mowed in summer 2010 and burned in spring 2011 to create the following treatments: mowing only (mow), mowing followed by burning (mow+burn), burn only (no mowing), and control. Within each of the three 8 ha experimental blocks, treatments were approximately 2 ha each (Figure 5-1). Each block received each of the four treatments and treatments within blocks were systematically allocated to facilitate burning operations by the ONF management and to create an edge between each treatment and all other treatments. Soils in both treatment areas were sandy or sandy over loamy, siliceous, thermic, ultic aloquods (USDA Soil Survey).

Mechanical treatments were conducted with forward mounted mowing heads, with fixed cutters, attached to tracked ground equipment. The treatment prescription was that all understory shrubs and trees <20 cm DBH were to be mowed and all residue left on site. Mowing treatments differ from roller chopping treatments, common in the region, in that mowing is not intended to disturb the soil. While roller chopping drums, filled with water, are pulled behind ground equipment with their full weight on the ground, front mounted mowing heads are not fixed in position, but are hydraulically controlled (up and down) by the operator. Burning treatments in the experimental blocks were conducted in February, 2011 by ONF personnel using strip-head firing techniques. Vegetation was ignited with hand-held drip torches with approximately 20 m spacing between ignition lines and fire moving with the wind. Conditions during burning were 17-24˚C with relative humidity ranging from 47-62% and under light winds (1.6-4.8 $km \cdot hr^{-1}$). Rate of fire spread was slow to moderate during burning (3.4-7.1 $m \cdot min^{-1}$) and while flame heights averaged 1.1 m in mowed sites, they were higher (3.3 m) in the un-mowed sites (Kreye Ch 4). Nearly 100% of the area was burned with almost all shrub foliaged consumed and 85% of litter consumed, but with little to no duff (humus and fermentation layers) consumed.

Vegetation Dynamics

Mowing in the buffer treatment occurred in August 2009. Vegetation was sampled immediately prior to treatment, and at 2, 8, 16, and 24 months following treatment. The 8-mos sampling period was conducted at the beginning of the growing season (Mar, 2010), 16-mos sampling after the growing season (Oct, 2010), and 24-mos in Aug, 2011. Pre-treatment sampling plots were systematically located within the linear buffer and subsequently re-sampled following treatment. Allocation of plots within stand types (mature N=12, mature/burned N=9, plantation N=6) were weighted based on the area represented by each stand type along the buffer. Plots were spatially arranged in triplets at 15, 45, and 75 m from the buffer edge, but arranged at a 45˚ angle between plots in reference the edge of the buffer (Figure 5-2). They were spatially established by locating the center of the stand type unit, to reduce edge influence from adjacent stand types, and were arranged so that an equal number of plots were located on either side of the center of the unit.

Within each plot, all trees ≥2.5 cm diameter at breast height (DBH, measured at 1.37 m above the ground) were measured for height and DBH within the entire 201 m^2 circular plot. Trees were measured before treatment, after treatment, and at two years following treatment. Basal area (m^2) and quadratic mean diameter (QMD) were calculated for each plot, at each sampling period. Shrubs and tree saplings (<2.5 cm DBH) that were at least 0.5 m in height were tallied, by species, within two 1×8 m belt transects located at 4 m north and south, respectively, of plot center (Figure 5-2). Height and basal diameter were measured for each shrub and sapling. Groundcover was sampled within four 1×1 m quadrats located at the four cardinal directions and 4 m from plot center (Figure 5-2). The north and south groundcover quadrats were nested within the shrub belt transects. For each quadrat, percent cover of herbaceous plants, grasses, vines, as well as shrubs and trees less than 0.5 m in height, were quantified using ocular estimation from a vertical perspective. Shrub and tree seedling cover (<0.5 m) was further classified by species. Percent cover of each group was estimated regardless of overlap across groups, therefore it was possible for cover to exceed 100%. Percent cover of litter or bare ground was estimated where vegetation cover did not occur.

To determine the effects of mowing on vegetation dynamics, vegetation measurements were compared across time since treatment (TST), including pre-treatment, within each of the stand types (mature, mature-burned, plantation) in the buffer treatment. Tree (>0.5 m) density, basal area, and diameter (QMD) were compared across TST (pre, post, 2 yr post) and stand type using a repeated measures analysis of variance (ANOVA), with TST as the within-subjects variable and plot as the subject. Analyses included both fixed effects and their interaction. Using all trees pooled, within stand types, diameter and height distributions were also created and compared between pre- and post-treatment. To evaluate treatment effects on the understory strata, density of saw palmetto, shrubs (including saw palmetto), and small trees (<2.5 cm DBH), as well as species richness of shrubs and small trees, pooled within plots, were compared across TST and stand type using repeated measures ANOVA. Mean density of shrubs and small trees, by species, were determined for each TST within stand types. Species that rarely occurred were not included. Percent groundcover by cover type (shrubs <0.5 m in height, tree seedlings <0.5 m in height, herbs, grasses, vines, litter, and bare ground) and species richness of groundcover shrubs and trees were each compared across TST and stand type using repeated measures ANOVA. For all analyses, statistical significance was tested at the $\alpha=0.05$ level, and the Tukey-Kramer post-hoc comparison of the means test was used to determine differences amongst groups. Each ANOVA was conducted as a within-subjects analysis with TST as the within-subject variable and each plot as the subject. When model assumptions were not met, data were log or square-root transformed to meet assumptions. In circumstances where occurrences were too rare for GLMANOVA (understory small tree density and herb groundcover), the Chi-Square test was used to determine if occurrences across levels of fixed effects were unlikely to have occurred at random.

To evaluate the effects of both mowing and burning on vegetation dynamics, vegetation sampling was conducted following treatments in the experimental blocks. Mow and mow+burn treatments were mowed in August 2010 and all treatments, including controls, were sampled in October 2010. Mow+burn and burn only treatments were burned the last week of February 2011 (Ch 4) and subsequently sampled in March/April, 2011. Vegetation sampling was then conducted again at one year following burning in March 2012. Three sampling plots were systematically located within each treatment 50 m from the edge of each treatment, to avoid possible edge effects, and 50 m apart (Figure 5.X). The same vegetation sampling technique was used as conducted in the buffer, except that saw palmetto cover (%) was also quantified over the entire 8 m radius plot (201 m^2), using ocular estimation, at all sampling periods.

Tree density, basal area, and QMD were compared across treatments (mow, mow+burn, burn only, control), within each sampling period. Saw palmetto, shrub (including saw palmetto), and small tree (<2.5 cm DBH) density were compared across treatments, within sampling period, as well as saw palmetto cover and species richness of understory shrubs and small trees pooled. Groundcover (%), by cover type (shrubs <0.5 m, tree seedlings <0.5 m, herbs, grasses, vines, litter, and bare ground), were compared across treatments, within sampling period, as well as species richness of ground cover shrubs and trees pooled. All comparisons were conducted using a GLMANOVA, except where occurrences were rare (understory small trees, herb and vine groundcover) where the Chi-Square test was used, as above.

Microclimate and Fuel Moisture Dynamics

Microclimate and moisture dynamics in surface litter and shrubs were evaluated within the experimental block treatments. At each plot location, between October 2010

(2 months post-mowing) and January 2012, air temperature and relative humidity were recorded every 30 minutes using EasyLog EL USB-2 data loggers (DATAQ Instruments, Inc. Akron, OH) located at plot center 1 m above the ground, and soil temperature was recorded every 30 minutes using Watermark Soil Moisture Sensors, located 10 cm beneath the mineral soil, attached to Watchdog 450 data loggers (Spectrum Technologies, Inc. Plainfield, IL). Surface litter moisture content and foliar moisture content of shrubs were sampled at each plot location every 3-4 weeks between June 2011 (14 weeks after burning) and March 2012. Fuel moisture content (FMC) sampling was initiated at 2.5 months following burning treatments to allow litter input and reestablishment of shrubs in the burned sites. Burning in the burn only and mow+burn treatments resulted in 100% area burned with high consumption of surface litter and understory shrubs (Ch 4). Surface litter was collected at two locations within each plot and pooled and foliar samples were clipped from two individuals of the dominant shrub species in each plot and pooled. Moisture samples were bagged, transported to the laboratory, oven dried at 65 ˚C for 72 h, and gravimetric FMC (water mass as a percentage of dry mass) calculated.

Air temperature, relative humidity, soil moisture, and soil temperature were each averaged by day and within two time period categories: day (08:00-19:59) and night (20:00-07:59). Each microclimate metric was then compared across treatments using a repeated measures general linear model analysis of variance (GLM ANOVA) in NCSS (Hintze 2008) with time since treatment (TST), by month, as the within subject factor, treatment (mow, mow+burn, burn, and control) as the between subject factor, and plot as the subject. Since burn treatments were conducted six months following mowing treatments, planned comparisons were conducted to detect differences between mow (mow and mow+burn) and un-mowed (burn and control) treatments, pooled, prior to burning treatments and to detect if differences occurred between mow and mow+burn sites as well as burn and control sites prior to burning. Following burning treatments repeated measures analysis was conducted with data separated into growing season (March-August 2011) and dormant season (September-January 2012) as seasonal effects were anticipated. Surface litter moisture and foliar moisture content of shrubs were compared across all treatments immediately prior to ignition on the February burn day using an analysis of variance. Subsequently, FMC of litter and shrubs were each compared across all treatments between the June 2011 and May 2012 collections using a repeated measures GLM ANOVA as above, but with each sampling period as the within subject factor. Data were analyzed within season as above with growing season occurring between June and August 2011, and dormant season occurring between September and March 2012.

Decomposition

Decomposition of mowed surface debris (fuels) was evaluated over a one year period. Recently mowed surface fuels were collected from an adjacent site to that of the experimental block treatments, with similar overstory and understory vegetation. Surface debris was collected and transported to the University of Florida Fire Science Laboratory. Fuels were oven dried at 50˚C for one week. Fuels were then sorted into foliar litter (primarily saw palmetto) and woody debris separated into two size classes: <0.635 cm (1 h) and 0.635 2.54 cm (10 h). Woody fuels >2.54 cm were not collected in the field as there were only a few pieces found. Fuels, by type, were mixed by hand to reduce heterogeneity.

Decomposition bags (20×30 cm) were created from 2mm mesh screen material and sealed along edges with staples. 216 bags were filled with 50 g of foliar litter and 216 bags were filled with 50 g of 1 h woody fuels. In addition, 36 bags were filled with 10 h woody fuels, ranging from 23 to 58 g of fuel per bag. All bags were placed in laboratory conditions for 3 days, along with 10 birch (*Betula papyrifera* Marsh.) medical-grade tongue depressors ("blanks") to estimate lab fuel moisture content (FMC). All decomposition bags, and blanks, were weighed prior to transporting bags to the field. Blanks were oven-dried at 65˚C for 72 h and weighed to back calculate gravimetric FMC (Eq. 5-1).

Within each mowed (N=9) and control (N=9) plot, in the experimental treatment sites, litter (6 ea) and 1 h (6 ea) decomposition bags were placed on surface fuels in a grid pattern and anchored with pin flags. Litter and 1 h bags were placed in treatment sites in February 2011, approximately 6 months following mowing. Since there were not enough 10 h woody fuels to create six decomposition bags per plot, one 10 h bag was placed in each plot, however they were not placed in plots until April 2011 during the first collection of litter and 1 h bags.

Litter and 1 h decomposition bags were collected at two month intervals, following initial placement, for 12 months (April 2011 through February 2012) for a total of six collection periods. 10 h bags were collected at the same time, but were only collected five times over a 10 month decomposition period because they were initially placed in the field two months following litter and 1h fuels. During collection, one litter bag and one 1 h bag was randomly selected, from each plot, for destructive sampling. The one 10 h bag in each plot was also collected, but returned following weighing. All bags were transported to the UF laboratory, air dried for 3 days, and weighed. While 10 h bags were weighed and returned to the field, litter and 1 h bags, with enclosed fuel, were weighed and then fuel was removed and bags reweighed to calculate fuel weight, exclusively. Bag weights, without fuel, were subtracted from initial bag weights, at the start of the study, to determine initial fuel weight, exclusively. 10 h fuels were removed from bags at the end of the study (Feb 2012) and subtracted from initial fuel weights, as well as all collection period weights, to calculated fuel weights, exclusively. Fuel weights at each time period were divided into original weights to calculate the proportion remaining at each collection period throughout the study.

For each fuel type, the proportion remaining, as a percentage, was compared across treatments (mow and control) using a repeated measured ANOVA with collection period as the within subject factor, treatment as the between subject factor, and plot as the subject. While litter and 1 h decomposition bags consisted of the same mass and 10 h bags did not differ in weight between treatments (P=0.197), differences in decomposition between mowed and control sites were sought to determine if shrub cover influenced decomposition since shrub recovery is rapid in this system and over longer periods decomposition rates may be influenced by this recovery.

Soil Nutrients

To evaluate the effects of mowing and burning on soil nutrients, soils were sampled within the experimental block treatments prior to implementing burn treatments (Feb 2011) and then again at one year following treatment.

Soil nutrient pools were sampled, across all treatments, on Feb 1, 2011 three weeks prior to burning. At each plot, two soil samples were extracted at 4 m from plot center, at each of the four cardinal directions, using a 2 cm diameter soil push probe.

Samples were separated into 0-5 cm and 5-10 cm soil depths and the two samples at each cardinal direction, by depth, combined. Three of the four resulting subsamples, of each depth, were randomly selected and pooled for nutrient analysis, and the fourth used to estimate soil bulk density. Samples for nutrient analysis were air dried in a laboratory, sieved to remove roots >2 mm, and homogenized. Samples were analyzed by Waters Agricultural Laboratories (Camilla, GA, US). Soil pH and cation exchange capacity (CEC) were determined. Total P, available P, exchangeable K, Mg, and Ca, as well as the base saturation of K, Mg, Ca, and H were determined from Mehlich-1 extractions analyzed on an ICAP spectrometer. Total N was determined from Kjeldahl digestion, total C from acid digestion, and percent organic matter from loss on ignition. Bulk density samples were oven dried at 105˚C for 24 h and weighed. All soil nutrient data were compared across treatment and time since treatment using a within-subjects GLMANOVA.

Results

Vegetation Dynamics in the Buffer Area

Mowing in the buffer treatments reduced overstory tree density in all stand types (mature, mature-burned, plantation), but only significantly reduced basal area in the mature stands (Table 5-1). While density did not statistically differ between pre- and post-mowing in the plantation stands, density was lower 2 years following mowing. Quadratic mean diameter (QMD) in mature and mature-burned stands significantly increased, however QMD was not affected by mowing in plantation stands. When pooling all trees within stand types, reduction in tree density in both mature and mature/burned stands primarily occurred in smaller diameter trees (<20 cm DBH), while trees in the plantation stands were reduced across all diameter classes, however less so at greater diameters (Figure 5-3). Pre-treatment DBH ranged between 2.5 to 59.7 cm, 2.6 to 51.8 cm, and 2.8 to 30.7 cm in the mature, mature/burned, and plantation stands, respectively (Table 5-2, Figure 5-3).

Immediately following treatment, understory shrub density (>0.5 m in height) was reduced by 90, 85, and 70 % in the mature, mature/burned, and plantation stands, respectively, following mowing. Saw palmetto density, exclusively, was reduced by 74, 66, and 77 % in mature, mature/burned, and plantations stands, respectively. By 16 months, shrub and saw palmetto densities had increased to levels that did not differ from pre-treatment values (Table 5.2, Figure 5-4). Density of understory small trees (<2.5 cm DBH) did not statistically differ across time since treatment (TST) or stand type according to Chi-Square analysis. Small tree occurrence was rare, resulting in high variability (Table 5-2, Figure 5-4). Species richness of understory shrubs and small trees was reduced following mowing across all stand types, due to immediate loss of most species (Figure 5-5), but did not differ from pre-treatment values at 16 months following treatment (Table 5-2, Figure 5-4), with most species re-emerging (Figure 5-5).

Pre-treatment groundcover was dominated by litter in the mature and plantation stands (~80%), and by both litter and shrubs (~50% ea) in the mature-burned stands (Table 5-3, Figureure 5-6). Shrub groundcover (<0.5 m in height) was not affected by mowing in mature and plantation stands, however shrub cover was less in the mature/burned stands at 16 months, but then did not differ from pre-treatment values after 2 years. Grass cover, ranging from only 0 to 2.4%, was reduced following treatment in all stands, but recovered to pre-treatment values by 16 months. Herb cover was rare and the Chi-Square analysis indicated a difference by stand type, but not TST, however TST was marginal (P=0.077). Prior to treatment, herb cover was only observed in mature stands, but 2 months following treatment, herbs existed in all stands. For up to two years, herb cover continued to be observed in the mature stands, but only once again in the mature/burned stands at 16 months, and not at all in plantations. Vines were greater in cover in mature (4.3%) and plantation (4.4%) stands compared to mature/burned stands (1.5%) prior to treatment. Vines did not differ at 2 or 8 months following treatment in mature stands, but by 16 months vine cover had increased to 8.7%. Vines were not affected in mature/burned stands, but were greater in plantation stands at 24 months compared to 8 months. In mature stands litter cover was reduced from 81.0% pre-treatment values to 68.3% at 16 months following treatment and even lower (55.0%) after 2 years. In mature/burned stands, litter cover increased to 69.4% following treatment, but then was reduced to 54.7% at 8 months and did not differ from pre-treatment values after that. Litter cover was unaffected in plantation stands. Bare ground was rare across stand types and TST (<3%) and variation was high where it did occur, however Chi-Square analysis revealed a TST affect (P=0.049). Species richness of shrub and tree seedling groundcover was highest in mature/burned stands compared to others (P=0.015) and richness only differed between the post-treatment sampling (2 months) and the 16 and 24 months sampling periods (P=0.007).

Vegetation Dynamics in the Experimental Block Area

In the experimental block treatments, overstory tree density, basal area, QMD, and tree height did not differ across treatments (mow, mow+burn, burn only, control) during any stage of sampling (post-mow, post-burn, 1 yr post-burn) (Table 5-4). Average pre-treatment tree density, basal area, QMD, and height, across all treatments, were 358±29.5 tph, 19.3±1.2 $m^2 \cdot ha^{-1}$, 27.2±0.8 cm, and 22.1±0.5 m, respectively.

Understory shrub density (>0.5 m in height) was lower in the mow treatments compared to all other treatments following mowing (P=0.049), while saw palmetto density and cover in the mow and mow+burn treatments were both lower than the control and burn only treatments (P<0.001) (Table 5-5, Figure 5-7). Following burning treatments, shrub density was lower in both the burn only and mow+burn treatments (P<0.001), but the mow only treatment no longer differed from the control. Saw palmetto density was still lower in the mow only treatment compared to the control following burning, but lowest in both burn only and mow+burn treatments (P<0.001). Saw palmetto cover was lower in all treatments (mow, mow+burn, burn only) compared to the control, but mow+burn treatments were even lower than that of the burn only treatments (P<0.001). One year following burning, shrub density no longer differed amongst treatments (P=0.195), however both saw palmetto density (P=0.034) and cover (P<0.001) were lower in both the mow only and mow+burn treatments compared to the control and burn only treatments, but did not differ between mow and mow+burn treatments or between burn only treatments and controls. Small understory trees (<2.5cm DBH) were rare across treatments with no significant differences between treatments, using a Chi-Square analysis, during any sampling periods. Small trees were only observed in control and mow only treatments during all sampling periods (Table 5-5).

Shrub height (≥0.5 m) and saw palmetto height were lower in both mowed treatments prior to burning, when compared with controls. Both shrub and saw palmetto height were reduced following burning, but while shrub height was still lower in mow only sites compared to controls, saw palmetto height did not differ between mow only and controls. Saw palmetto height was lowest in mow+burn sites compared to all others after burning. One year following burning, shrub heights were lower in mow and mow+burn sites compared to burn only and controls. Burn only shrub heights were similar to those of controls, and there were not differences between mow only and mow+burn sites. One year following burning, saw palmetto height, however, was lower in both mow and mow+burn sites compared to controls, but did not differ from burn only sites. Understory species richness of shrubs and small trees only differed during post-burn sampling where the burn only and mow+burn treatments were lower in species diversity than control and mow only treatments. On average, species richness was very low, totaling fewer than three species.

Groundcover was dominated by litter across all treatments during all sampling periods and did not differ in cover (%) across treatments during any sampling period (Table 5-6, Figure 5-8). Shrub groundcover (<0.5 m in height) was next in dominance and only differed by treatment during post-burn sampling, where shrub cover was lowest in the mow+burn treatment, but did not differ from the burn only treatment. Average grass cover was approximately double in the mow and mow+burn sites compared to the control and burn only sites, during initial post-mow (pre-burn) sampling, but did not differ statistically due to high variation. Following burning treatments, grass cover was lower in the burn only treatments than mow and mow+burn treatments, but did not differ from the control. One year following burning, average grass cover was 10.8±5.5% and 8.3±3.6% in the mow and mow+burn treatments, respectively, compared to the 2.7±0.9% and 2.0±1.5% cover in the control and burn only treatments, respectively, however treatment effects were marginal (P=0.057). Herb and vine cover were both rare across treatments and a significant treatment effect could not be detected using the Chi-Square analysis during any sampling period. Prior to burning, bare ground was not observed in burn only treatments or controls, but was observed in both the mow and mow+burn treatments. Mow only treatments were higher in bare ground (3.9±1.8%) versus burn only and control, but mow+burn treatments (0.8±0.6%) did not differ from any other treatment. Species richness of shrub and tree seedling groundcover did not differ across treatments prior to burning (4.3-5.7), but mow+burn treatments were lower in richness following burning compared to the mow only treatments and controls. At 2 years following burning, shrub/tree richness again did not differ across treatments. Species richness of all groundcover plants, including shrubs (<0.5 m), trees (<0.5m), herbs, vines, and grasses, were only evaluated at one year following burning treatments and did not differ statistically, however marginal results (p=0.062) provided some evidence of higher richness in the mowed sites (mow 10.3±1.3, mow+burn 10.2±1.0) compared to the un-mowed sites (control 6.7±0.7, burn only 8.2±0.8).

Microclimate and Moisture Dynamics

For up to six months following the August 2010 mowing treatments, and prior to prescribed burning, relative humidity (1 m aboveground) was lower in the mowed sites versus the un-mowed (P<0.001), but there were no differences between controls and the pre-burn burn only sites (P=0.523) or between the mow only sites and pre-burn mow+burn sites (P=0.659) (Figure 5-9). Air temperatures (1 m aboveground) did not differ among any treatments (P=0.979) prior to burning. Following the February 2011 burning treatments, relative humidity did not differ among treatments (P=0.515) during the March to August growing season, however air temperatures were lower in the mow+burn sites versus the controls (P=0.036), but with a significant interaction between treatment and time since treatment (P=0.004). Air temperatures did not differ across treatments during the month of March. Between September and January 2011, 13 to 17 months following mowing treatments and 7 to 11 months following burning, no differences were detected in above ground air temperature (P=0.881) or relative humidity (P=0.477) among all fuels treatments.

Soil temperatures, at 5 cm depth, did not differ between mowed and non-mowed sites (P=0.645), between controls and pre-burn burn only sites (P=0.799), or between mowed and pre-burn mow+burn sites (P=0.831) during the six months following mowing, and prior to burning (Figure 5-10). Following the February 2011 burning treatments, growing season (Mar-Aug) soil temperatures differed across all treatments (mow, mow+burn, burn only, control) (P=0.013), except during the month of March where mow only treatments and controls did not differ based on the interaction between treatment and time (P<0.001). During the remainder of the growing season (April-Aug), soil temperatures consistently ranked highest to lowest across mow+burn, burn only, mow only, and controls, respectively. Soil temperatures did not differ consistently across treatments from September and January 2011 (P=0.723), however a strong interaction between treatment and time (P<0.001) revealed that an influence of treatment on soil temperatures differed across time. In September mow only and control sites did not differ in soil temperature, however burn only sites were higher than both non-burned sites, and mow+burn sites were higher than all others. In October burned sites (burn only and mow+burn) had higher soil temperatures than unburned sites (mow only and controls). In November burn only and mow only sites were actually lower in soil temperature than controls, and in December burn only sites were lower than all other treatments.

Differences of moisture content in both surface litter ($P<0.001$) and live shrub foliage ($P<0.001$) were detected across treatments during the 10 months of sampling (3-13 months following burning), however interactions between treatment and time ($P<0.001$) indicate that differences were not consistent throughout the sampling period (Figureure 5-11). When separating the growing season (June-August), litter moisture was low and the interaction between treatment and time was not significant ($P=0.073$). During this period, controls were the wettest (13.2±0.8%), mowed treatments drier (9.7±0.6%), and mow+burn (7.1±0.4%) and burned (7.0±0.3%), not differing, were the driest. During the remainder of the sampling period (September-March), differences in litter moisture across treatments were not consistent ($P<0.001$), but were generally highest in controls, lower in the mowed treatments, and lowest in the burn only and mow+burn treatments. Burn only treatments do appear to have higher litter moisture than mow+burn only during the wettest months (Sep-Dec). Also, differences in litter moisture detected across all treatments were most pronounced during these wetter periods.

Decomposition

Decomposition, quantified as dry mass remaining as a percentage of original, did not differ between mow treatments and controls throughout a year of decomposition of foliar litter ($P=0.249$) or 1h (<0.635 cm) woody fuels ($P=0.386$) (Figure 5-12). Mass remaining of 10h (0.635-2.54 cm) woody fuels also did not differ between treatments throughout 10 months of decomposition (P=0.438). Interactions between treatment and time were not significant for all three fuel types, however there is some evidence that final litter mass was higher in the mow treatments after one year. Foliar litter mass remaining after one year of decomposition was 74.1±6.0%, 1h woody mass remaining after one year was 82.3±5.3%, and 10h woody mass remaining after 10 months of decomposition was 81.2±5.0%.

Soil Nutrients

Soil bulk density, ranging from 0.94 to 1.10 $g \cdot cm^{-3}$ (0-5 cm) and 1.27 to 1.36 cm^{-3} (5-10 cm), did not differ across experimental treatments (mow, mow+burn, burn only, control) before burning (2011) or one year following burning (2012). Pre-burn sampling was conducted six months following mowing in the mow and mow+burn treatments. Soil pH ranged from 3.6 to 3.9 at 0-5 cm depths, and from 3.8 to 4.1 at 5-10 cm, but did not differ across treatments pre- or 1 yr post-burn. Cation exchange capacity (CEC), ranging from 7.20 to 8.65 (0-5 cm) and 3.79 to 5.47 (5-10 cm) $meq \cdot 100g^{-1}$, did not differ across treatments pre- or post-burn. Prior to burning, the only difference in soil nutrients was that exchangeable K within 0-5 cm was lower in mow+burn treatments (0.72 $g \cdot m^2$) compared to controls (1.04 $g \cdot m^{2)}$) (P=0.037). All other nutrients were similar across treatments. The only soil nutrient difference between treatments one year after burning was that base saturation of H within 0-5 cm was lower in burn only treatments (83.36%) compared to controls (90.39%)(P=0.047).

Discussion

The immediate ecological effects of mechanical mastication ("mowing") in palmetto/gallberry pine flatwoods in this study were short-lived, suggesting that this ecosystem may recover quickly from such treatments. Ecological attributes were evaluated only up to 2 years following treatment, however, and there was also evidence that saw palmetto, where abundant, may be significantly reduced through mowing. Findings indicate that while understory vegetation is significantly reduced following mowing, recovery to pre-treatment conditions occurs rapidly.

Mastication is a fuels treatment methods aimed at altering only understory shrubs and small trees, while leaving the overstory intact (Kane et al. 2009). In this study, while tree density was reduced following mowing treatments, basal area was only reduced in mature stands that had gone unburned for several years, where abundant smaller diameter trees occurred. Even in mature stands burned within 5 years prior to mowing, tree density was reduced >40%, but basal area did not differ. Mature unburned stands had more small diameter trees, prior to mowing, contributing to greater basal area than in burned stands. Long term fire exclusion in southeastern US pine forests typically results in increases in tree density and basal area and restoration goals often include the removal of under- and mid-story hardwood trees. Tree removal from mowing in this study resulted in a 73% reduction in hardwood density in the mature stands. Mechanical treatments are likely to be used to reduce hazardous fuel accumulation in the understory, but also for restoration purposes in mature pine flatwoods where fire has been excluded.

Rapid shrub recovery following mowing in pine flatwoods is likely due to the sprouting ability of dominant species in this ecosystem. Saw palmetto and gallberry are common understory shrubs in the lower coastal plain of the southeastern US (Hough and Albini 1978) and dominated the pine flatwoods in this study. This vegetation strata is the primary driver of fire behavior and effects in flatwoods ecosystems and rapid recovery of dominant species is common following burning (Hough and Albini 1978, Abrahamson 1984a&b, Brose and Wade 2002). Recovery of shrub and saw palmetto cover to pre-treatment conditions may occur as rapidly as 1 to 2 years following fire (Abrahamson 1984a, Brose and Wade 2002) and desired prescribed burning cycles, as a fuels treatment method, is typically < 5yrs. Mowing in the buffer treatments in this study indicated recovery of shrub and saw palmetto density as quickly as 16 months following treatment. In the experimental treatments, however, saw palmetto cover was much lower in mowed sites. While pre-treatment data were not available in these treatments, reduction in saw palmetto cover following mowing in a nearby 500 ha areal treatment was similar to differences observed between mowed and control sites in the experimental treatments (Ch 2). Both sites had similar soils as well as over- and under-stories prior to treatment. Saw palmetto cover may have been lower in mowed sites due to mechanical damage to meristematic tissue in horizontal stems. Stems existed in the mow treatments that appeared damaged, and where continued growth of palmetto fronds did not occur following treatment. While other sprouting shrubs have underground storage organs, apical meristems of saw palmetto occur above-ground. They may be damaged from mowing where mowing heads are operated close to the ground or especially in areas where stems are elevated as a result of poorly drained soils.

Burning in pine flatwoods resulted in recovery of shrub density to that of pre-treatment densities regardless of mowing treatments. Shrubs were less dense in mow only sites prior to burning, but did not differ from other treatments, or controls, one year following burning. Shrub density was measured for shrubs >0.5 m in height and many of the resprouting shrubs, e.g. gallberry, were likely not tall enough to be considered in the understory when pre-burn sampling occurred in the mow only sites. While saw palmetto cover was reduced to near zero immediately following burning in burn and mow+burn treatments, cover was no different between mow and mow+burn or between burn only and controls one year later, however saw palmetto cover remained lower in both mowed treatments compared to burn only and controls. Mowing on the ONF as a management tool is primarily being conducted as a pre-treatment to alter fuel structure prior to reintroduction of frequent prescribed burning. Mowing in pine flatwoods may have the potential for reducing saw palmetto cover, but following mechanical fuels treatments with burning may not result in additional deleterious effects to the understory. This study, however, only revealed treatment effects and vegetation recovery up to two years following mowing and one year following single prescribed burns. Additional study would reveal possible longer term effects, especially under varying mowing and burning regimes over time.

Groundcover was largely unaffected by mowing or burning treatments in this study. Litter and shrubs dominated groundcover across all study sites and at all stages of treatment. In the buffer, mature stands that were recently burned had more shrub groundcover than unburned stands or younger pine plantations across all time since treatment sampling, but shrub cover was not affected by mowing across stand types. Litter cover only decreased after two years in the mature unburned sites where vine cover had increased. While vines were prevalent in these stands prior to mowing they were primarily above 1 m in height and not considered part of the groundcover. Vine cover was minimal in recently burned mature stands and did not increase in the groundcover strata following mowing. Pre-treatment vine cover in the pine plantation was similar to mature unburned stands, but increases in post-treatment cover were not statistically significant due to higher variation. Herbs and grasses were minor components of groundcover in this study and are likely inhibited by dominance of understory shrubs (Lewis and Hart 1972, Abrahamson 1984). Grass cover was reduced immediately following treatment across all stand types in the buffer, but while average grass cover appeared to approximately double that of pre-treatment after 2 years in all stand types, differences were not significant, due to high variation. In addition, mowed sites in the experimental treatments had over twice the average grass cover than un-mowed sites, but a high degree of variation resulted in insignificant differences. One year post-burning, however, grass cover of mow only sites was 4 times that of controls and mow+burn sites were 4 times that of burn only sites, and differences were marginally detected. Because grass cover was low in un-mowed sites and variation of grass cover high in mowed sites, differences were likely undetectable, even after transforming data to meet model assumptions. Both study locations revealed some evidence that grass cover increased due to mowing and the reduction of saw palmetto cover in experimental mowed treatments may have resulted in open ground for grasses to establish or spread. Bare ground was higher in mowed sites prior to burning in the experimental treatment blocks. While burning treatments were implemented in February in this study, flowering response in grasses occur more readily during growing season (May-July) burns in flatwoods communities (Abrahamson 1984). Glitzenstein et al. (2003) found that while more frequent burning in Ultisol flatwoods in South Carolina shifted communities from being woody to herbaceous dominated, they did not find increases in herbaceous cover in Spodosol flatwoods on northern Florida, but did observe reduced dominance in saw palmetto and slight increased importance of forbs and grasses. Future study may reveal that a reduction in saw palmetto cover following mowing treatments may increase grass cover over time, especially under frequent growing season burning regimes.

Species richness of understory shrubs (≥0.5 m) and understory small trees (<2.5 cm DBH, but ≥0.5 m in height) was reduced following mowing, but recovered to pre-treatment diversity after 16 months in the buffer treatments, yet did not differ between mowed and un-mowed treatments in experimental blocks prior to burning. Burning did reduce understory shrub/tree species richness, but diversity recovered after one year. Understory diversity is quite low in this ecosystem, however, and richness was only evaluated at the 8 m^2 scale. While richness of understory shrubs and trees (both ≥0.5 m) was initially reduced by burning, species richness of groundcover shrubs (<0.5 m) and trees (<0.5 m) was only reduced in mowed sites following burning, but sites were similar in diversity after one year. Abrahamson (1984b) observed an increase in diversity of woody plants following fire in flatwoods only after the first year and diversity was associated with an increase in overall evenness in abundance, not due to species ingress. Shrub and tree diversity recovers quickly in our flatwoods sites and is reflected in little change to groundcover following treatment and most notably by the fast recovery into the higher-statured understory strata. When including all plant species into groundcover richness, however, marginal evidence suggested here that mowing increased species richness one year following treatment, yet burning alone did not. While herb and grass cover were fairly low, compared to shrub cover in this study, there was more variation in cover observed in mowed sites and the potential for increased diversity of all ground cover species following mowing may be a longer term effect of these treatments. Reduction of saw palmetto cover may have attributed to such increases, where increased resources, especially light, could be allocated to more herbs and grasses. Increases in species diversity as a result of mowing in this ecosystem will likely be associated with non-woody species and longer term study may provide important insight into such an important effect.

Increased herbs or grasses at the cost of saw palmetto may have ecological benefits, but also potential negative effects. In well drained *Pinus palustris* uplands, high understory plant diversity depend largely on frequent fire, where herbs and grasses dominate groundcover (Varner et al. 2000, Glitzentein et al. 2003). These fine fuels also aid in the ignitability in these uplands, promoting frequent fire and further perpetuating their dominance. In mesic flatwoods, high fire frequency may also reduce shrub cover and enhance non-woody herbaceous groundcover, however not to the extent of the more xeric uplands (Glitzenstein et al. 2003). Restoration efforts in southern pine forests are often aimed at reducing shrubs and understory trees while increasing herbs and grasses (Varner et al. 2000). Many wildlife species depend on this herbaceous groundcover as a food source and its loss has been associated with declines in several faunal species (Van Lear et al. 2005). In flatwoods, where shrubs dominate the understory, diversity is lower, however shrubs are quite resilient to frequent fire (Abrahamson 1984a) and saw palmetto is an important food source for many wildlife species and individuals may be as old as 500-700 years (Tanner et al. 1996). While some loss of saw palmetto and slight increases in grasses and herbs from understory mowing was observed in this study, further shifts in species composition may be an important management concern if such treatments are to repeated through a frequent management regime.

Mowing and burning had minimal effects on understory microclimate, however the moisture regime in surface litter and live shrub foliage was significantly impacted. Although mowed residues may have a mulching effect by slowing moisture loss (Kreye et al. 2012), the drier litter in mowed sites compared to controls in this study was likely due to less saw palmetto cover and lower shrub heights increasing solar radiation and/or wind speed at the forest floor surface. It is unclear if a mulching effect in mowed residues attributed to higher litter moisture in mowed sites compared to burned sites because shrub heights and saw palmetto cover were higher in non-burned sites, potentially resulting in similar effects on surface moisture. Although treatment effects on litter moisture were most pronounced during wetter months in the fall, effects on moisture during the drier sample periods in the summer were significant enough to have potential impacts on surface fire behavior. Although lower shrub cover and height may reduce fire intensity during burning (Ch 4), drier litter moisture during burning of mowed sites may result in longer durations of lethal temperatures at the surface or in underlying soils (Ch 4). Potential tree mortality from burning in compact mowed residues (Knapp et al. 2011) may result from long duration heating in these fuels (Kreye et al. 2011, Ch 4).

When burning as a follow up treatment is not used, decomposition of mowed residues may be an important factor regarding fuel dynamics in these treatments (cite). While higher moisture content, all else equal, tends to increase decomposition rates

(Enriquez et al. 1993, Prescott et al. 2004), decomposition of residues in this study did not differ between mowed sites and controls. Decomposition rates of surface litter, however, were slightly higher than that observed in pine plantations in the region (Gholz et al. 1985). Dry litter mass remaining did not differ between mowed sites and controls during each 2 month collection period, except that there was some evidence of greater mass remaining in the mow treatment at the last collection (369 days). Whether this difference would have been observed under further decomposition is unknown since it was the end of the study. The average 74% remaining litter mass after one year was slightly less than the 85% litter mass remaining observed by Gholz et al. (1985). Their study suggested that high lignin content and low P and N content in the needle dominated litter accounted for slower decomposition rates compared to other studies, and not microclimate environments. In mowed residues in our sites, saw palmetto leaves were likely a large proportion of surface litter due to pre-treatment biomass, compared to the needle dominated litter in the Gholz et al. (1985) study. While lignin content of litter in their study was 33-37%, saw palmetto lignin has been observed to be 18% (Pitman 1993). Also, C:N ratios in litter observed by Gholz et al. (1985) was 125-172, while C:N ratios of collected mowed residues in a similar site near this study, was 76.6±3.2 and 86.9±3.1 immediately post-treatment and at one year following treatment, respectively (Kreye unpublished data). C:N ratios, like C:P ratios, are generally inversely related to decomposition rates (Enriquez et al. 1993) and the lower C:N ratios in litter following mowing may also attribute to faster decomposition rates compared to needle dominated litter in these pine forests. Understanding decomposition rates of mowed residues will be important for predicting biomass, nutrient, carbon, and fuel dynamics under varying treatment regimes in areas where burning may be difficult and mowing treatments used, exclusively, as a fuels treatment method.

Soils nutrients were generally unaffected by mowing treatments or prescribed burning. Even where statistical differences between treatments occurred, there was no clear impact by either treatment exclusively. At 0-5 cm depths, K was only lower in mow+burn treatments compared to controls prior to burning and while base saturation of H at 0-5 cm was lower in burn only treatments compared with controls after burning, they didn't differ from mow or mow+burn sites. Lavoie et al. (2010) found increases in P, Ca, Mg, and K in the upper 5 cm of mineral soil 2 days following burning in a similar longleaf pine-slash pine flatwoods forest in northern Florida, but after one year P returned to pre-burn levels and Ca, Mg, and K appeared to have had declined from that of elevated levels observed initially following burning. P and Mg levels were similar between sites in both studies prior to burning, however K was higher and Ca lower in our sites. Little research has been conducted on understory mechanical fuels treatments on soil properties, especially from mastication type of treatments. Reduction of soil moisture and soil respiration were observed following mastication in Sierra Nevada pine plantations, with mitigating effects on soil temperature changes (Kobziar and Stephens 2006). Moghaddas (2007) examined thinning treatments followed by burning n Sierra Nevada forests to increase N pools, exchangeable Ca, and pH. Consumption of duff (humus and fermentation layers) was high in their study, while little to no duff was consumed during burning in our study (Ch 4). And following burning in the flatwoods site in the Lavoie (2010) study, there was a substantial reduction in C pools in these layers as well, indicating duff consumption during burning. Although litter and understory shrub foliage was almost completely consumed, the remaining duff layer in our sites may have inhibited nutrient input, as a result of burning, into the mineral soil. Rhoades et al. (2012) found initial decreases in soil available N following addition of masticated mulch residues in Colorado coniferous forests, but after 3-5 years available N was greater in masticated sites versus controls.

Masticated residues immediately add a nutrient pool to the forest floor, however these nutrients are unavailable to plants until they are broken down and released in available forms. And when residues are left on site, nutrients may be slowly released into the mineral soil over time. One year following treatment may not be enough time to observe changes to mineral soils from the addition of these residues. The importance of nutrients in metabolic processes means that plant foliage should have a greater proportion of plant nutrients contain within their tissues as compared to woody tissues, although Ca is an important component of wood cell walls (Chapin et al. 2002). The high proportion of foliar litter in residues following mowing of palmetto/gallberry understories (Ch 2) may result in longer term inputs of nutrients into mineral soils when residues aren't burned. Especially where saw palmetto is abundant. Fire tends to alter N and P, two primary limited nutrients in this ecosystem, disproportionately due to the lower volatilization temperature of N versus P. Although available forms of soil N, such as NH^{4+}, may increase following burning in palmetto flatwoods, increases in available P (PO_4^{3-}) may be greater, thus reducing soil N:P ratio in the short term (Schafer 2012). These effects can attributed to similar changes in foliar N and P in saw palmetto following these same burns, where foliar N:P were also reduced (Schafer 2012). If mowed residues are not burned, total N and P may both increase as litter is added to the forest floor, but changes in nutrient availability to plants may rely on post-treatment nutrient mineralization. Decomposition rates were a bit faster in these mowed residues than needle-dominated litter in pine flatwoods plantations, but slower than many other areas (Gohlz et al. 1985). Mowing may alter soil nutrients over time in areas where mowing is used as a stand-alone treatment option where frequently treating fuels will continue to add nutrients to the soil without the losses typically incurred during burning. Longer term study is required to better understand potential long term effects of such treatments on soil properties in southeastern forests.

While increased attention has been given to evaluating effects of fuels treatments in forest and shrub ecosystems, little has been conducted with regard to understory mastication, especially in the southeastern US. Much of the research evaluating mastication treatments has been conducted in the western US and studies often address implications on fuel properties and potential impacts of treatments in altering fire behavior (Bradley et al. 2006, Hood and Wu 2006, Kane et al. 2009, Kobziar et al. 2009, Battaglia et al. 2010, Kreye et al. 2011). Unforeseen consequences of burning in masticated treatments has been documented in shrublands (Bradley et al. 2006) and coniferous forests (Knapp et al. 2011) in California, where heavy loading of woody dominated residues result from mastication (Kane et al. 2009). Although compact, these woody dominated residues may result in long duration surface (Kreye et al. 2011) and soil (Busse et al. 2005) heating, and high fire severity (Bradley et al. 2006, Knapp et al. 2011) when burned. Studies aimed at evaluating vegetation response to mastication is lacking, but is gaining attention in the west. Kane et al. (2010) found that mastication alone in a northern Sierra Nevada ponderosa pine forest reduced midstory vegetation, but did not affect understory diversity. Follow up prescribed burning, however, did increase diversity of both native and non-native species. Potts and Stephens (2009), in contrast, found greater abundance of non-native invasive species in masticated sites versus burned sites in chamise (*Adenostoma fasciculatum*) dominated chaparral in northern California, but had had no affect on overall diversity. Increased cover of forbs and grasses in masticated pinyon-juniper woodlands has been observed, but no differences in shrubs (Ross et al. 2012). While plant responses to understory mastication treatments will likely vary across ecosystems, southeastern pine forests dominated by saw palmetto/gallberry understories is a unique ecosystem in its rapid recovery of vegetation composition and structure following mowing and burning. The potential reduction in saw palmetto was the one major effect observed in this study.

The resiliency of palmetto/gallberry pine flatwoods to mastication ("mowing") and burning treatments was striking in this study. Effects to vegetation, microclimate, moisture regimes, and edaphic features were either minimal or short-lived. Other than reduction in saw palmetto, effects of a single mechanical treatment alone or followed by prescribed burning is minimal, at least in the short term. If mastication type of fuels treatments are to be used as an alternative to prescribed burning, treatment regimes are likely to occur on a frequent basis due to rapid recovery of shrubs. Evaluating ecological response to repeated treatments over time will be imperative if such treatment regimes are to be implemented. This study suggests that using mastication as pre-treatment to follow-up prescribed burning is a feasible option with minimal effects to the ecological integrity of this ecosystem.

Table 5-1. Tree density, basal area, and quadratic mean diameter (QMD) following mowing treatments in pine flatwoods of northern Florida, USA.

	Stand Type: mature	Stand Type: mature-burned	Stand Type: plantation	Stand Type	TST[a]	Stand Type ×TST
				--------------------*p value*----------------------		
Tree Density	--------------*trees·ha^{-1}*-------------			<0.001	<0.001	<0.001
Pre-Treatment	941 (179)^{A}	365 (36)^{A}	1020 (185)^{a}			
Post-Treatment	327 (58)^{B}	216 (30)^{B}	804 (82)^{ab}			
2yrs Post-Treatment	290 (46)^{B}	216 (30)^{B}	713 (71)^{b}			
Basal Area	------------*m^{2}·ha^{-1}*------------			0.029	<0.001	0.043
Pre-Treatment	28.3 (3.3)^{A}	17.9 (2.2)^{A}	34.0 (5.9)^{A}			
Post-Treatment	23.2 (2.9)^{B}	17.3 (2.4)^{A}	27.5 (2.2)^{A}			
2yrs Post-Treatment	23.4 (2.8)^{B}	18.2 (2.3)^{A}	26.3 (2.5)^{A}			
QMD	--------------*cm*--------------			0.004	<0.001	<0.001
Pre-Treatment	21.8 (1.7)^{A}	25.6 (2.1)^{A}	20.7 (0.4)^{A}			
Post-Treatment	32.2 (2.0)^{B}	32.8 (2.2)^{B}	21.0 (0.5)^{A}			
2yrs Post-Treatment	33.6 (1.7)^{B}	33.9 (2.2)^{B}	21.8 (0.6)^{A}			

[a] Time since treatment

Note: Values sharing letters within rows are not statistically different (Tukey-Kramer Test, α=0.05)

Table 5-2. Density and species richness of understory shrubs and small trees following mowing of understory shrubs and small trees in pine flatwoods of northern Florida, USA.

	Stand Type Mature	Mature/Burned	Plantation	Stand Type	TST[a]	Stand Type ×TST
	---------------------*individuals·ha^{-1}*	---------------------	---------------------	-------------------*p value*	------------------	------------------
Saw Palmetto[b]				0.060	<0.001	0.855
Pre-Treatment	4038 (1032)[A]	6094 (1303)[A]	2708 (936)[A]			
2 months	1042 (431)[B]	2083 (551)[B]	625 (280)[B]			
8 months	909 (380)[B]	2778 (972)[B]	833 (417)[B]			
16 months	2604 (877)[A]	4844 (1386)[A]	2292 (879)[A]			
24 months	2604 (820)[A]	4375 (1398)[A]	2083 (768)[A]			
Shrubs[c]						
Pre-Treatment	42308 (7093)[A]	69821 (16555)[A]	22500 (5995)[A]	0.049	<0.001	0.187
2 months	4167 (861)[B]	10694 (3126)[B]	6667 (2534)[B]			
8 months	5227 (2177)[B]	15278 (2809)[B]	6250 (3354)[B]			
16 months	37500 (9606)[A]	50417 (7321)[A]	22083 (5017)[A]			
24 months	34545 (8013)[A]	43393 (6224)[A]	24792 (4113)[A]			
Small Trees[d]				0.455[‡]	0.427[‡]	na[‡]
Pre-Treatment	577 (304)	2083 (1021)	417 (264)			
2 months	208 (208)	0 (0)	833 (833)			
8 months	341 (244)	0 (0)	208 (208)			
16 months	625 (288)	556 (303)	208 (208)			
24 months	833 (444)	1528 (1098)	625 (280)			
Species Richness[e]	---------------------*species·8m^{-2}*	--------------------		0.001	<0.001	0.543
Pre-Treatment	3.5 (0.3)[A]	4.9 (0.5)[A]	2.5 (0.3)[A]			
2 months	1.3 (0.1)[B]	2.6 (0.4)[B]	1.7 (0.2)[B]			
8 months	1.5 (0.3)[B]	2.1 (0.3)[B]	1.5 (0.3)[B]			
16 months	2.9 (0.6)[A]	3.8 (0.2)[A]	2.7 (0.4)[A]			
24 months	3.1 (1.4)[A]	4.1 (1.4)[A]	2.8 (0.2)[A]			

Note: Values sharing letters within columns are not statistically different (Tukey-Kramer Test, α=0.05)
[a] Time since treatment,[b] Saw Palmetto (*Serenoa repens*) individuals,[c] All shrubs including saw palmetto,[d] Trees <2.5 cm DBH,[e] All understory shrubs and trees (<2.5 cm) pooled,[‡] Chi Square test used to test main effects only due to rarity of occurrence of small trees across all stand types and time TST (time since treatment).

Table 5-3. Percent groundcover, by vegetation type, and species richness of shrubs (<0.5 m) and tree saplings (<0.5 m) following mowing of understory shrubs and small trees in pine flatwoods of northern Florida, USA.

	Stand Type					
	Mature	Mature/ Burned	Plantation	Stand Type	TST[a]	Stand Type ×TST
	--------------%---------------				*p value*	
Shrub Cover[b]				<0.001	<0.001	0.004
Pre-Treatment	18 (3)^{A}	57 (8)^{A}	17 (3)^{A}			
2 months	18 (3)^{A}	42 (4)^{AB}	17 (3)^{A}			
8 months	20 (3)^{A}	43 (2)^{AB}	18 (4)^{A}			
16 months	18 (3)^{A}	34 (3)^{B}	12 (2)^{A}			
24 months	25 (4)^{A}	53 (6)^{A}	17 (3)^{A}			
Grass Cover				0.265	<0.001	0.887
Pre-Treatment	0.9 (0.4)^{AB}	1.0 (0.4)^{AB}	0.6 (0.4)^{AB}			
2 months	0.0 (0.0)^{C}	0.9 (0.5)^{C}	0.0 (0.0)^{C}			
8 months	0.3 (0.2)^{BC}	1.7 (1.0)^{BC}	0.2 (0.2)^{BC}			
16 months	1.4 (0.7)^{A}	2.4 (0.6)^{A}	1.9 (1.4)^{A}			
24 months	1.7 (0.6)^{A}	1.9 (0.8)^{A}	1.5 (0.9)^{A}			
Herb Cover				<0.001‡	0.077‡	na‡
Pre-Treatment	1.7 (0.8)	0.0 (0.0)	0.0 (0.0)			
2 months	0.4 (0.2)	0.1 (0.1)	3.8 (3.7)			
8 months	0.2 (0.2)	0.0 (0.0)	0.0 (0.0)			
16 months	1.1 (0.6)	0.1 (0.1)	0.0 (0.0)			
24 months	0.1 (0.1)	0.0 (0.0)	0.0 (0.0)			
Vine Cover[c]				0.014	<0.001	0.001
Pre-Treatment	4.3 (2.1)^{A}	1.2 (0.5)^{A}	4.4 (1.5)^{AB}			
2 months	3.8 (1.2)^{A}	2.0 (1.3)^{A}	4.4 (2.6)^{AB}			
8 months	2.2 (0.6)^{A}	1.3 (0.8)^{A}	3.5 (2.0)^{A}			
16 months	8.7 (2.6)^{B}	1.0 (0.4)^{A}	10.8 (4.2)^{AB}			
24 months	16.4 (5.1)^{B}	1.9 (1.2)^{A}	13.0 (5.2)^{B}			
Litter				<0.001	<0.001	0.001
Pre-Treatment	81.0 (3.1)^{A}	53.6 (5.5)^{AC}	82.6 (2.5)^{A}			
2 months	79.4 (2.5)^{AB}	69.4 (3.9)^{B}	79.5 (5.7)^{A}			
8 months	76.3 (3.2)^{AB}	54.7 (3.4)^{AC}	78.0 (4.4)^{A}			
16 months	68.3 (4.2)^{B}	61.3 (3.7)^{ABC}	75.0 (2.7)^{A}			
24 months	55.0 (5.8)^{C}	45.8 (4.8)^{ACD}	70.7 (2.9)^{A}			
Bare Ground				0.714‡	0.049‡	na‡
Pre-Treatment	0.1 (0.1)	2.5 (2.2)	0.3 (0.2)			
2 months	2.4 (1.0)	3.0 (1.5)	0.6 (0.5)			
8 months	0.3 (0.3)	0.0 (0.0)	0.2 (0.2)			
16 months	1.7 (1.3)	0.6 (0.4)	0.1 (0.1)			
24 months	0.5 (0.4)	0.4 (0.3)	0.7 (0.3)			
Species Richness[d]	------------------*species·m^{-2}*----------------			0.015	0.007	0.511
Pre-Treatment	4.2 (0.5)^{AB}	5.1 (0.4)^{AB}	3.7 (0.3)^{AB}			
2 months	3.3 (0.5)^{A}	5.8 (0.2)^{A}	3.0 (0.6)^{A}			
8 months	3.6 (0.6)^{AB}	5.1 (0.5)^{AB}	3.7 (0.5)^{AB}			
16 months	4.4 (0.7)^{B}	6.1 (0.4)^{B}	4.2 (0.3)^{B}			
24 months	4.5 (0.8)^{B}	6.2 (0.6)^{B}	4.0 (0.6)^{B}			

Note: Values sharing letters within columns are not statistically different (Tukey-Kramer Test, α=0.05)

Table 5-3. Continued

[a] Time since treatment
[b] Shrubs <0.5 m in height
[c] Vines <1 m above the ground
[d] Groundcover of shrubs and tree seedlings (both <0.5 m in height)
‡ Chi Square test used to test main effects only due to rarity of occurrence of small trees across all stand types and time TST (time since treatment).

Table 5-4. Tree density, basal area, and quadratic mean diameter (QMD) across experimental treatments following mowing and burning in pine flatwoods of northern Florida, USA.

	Treatment Status		
	Post-Mow	Post-Burn[a]	1 yr Post-Burn
Tree Density		*trees·ha^{-1}*	
Control	426 (64)^A	419 (59)^A	419 (59)^A
Burn Only	359 (60)^A	359 (58)^A	326 (45)^A
Mow	326 (69)^A	332 (69)^A	332 (69)^A
Mow+Burn	337 (47)^A	337 (47)^A	332 (45)^A
Basal Area		*m^2·ha^{-1}*	
Control	19.0 (2.3)^A	19.1 (2.3)^A	18.9 (2.2)^A
Burn Only	16.6 (1.4)^A	16.7 (1.5)^A	15.9 (1.4)^A
Mow	19.2 (2.4)^A	19.5 (2.4)^A	19.3 (2.5)^A
Mow+Burn	22.3 (3.4)^A	22.5 (3.4)^A	21.5 (3.3)^A
QMD		*cm*	
Control	24.3 (1.0)^A	24.5 (1.0)^A	24.4 (1.0)^A
Burn Only	26.0 (2.2)^A	25.7 (1.9)^A	25.9 (1.9)^A
Mow	29.0 (1.3)^A	29.0 (1.3)^A	28.7 (1.2)^A
Mow+Burn	28.9 (1.4)^A	29.0 (1.4)^A	28.5 (1.3)^A
Tree Height		*m*	
Control	22.2 (0.3)^A	21.7 (0.4)^A	22.5 (0.5)^A
Burn Only	25.2 (1.6)^A	20.4 (1.3)^A	23.0 (1.5)^A
Mow	22.7 (0.5)^A	22.5 (0.8)^A	22.2 (0.8)^A
Mow+Burn	22.3 (1.0)^A	22.4 (1.0)^A	24.1 (1.3)^A

Note: Values sharing letters within columns are not statistically different (Tukey-Kramer Test, α=0.05)

[a] 6 months post-mow.

Table 5-5. Density and species richness of understory shrubs and small trees, and percent cover of saw palmetto, across experimental mowing and burning treatments in pine flatwoods of northern Florida, USA.

	Treatment Status		
	Post-Mow	Post-Burn[f]	1 yr Post-Burn
		individuals·ha^{-1}	
Saw Palmetto[a]			
Control	12500 (2148)[A]	12857 (2451)[A]	11964 (1786)[A]
Burn Only	12222 (1246)[A]	139 (139)[B]	12639 (1537)[A]
Mow	3333 (1755)[B]	4861 (2209)[C]	5694 (1681)[B]
Mow+Burn	3056 (1781)[B]	0 (0)[B]	5694 (2448)[B]
Shrubs[b]			
Control	28393 (5521)[A]	28750 (8192)[A]	26071 (5916)[A]
Burn Only	30417 (4709)[A]	139 (139)[B]	39444 (9254)[A]
Mow	16528 (2355)[B]	26528 (5519)[A]	31111 (4950)[A]
Mow+Burn	23611 (3833)[A]	0 (0)[B]	48333 (8125)[A]
Small Trees[c‡]			
Control	357 (231)[A]	357 (231)[A]	357 (231)[A]
Burn Only	0 (0)[A]	0 (0)[A]	0 (0)[A]
Mow	694 (694)[A]	972 (828)[A]	972 (828)[A]
Mow+Burn	0 (0)[A]	0 (0)[A]	0 (0)[A]
Shrub Height		*m*	
Control	1.19 (0.05)[A]	1.17 (0.05)[A]	1.09 (0.04)[A]
Burn Only	1.16 (0.04)[A]	0.06 (0.06)[B]	1.00 (0.05)[A]
Mow	0.66 (0.03)[B]	0.69 (0.03)[C]	0.83 (0.05)[B]
Mow+Burn	0.65 (0.02)[B]	0.00 (0.00)[B]	0.67 (0.02)[B]
Saw Palmetto Cover[d]		*%*	
Control	47.4 (8.1)[A]	62.1 (8.9)[A]	58.6 (9.3)[A]
Burn Only	51.7 (8.7)[A]	19.4 (3.7)[B]	51.7 (7.0)[A]
Mow	10.6 (2.7)[B]	11.1 (1.6)[BC]	21.1 (3.8)[B]
Mow+Burn	8.9 (2.5)[B]	3.6 (1.0)[C]	13.3 (4.0)[B]
Saw Palmetto Height[d]		*m*	
Control	1.06 (0.06)[A]	1.04 (0.08)[A]	1.16 (0.04)[A]
Burn Only	1.09 (0.05)[A]	0.51 (0.05)[B]	0.93 (0.07)[AB]
Mow	0.68 (0.10)[B]	0.84 (0.04)[A]	0.89 (0.03)[B]
Mow+Burn	0.69 (0.10)[B]	0.30 (0.05)[C]	0.71 (0.09)[B]
Species Richness[e]		*species·8m^{-2}*	
Control	2.9 (0.3)[A]	2.4 (0.2)[A]	2.0 (0.2)[A]
Burn Only	2.9 (0.4)[A]	0.1 (0.1)[B]	2.1 (0.2)[A]
Mow	2.2 (0.2)[A]	2.8 (0.3)[A]	2.8 (0.5)[A]
Mow+Burn	2.3 (0.3)[A]	0.0 (0.0)[B]	2.2 (0.2)[A]

Note: Values sharing letters within columns are not statistically different (Tukey-Kramer Test, α=0.05)

[a] Saw Palmetto (*Serenoa repens*) individuals.

[b] All shrubs, including saw palmetto, in shrub belt transects (≥0.5 m in height).

[c] Trees <2.5 cm DBH.

Table 5-5. Continued
[d] Over entire 8 m radius plot (201 m^2), height includes all palmetto regardless of height.
[e] All understory shrubs and trees (<2.5 cm) pooled.
[f] 6 months post-mow.
[‡] Chi Square test used to test effects due to rarity of occurrence.

Table 5-6. Percent groundcover, by vegetation type, and species richness of shrubs (<0.5 m) and tree saplings (<0.5 m) across experimental mowing (mowing) and burning treatments in pine flatwoods of northern Florida, USA.

	Treatment Status		
	Post-Mow/ Pre-Burn	Post-Burn[f]	1 yr Post-Burn
		---------------------%----------------------	
Shrub Cover[a]			
Control	27.7 (6.0)[A]	26.9 (3.9)[A]	23.1 (7.7)[A]
Burn Only	19.6 (3.7)[A]	13.6 (1.9)[AB]	24.4 (2.5)[A]
Mow	16.2 (2.0)[A]	26.0 (3.6)[A]	19.1 (2.2)[A]
Mow+Burn	21.4 (2.7)[A]	8.0 (2.7)[B]	23.2 (3.5)[A]
Grass Cover			
Control	1.8 (1.0)[A]	4.1 (1.1)[AB]	2.7 (0.9)[A]
Burn Only	1.5 (0.9)[A]	0.9 (0.7)[B]	2.0 (1.5)[A]
Mow	4.6 (2.2)[A]	5.4 (2.4)[A]	10.8 (5.5)[A]
Mow+Burn	6.4 (3.4)[A]	6.6 (2.9)[A]	8.3 (3.6)[A]
Herb Cover[‡]			
Control	0.0 (0.0)[A]	0.0 (0.0)[A]	0.0 (0.0)[A]
Burn Only	0.2 (0.1)[A]	0.0 (0.0)[A]	0.0 (0.0)[A]
Mow	0.8 (0.8)[A]	0.2 (0.1)[A]	0.2 (0.1)[A]
Mow+Burn	0.0 (0.0)[A]	0.1 (0.1)[A]	0.2 (0.2)[A]
Vine Cover[b‡]			
Control	2.0 (2.0)[A]	0.7 (0.7)[A]	0.5 (0.5)[A]
Burn Only	0.3 (0.3)[A]	0.1 (0.1)[A]	1.7 (1.5)[A]
Mow	6.3 (3.6)[A]	4.0 (2.3)[A]	2.4 (1.3)[A]
Mow+Burn	3.6 (1.6)[A]	0.2 (0.1)[A]	0.3 (0.2)[A]
Litter			
Control	68.7 (5.8)[A]	67.9 (3.8)[A]	74.2 (7.3)[A]
Burn Only	78.0 (3.9)[A]	42.9 (6.1)[A]	62.7 (3.9)[A]
Mow	67.5 (4.1)[A]	62.4 (4.6)[A]	66.1 (5.5)[A]
Mow+Burn	68.1 (4.1)[A]	51.1 (13.8)[A]	66.2 (4.0)[A]
Bare Ground			
Control	0.0 (0.0)[A]	0.0 (0.0)[A]	0.1 (0.1)[A]
Burn Only	0.0 (0.0)[A]	41.9 (5.2)[B]	10.1 (2.5)[B]
Mow	3.9 (1.8)[B]	3.1 (1.2)[A]	1.3 (0.4)[C]
Mow+Burn	0.8 (0.6)[AB]	33.9 (11.2)[B]	5.7 (0.8)[B]
Shrub/Tree Richness[c]			
Control	4.7 (0.7)[A]	5.6 (0.5)[A]	5.7 (0.5)[A]
Burn Only	4.3 (0.4)[A]	4.2 (0.4)[AB]	5.7 (0.4)[A]
Mow	4.6 (0.3)[A]	6.0 (0.4)[A]	6.0 (0.4)[A]
Mow+Burn	5.7 (0.4)[A]	2.6 (0.7)[B]	5.8 (0.8)[A]
Species Richness[d]			
Control	-	-	6.7 (0.7)[Ał]
Burn Only	-	-	8.2 (0.8)[A]
Mow	-	-	10.3 (1.3)[A]
Mow+Burn	-	-	10.2 (1.0)[A]

Note: Values sharing letters within columns are not statistically different (Tukey-Kramer Test, α=0.05), [‡] Results of Chi-Square test, [ł] marginal results of ANOVA (P=0.062). [a] Shrubs <0.5 m in height, [b] vines <1 m above the ground, [c] shrubs (<0.5 m) and trees (<0.5) only, [d] all groundcover plant species (shrubs, trees, herbs, grasses, vines), [f] 6 months post-mow.

Table 5-7. Soil properties and nutrients across experimental mowing and burning treatments in pine flatwoods of northern Florida, USA.

	Bulk Density *g·cm^{-3}*				pH			
	C	B	M	M+B	C	B	M	M+B
0-5cm								
2011	1.07(0.05)^{A}	1.02(0.06)^{A}	1.07(0.06)^{A}	0.94(0.02)^{A}	3.6(0.04)^{A}	3.6(0.05)^{A}	3.8(0.03)^{A}	3.8(0.11)^{A}
2012	1.10(0.04)^{A}	0.96(0.03)^{A}	1.06(0.05)^{A}	1.04(0.06)^{A}	3.8(0.06)^{A}	3.9(0.03)^{A}	3.9(0.04)^{A}	3.9(0.16)^{A}
5-10cm								
2011	1.27(0.07)^{A}	1.36(0.04)^{A}	1.35(0.04)^{A}	1.30(0.03)^{A}	3.9(0.06)^{A}	3.8(0.04)^{A}	3.9(0.03)^{A}	3.9(0.06)^{A}
2012	1.29(0.03)^{A}	1.33(0.03)^{A}	1.35(0.03)^{A}	1.36(0.04)^{A}	4.1(0.07)^{A}	4.0(0.03)^{A}	4.1(0.05)^{A}	4.0(0.05)^{A}
	CEC *meq·100g^{-1}*				Exchangeable K *g·m^{-2}*			
	C	B	M	M+B	C	B	M	M+B
0-5cm								
2011	7.88(0.41)^{A}	8.18(0.43)^{A}	7.20(0.43)^{A}	7.54(0.53)^{A}	1.04(0.13)^{A}	0.99(0.07)^{AB}	0.87(0.05)^{AB}	0.72(0.06)^{B}
2012	8.17(0.27)^{A}	8.65(0.30)^{A}	8.34(0.36)^{A}	8.07(0.41)^{A}	0.95(0.05)^{A}	0.91(0.05)^{A}	0.99(0.09)^{A}	0.91(0.06)^{A}
5-10cm								
2011	3.79(0.37)^{A}	5.37(0.58)^{A}	4.65(0.41)^{A}	4.59(0.65)^{A}	0.52(0.07)^{A}	0.67(0.05)^{A}	0.79(0.07)^{A}	0.62(0.08)^{A}
2012	4.34(0.33)^{A}	5.47(0.58)^{A}	4.91(0.37)^{A}	4.73(0.48)^{A}	0.54(0.09)^{A}	0.72(0.08)^{A}	0.60(0.05)^{A}	0.68(0.06)^{A}
	Exchangeable Mg *g·m^{-2}*				Exchangeable Ca *g·m^{-2}*			
	C	B	M	M+B	C	B	M	M+B
0-5cm								
2011	1.73(0.17)^{A}	2.61(0.52)^{A}	2.33(0.33)^{A}	1.54(0.21)^{A}	6.33(1.12)^{A}	6.71(1.18)^{A}	6.98(0.84)^{A}	5.50(0.33)^{A}
2012	1.69(0.17)^{A}	2.69(0.38)^{A}	2.22(0.25)^{A}	2.33(0.36)^{A}	5.16(0.49)^{A}	6.46(0.51)^{A}	5.77(0.87)^{A}	6.59(0.88)^{A}
5-10cm								
2011	0.89(0.11)^{A}	1.73(0.29)^{A}	1.68(0.21)^{A}	1.27(0.26)^{A}	4.61(0.79)^{A}	5.71(0.82)^{A}	6.83(0.74)^{A}	5.83(0.70)^{A}
2012	0.83(0.14)^{A}	1.45(0.23)^{A}	1.20(0.24)^{A}	1.26(0.24)^{A}	3.63(0.44)^{A}	4.51(0.55)^{A}	3.95(0.64)^{A}	5.48(0.77)^{A}

Table 5-7. Continued

Base Saturation (K) %	C	B	M	M+B
0-5cm				
2011	0.63(0.06)^{A}	0.61(0.03)^{A}	0.62(0.03)^{A}	0.53(0.04)^{A}
2012	0.54(0.03)^{A}	0.56(0.02)^{A}	0.57(0.03)^{A}	0.57(0.04)^{A}
5-10cm				
2011	0.59(0.09)^{A}	0.50(0.04)^{A}	0.65(0.05)^{A}	0.59(0.08)^{A}
2012	0.51(0.09)^{A}	0.51(0.04)^{A}	0.51(0.05)^{A}	0.60(0.11)^{A}

Base Saturation (Mg) %	C	B	M	M+B
0-5cm				
2011	3.43(0.25)^{A}	4.84(0.56)^{A}	4.91(0.31)^{A}	3.69(0.45)^{A}
2012	3.14(0.25)^{A}	5.28(0.65)^{A}	4.21(0.41)^{A}	4.66(0.70)^{A}
5-10cm				
2011	3.10(0.24)^{A}	3.84(0.34)^{A}	4.42(0.30)^{A}	3.49(0.50)^{A}
2012	2.49(0.39)^{A}	3.38(0.52)^{A}	2.92(0.43)^{A}	2.82(0.56)^{A}

Base Saturation (Ca) %	C	B	M	M+B
0-5cm				
2011	7.35(0.97)^{A}	7.76(0.85)^{A}	9.20(0.86)^{A}	8.39(0.76)^{A}
2012	5.91(0.69)^{A}	8.82(0.91)^{A}	6.48(0.77)^{A}	7.86(0.92)^{A}
5-10cm				
2011	9.42(0.92)^{A}	7.89(0.70)^{A}	10.83(0.66)^{A}	10.25(1.46)^{A}
2012	6.59(0.77)^{A}	6.65(0.85)^{A}	5.85(0.87)^{A}	7.44(1.01)^{A}

Base Saturation (H) %	C[3]	B	M	M+B
0-5cm				
2011	88.59(1.14)^{A}	86.80(1.27)^{A}	85.28(0.91)^{A}	87.26(1.09)^{A}
2012	90.39(0.82)^{A}	83.36(1.24)^{B}	88.75(1.08)^{AB}	83.79(1.54)^{AB}
5-10cm				
2011	86.86(1.16)^{A}	87.77(0.84)^{A}	84.11(0.93)^{A}	85.73(1.74)^{A}
2012	90.39(1.11)^{A}	89.45(1.16)^{A}	90.62(1.18)^{A}	89.24(1.51)^{A}

Available P $g \cdot m^{-2}$	C	B	M	M+B
0-5cm				
2011	0.38(0.09)^{A}	0.29(0.03^{A}	0.28(0.04)^{A}	0.22(0.03)^{A}
2012	0.18(0.03)^{A}	0.28(0.07)^{A}	0.17(0.02)^{A}	0.21(0.04)^{A}
5-10cm				
2011	0.27(0.05)^{A}	0.31(0.03)^{A}	0.45(0.08)^{A}	0.26(0.04)^{A}
2012	0.23(0.05)^{A}	0.31(0.05)^{A}	0.23(0.04)^{A}	0.23(0.03)^{A}

Organic Matter %	C	B	M	M+B
0-5cm				
2011	2.77(0.18)^{A}	3.18(0.29)^{A}	2.50(0.24)^{A}	2.26(0.26)^{A}
2012	2.75(0.20)^{A}	3.34(0.34)^{A}	2.79(0.22)^{A}	2.64(0.27)^{A}
5-10cm				
2011	0.88(0.08)^{A}	1.30(0.16)^{A}	1.07(0.10)^{A}	1.11(0.21)^{A}
2012	1.09(0.12)^{A}	1.26(0.12)^{A}	1.18(0.12)^{A}	1.11(0.11)^{A}

Table 5-7. Continued

	Total P ppm				Total N %			
	C	B	M	M+B	C	B	M	M+B
0-5cm								
2011	52.60(2.34)^A	57.04(4.17)^A	50.31(2.70)^A	52.38(3.59)^A	0.20(0.00)^A	0.21(0.01)^A	0.20(0.01)^A	0.21(0.02)^A
2012	34.49(3.20)^A	42.86(3.83)^A	38.28(2.99)^A	34.44(3.93)^A	0.21(0.01)^A	0.25(0.02)^A	0.23(0.01)^A	0.22(0.01)^A
5-10cm								
2011	32.02(1.62)^A	37.41(1.78)^A	36.54(2.09)^A	33.85(1.78)^A	0.15(0.01)^A	0.16(0.00)^A	0.16(0.01)^A	0.16(0.01)^A
2012	14.76(1.77)^A	18.22(1.67)^A	16.70(1.36)^A	16.36(1.16)^A	0.17(0.01)^A	0.18(0.01)^A	0.18(0.01)^A	0.18(0.01)^A

	Total C %			
	C	B	M	M+B
0-5cm				
2011	2.08(0.25)^A	2.46(0.38)^A	1.77(0.11)^A	1.88(0.36)^A
2012	2.24(0.22)^A	3.10(0.41)^A	2.60(0.25)^A	2.18(0.28)^A
5-10cm				
2011	0.50(0.06)^A	0.83(0.14)^A	0.67(0.08)^A	0.71(0.15)^A
2012	0.60(0.08)^A	0.89(0.11)^A	0.71(0.11)^A	0.88(0.16)^A

Note: Values sharing letters within rows, by soil property, are not statistically different (Tukey-Kramer Test, α=0.05) between treatments: control (C), burn only (B), mow only (M), mow followed by burning (M+B)
Samples taken 6 months following mowing, 1 week prior to burning (2011); and 1 year following burning (2012)
.

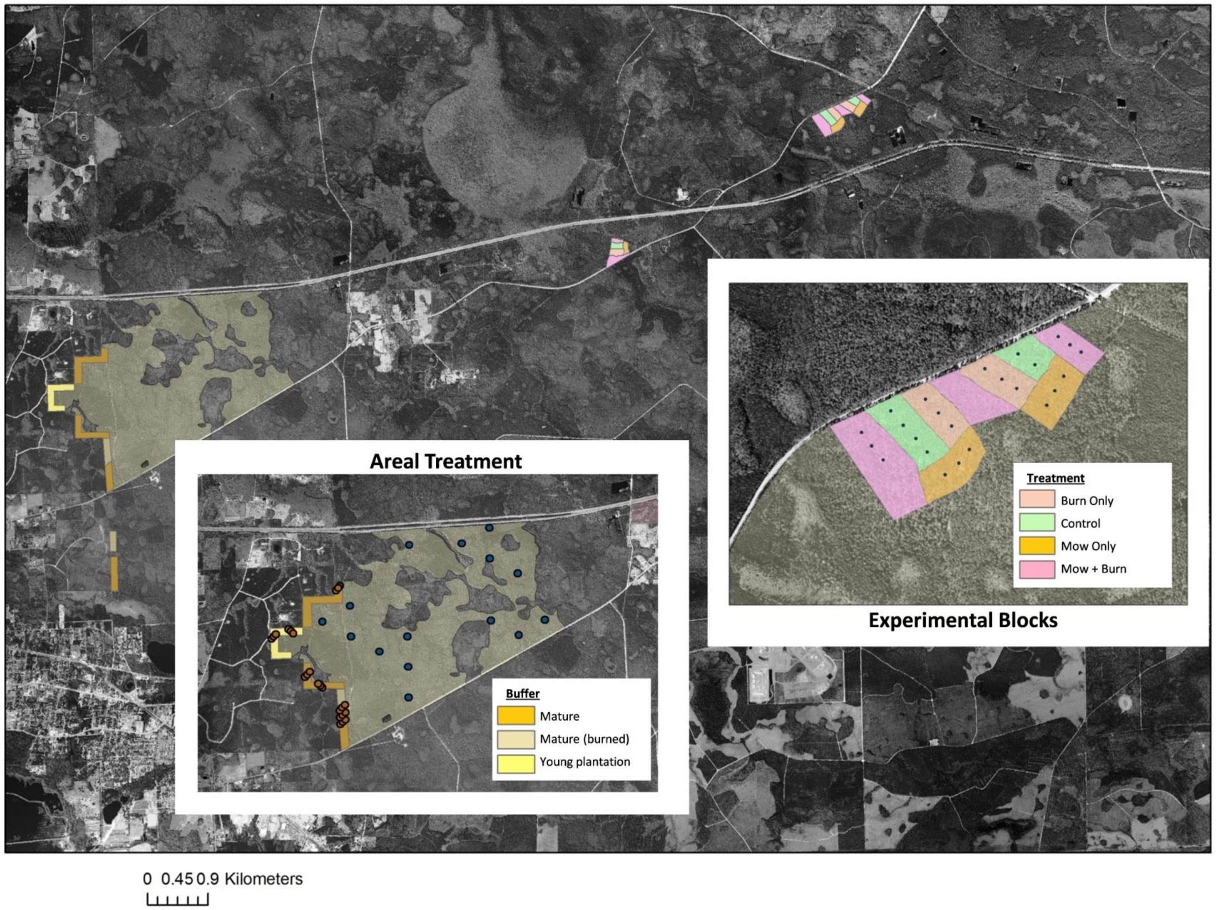

Figure 5-1. Fuels treatments used for the study of the ecological effects of understory mowing in pine flatwoods of the Osceola National Forest (ONF) in northern Florida, USA. Three treatment areas are shown. 1) a 100 m wide and 6 km (60 ha) buffer masticated ("mowed") in 3 stand types: mature pine (ca. 80 yrs old), mature pine recently burned (5 yrs prior to mowing), and young pine plantation (28 yrs old); 2) a 500 ha areal treatment (sampling plots exist in mature pine only); and 3) three experimental blocks each with the following treatments: mow, mow followed by burning, burn only, and control.

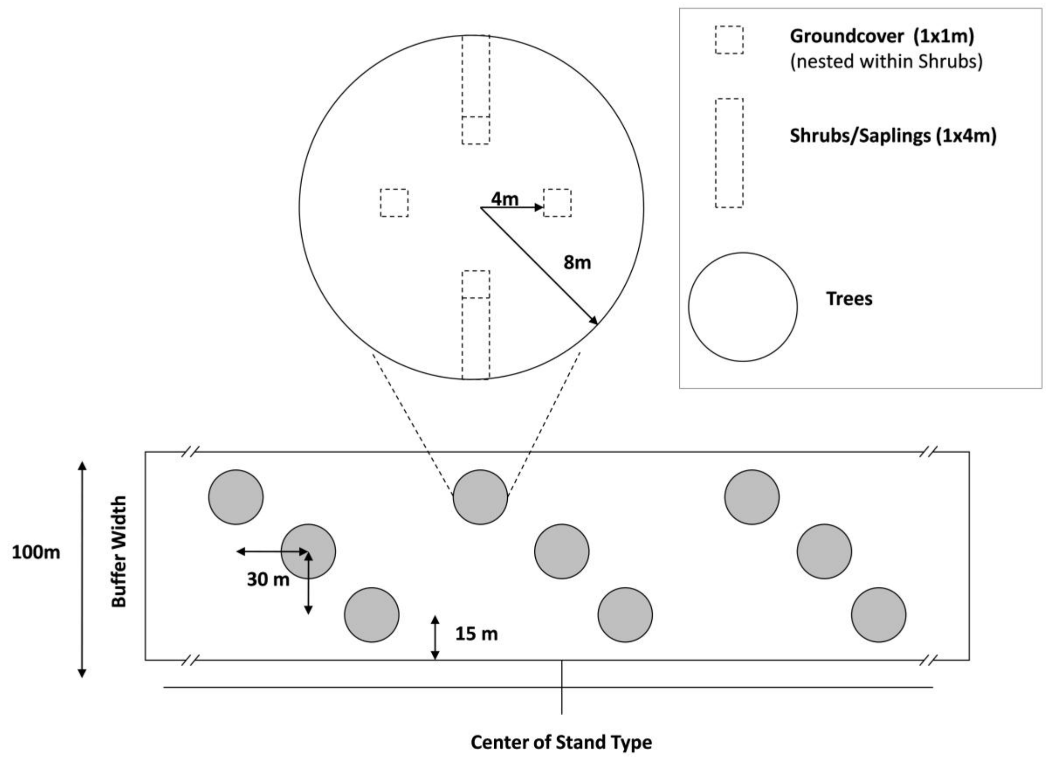

Figure 5-2. Vegetation sampling plots systematically allocated within a fuels treatment buffer on the Osceola National Forest in northern Florida, USA. Plots were located at the center of delineated stand types (mature, mature-burned, young plantation).

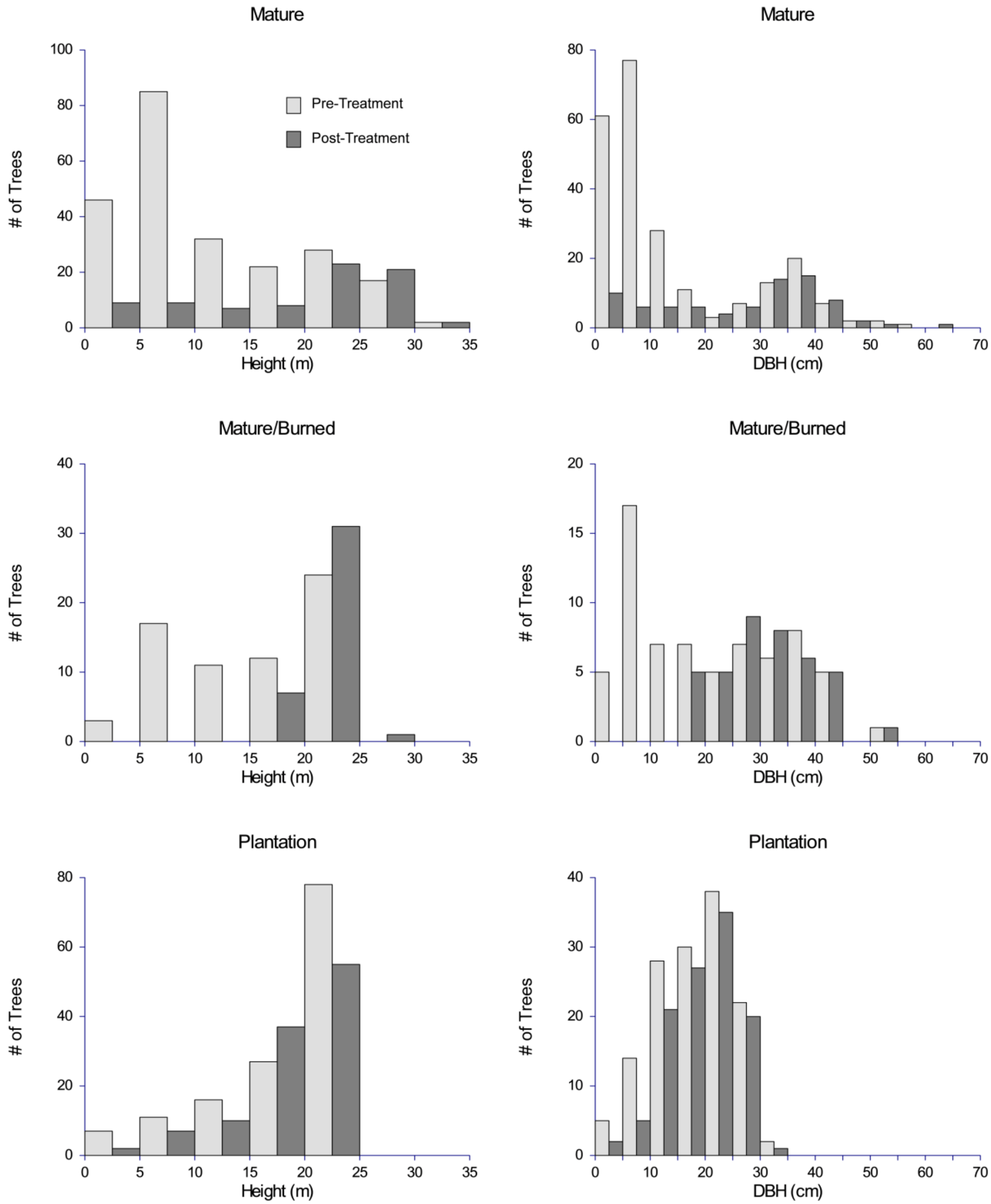

Figure 5-3. Tree height and diameter distributions pre- and post-treatment following mowing in 3 stand types (mature, mature/burned, plantation) in pine flatwoods in northern Florida, USA.

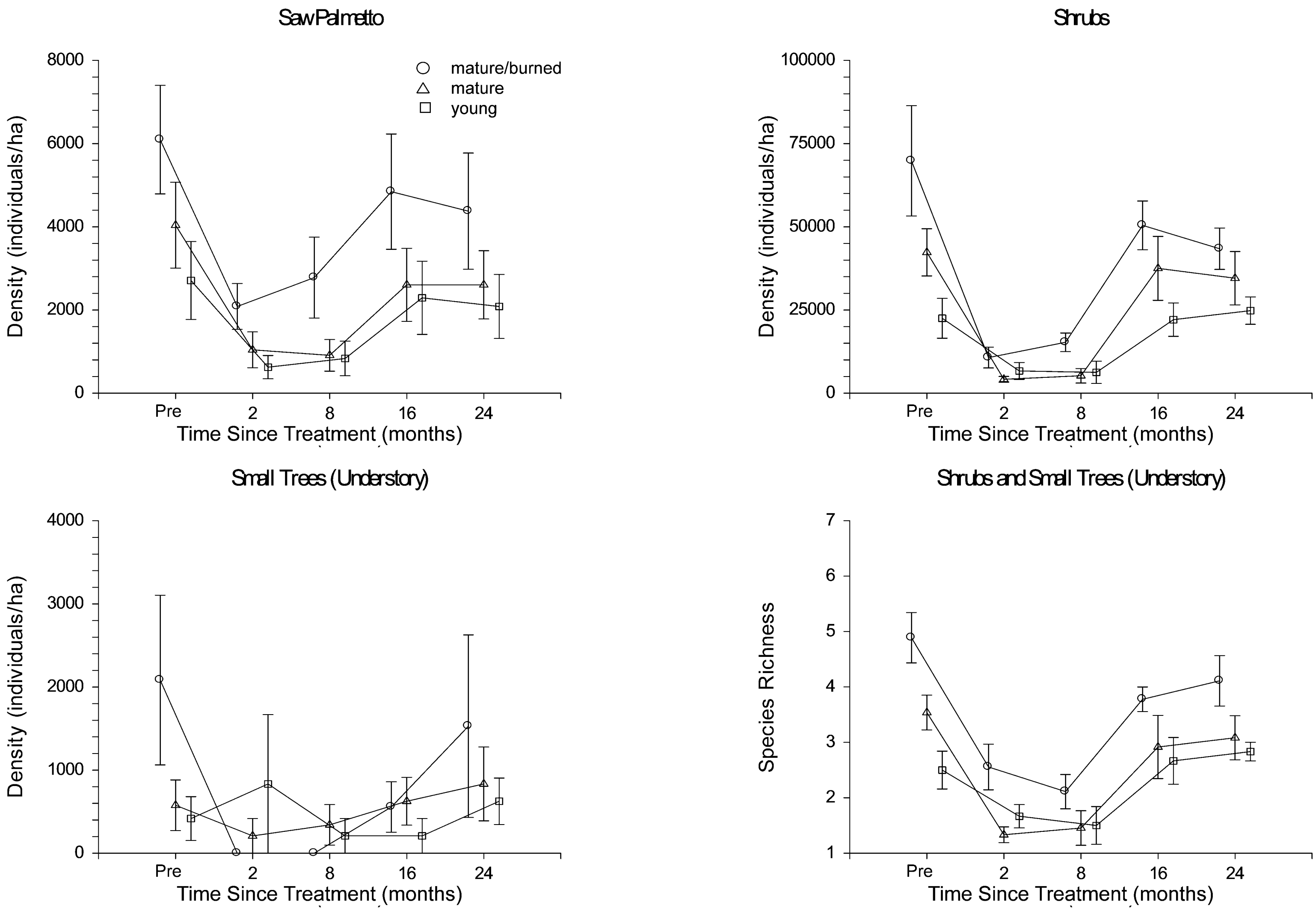

Figure 5-4. Density and species richness of understory shrubs and small trees following mechanical mowing of understory shrubs and small trees in pine flatwoods of northern Florida, USA.

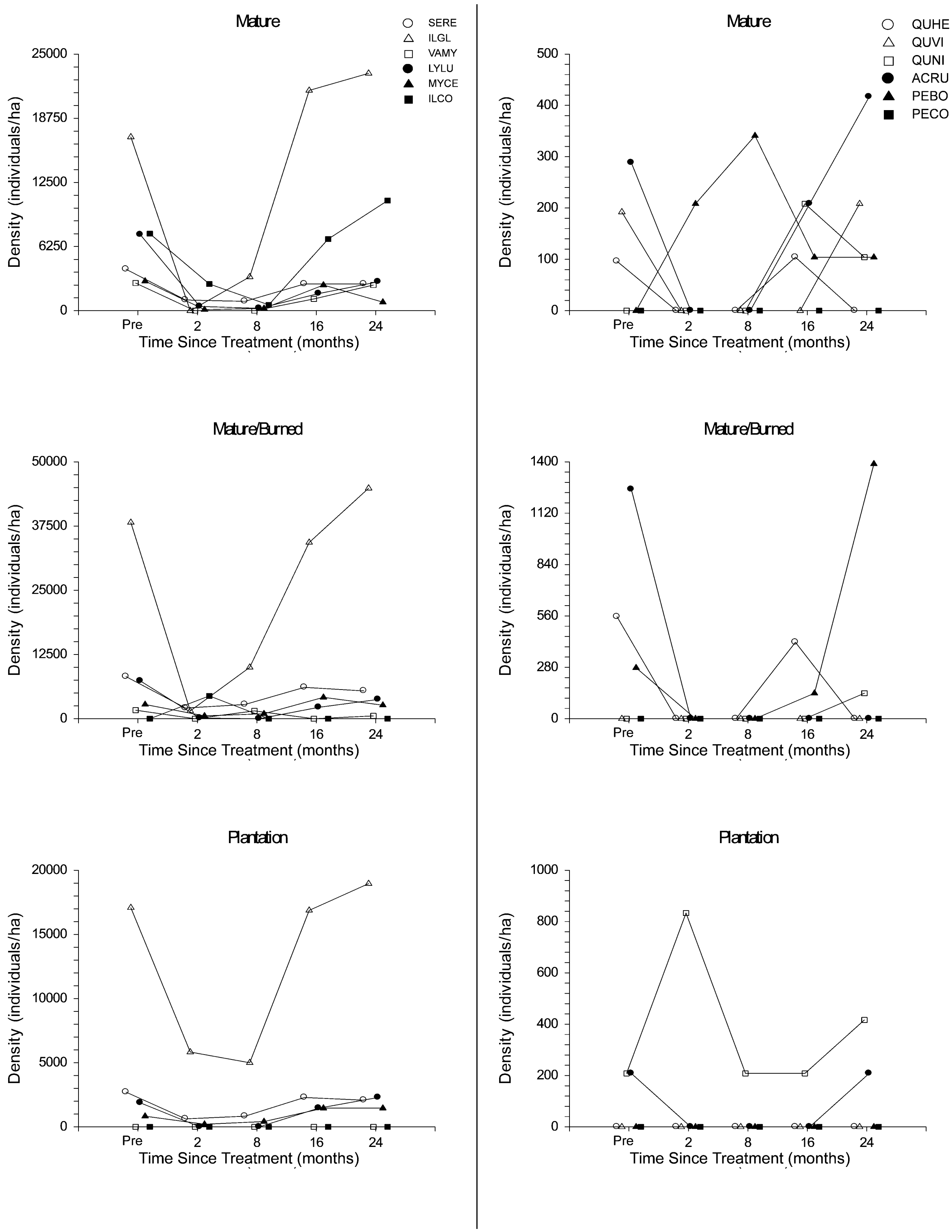

Figure 5-5. Density by species of understory shrubs (left) and trees <2.5 cm DBH (right).

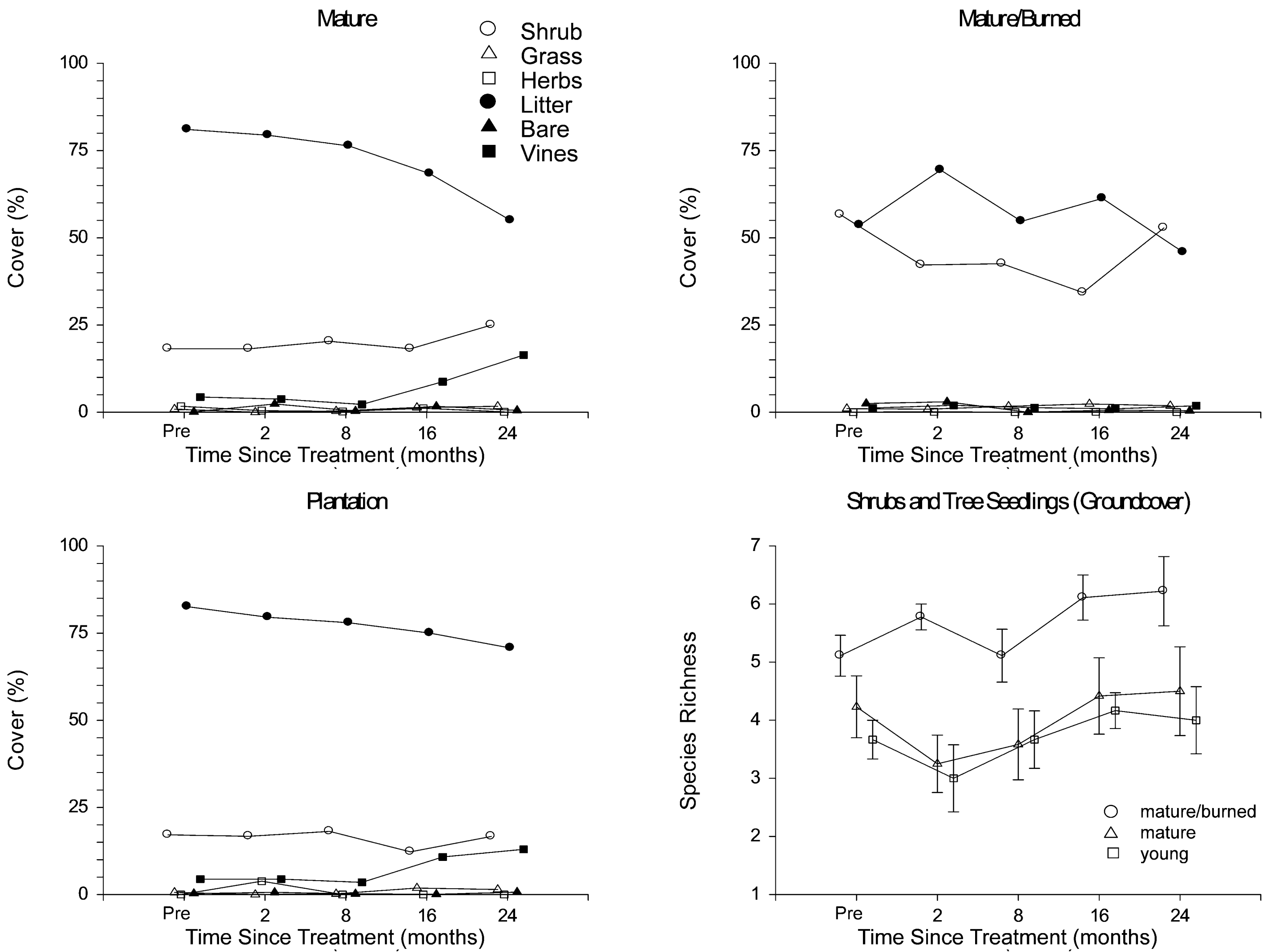

Figure 5-6. Groundcover (%), by cover type, and species richness of shrubs (<0.5m in height) and tree seedlings (<0.5 m in height) following mowing in 3 stand types (mature, mature/burned, plantation) in pine flatwoods in northern Florida, USA.

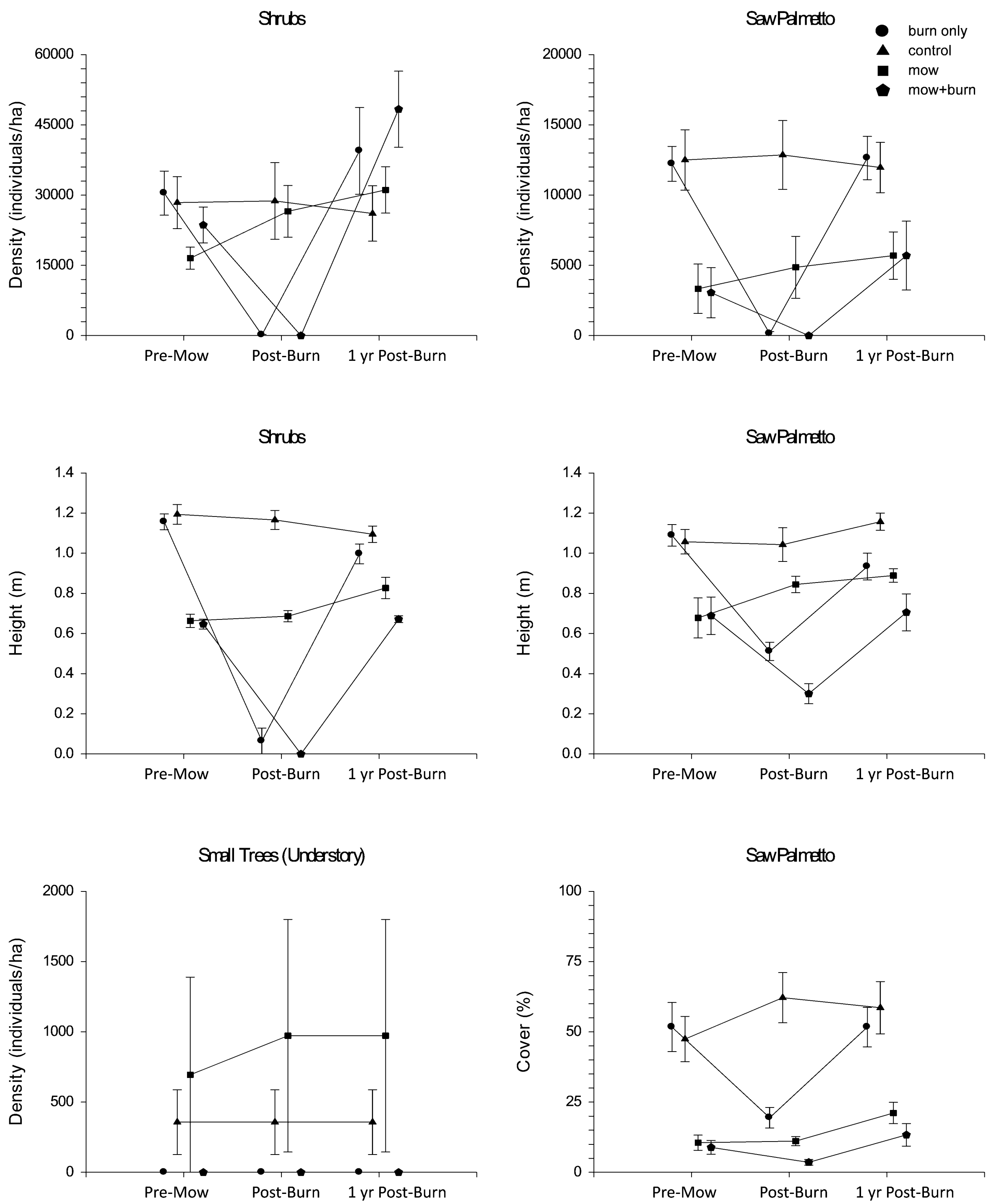

Figure 5-7. Density and species richness of understory shrubs and small trees across experimental mowing and burning treatments in pine flatwoods of northern Florida, USA.

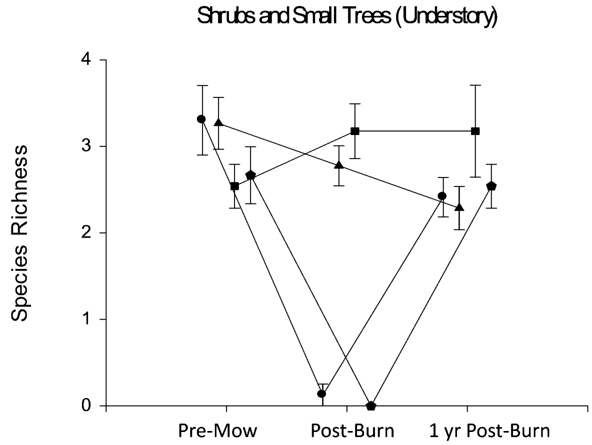

Figure 5-7. Continued

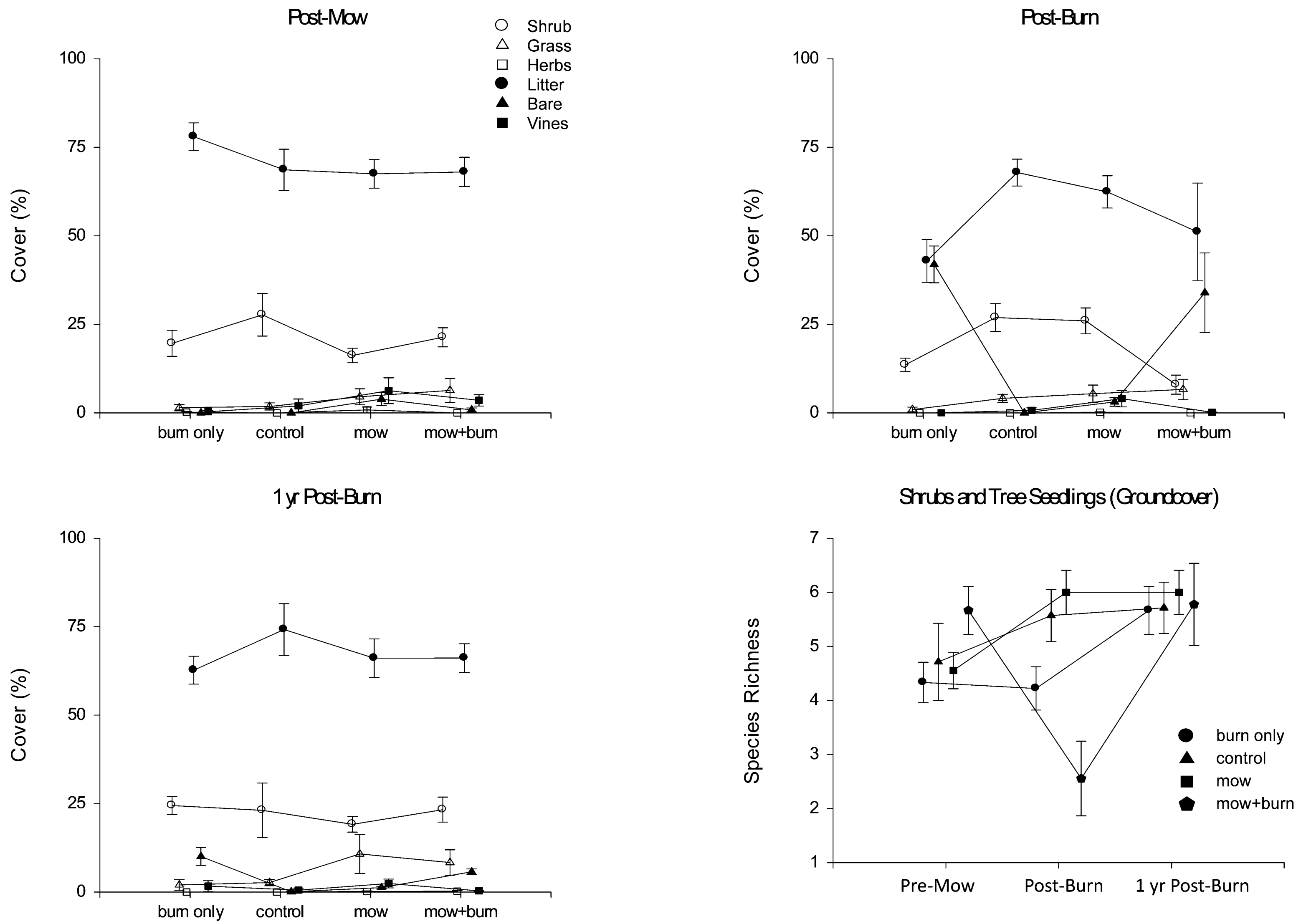

Figure 5-8. Percent groundcover, by cover type, and species richness of shrubs (<0.5 m) and tree saplings (<0.5 m) across experimental mowing and burning treatments in pine flatwoods in northern Florida, USA.

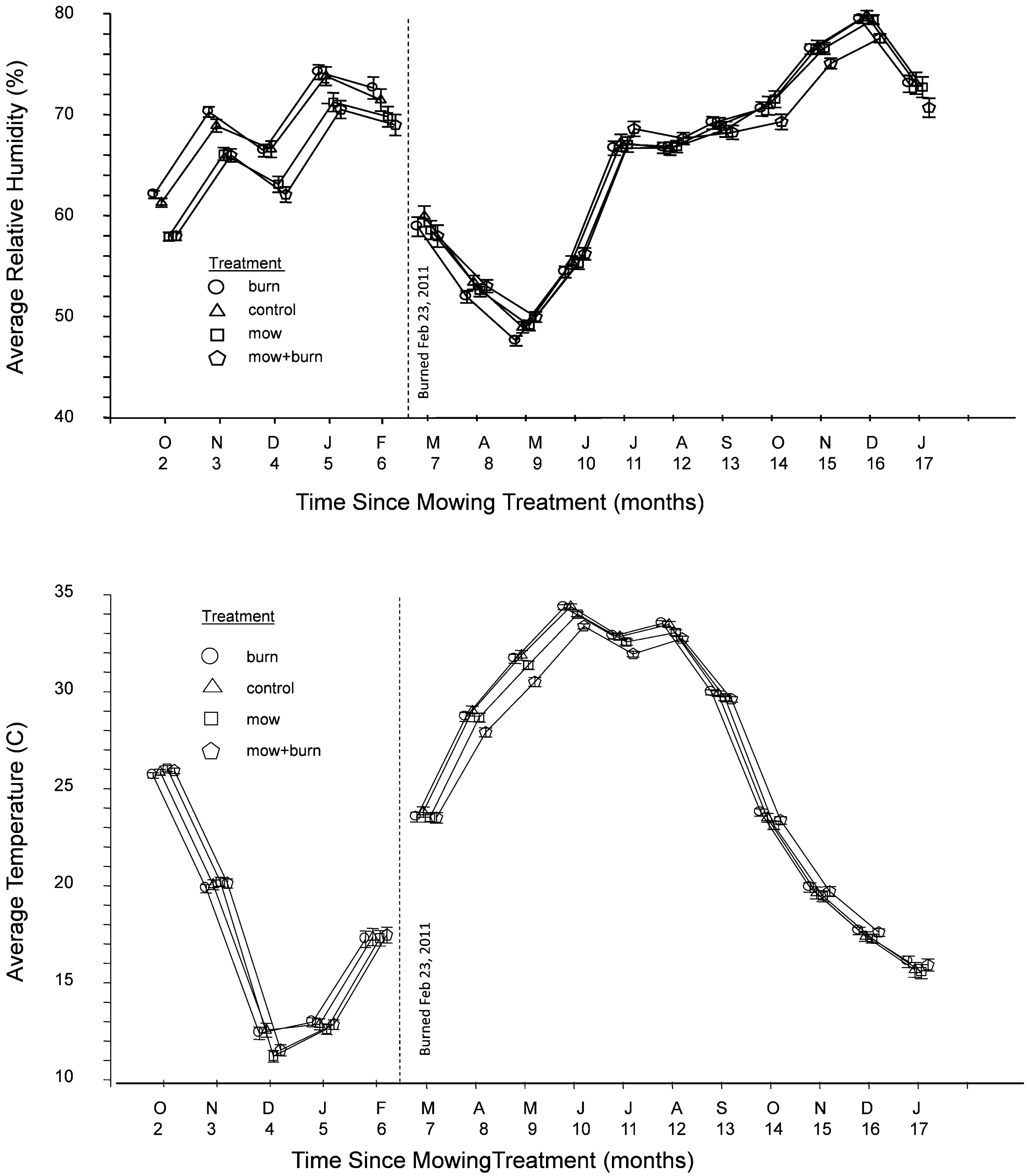

Figure 5-9. Average temperature (above) and relative humidity (below) across 3 fuels treatments (burn, mow, mow+burn) and controls up to 17 months following mowing treatments conducted in August 2010. Burning treatments were conducted in Feb 2011, six months following mowing.

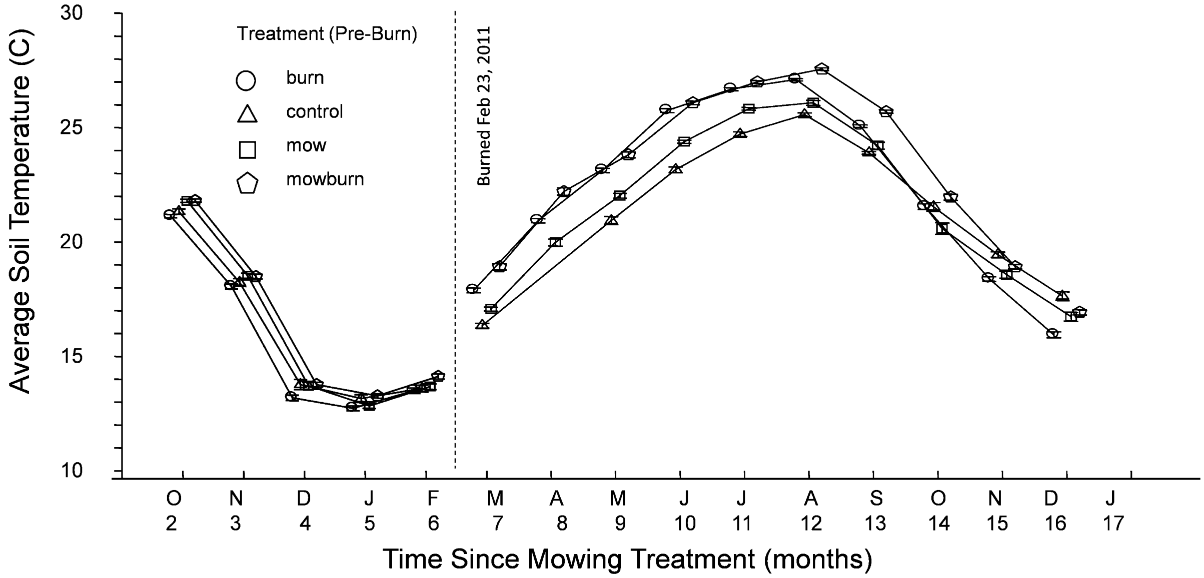

Figure 5-10. Average soil temperature, at 5 cm depth, across 3 fuels treatments (burn, mow, mow+burn) and controls up to 16 months following mowing treatments conducted in August 2010. Burning treatments were conducted in Feb 2011, six months following mowing.

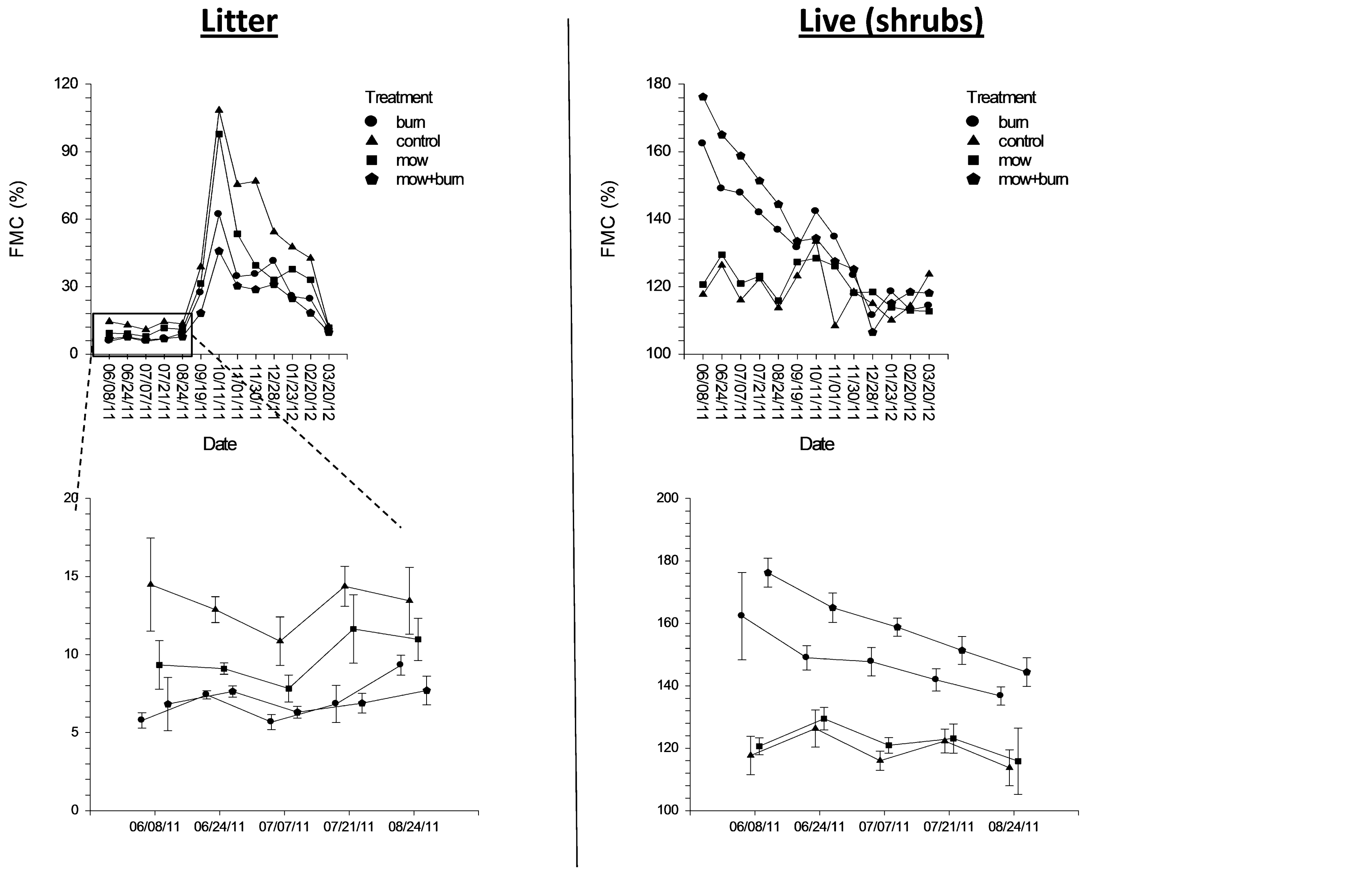

Figure 5-11. Moisture content (%) of surface litter (left) and live shrub foliage (right) across fuels treatments (mow, mow+burn, burn only), and controls, in mature pine flatwoods of northern Florida, USA. Moisture content sampled every 3 to 4 weeks between June 2011 and March 2012. Inserts indicate moisture content differences by treatment during the driest season.

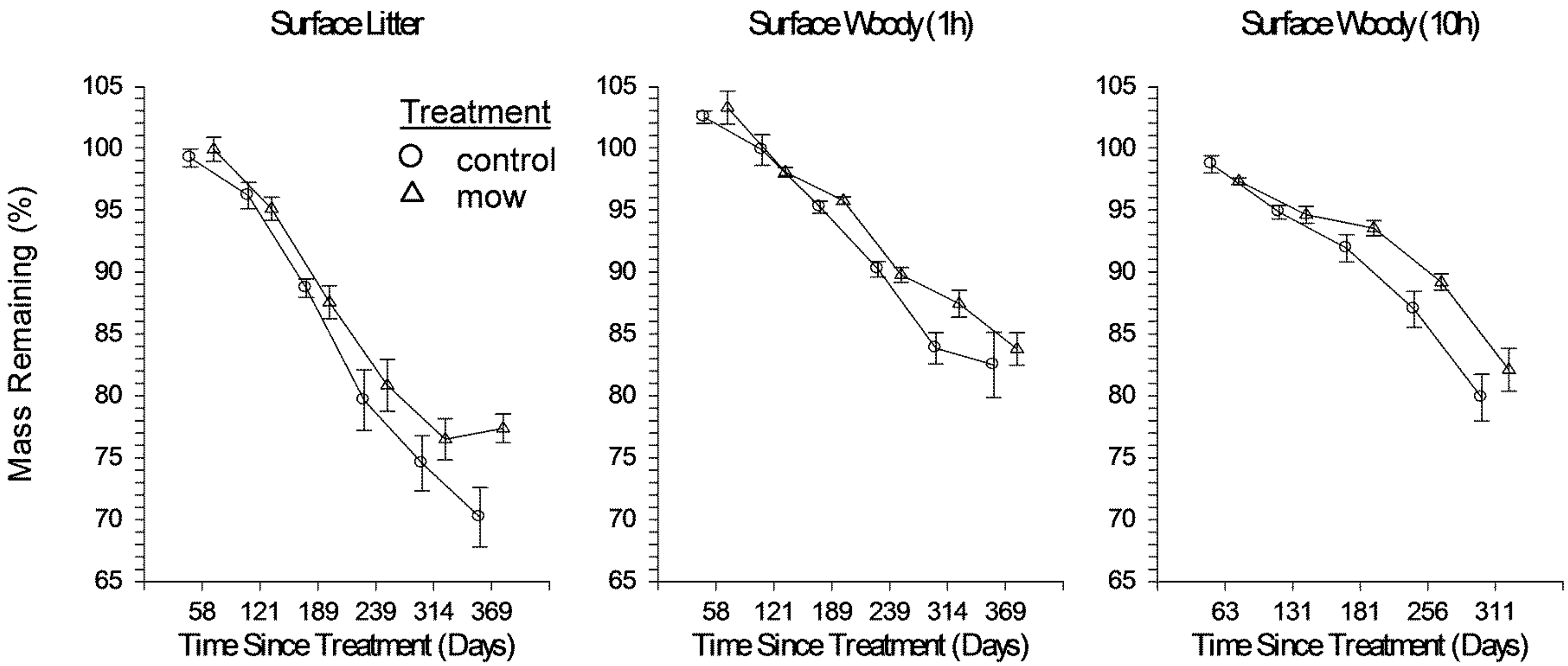

Figure 5-12. Comparison of decomposition of surface litter and surface woody debris (1h: <0.625 cm; 10h: 0.625-2.54 cm) created from mowing of saw palmetto and gallberry dominated understory of mature pine flatwoods of northern Florida, USA between mowed treatments and un-mowed controls. All material collected for decomposition study were derived from understory mowing, however decomposition rates evaluated in un-mowed controls was to determine if shrub cover influenced decomposition since shrub recovery following mowing is rapid. No differences in decomposition were detected between treatments across any of the fuel types: litter (P=0.249), 1h woody (P=0.386), 10h woody(P=0.438).

CHAPTER 6
CONCLUSIONS

The research presented here provides much needed insight into the effectiveness and effects of an increasingly utilized mechanical fuels treatment method in a common forest ecosystem of the southeastern US.

While studies have begun to evaluate mastication as a fuels treatment option, much of this research has been in the western US and in ecosystems where post-treatment fuels are primarily woody-dominated surface fuelbeds. Mastication ("mowing") in palmetto/gallberry pine flatwoods results in unique surface fuelbeds dominated by litter. While surface fuel loading precisely controlled fire behavior during small scale fire behavior experiments, recovering shrubs controlled fire behavior in field-scale experiments in these treatments. Fuel models have been a common approach to categorizing fuels for fire behavior prediction. Developing fuel models for mastication treatments will need to take into account the ability of shrubs to resprout following these treatments. The fast recovery of shrubs following mastication in these flatwoods sites, along with their control over fire behavior, suggest that a shrub model would be appropriate for these treatments as soon as six months treatment. Unless sites are burned right after treatments, shrubs will dominate fire behavior.

Treatments were effective at reducing fire behavior by reducing shrub biomass, however longevity of this treatment may be short-lived as shrubs recover rapidly. Moreover, while shrubs control fire behavior, long duration heating from combustion of surface fuels may influence fire effects. Surface heating, observed during small-scale experimental burning, may have contributed to tree mortality observed during summer season burns conducted in the field. These flatwoods sites are highly flammable and have likely adapted to fast burning shrub fires with significant intensity. Although these southeastern pines are very resilient to crown damage ensued from burning, they are more susceptible to fine root and basal cambium damage when surface fuels burn for long durations. Mastication, while only reducing shrub biomass in the short term, increases surface fuels. Since treatments are likely to be prioritized in long-unburned stands where duff has accumulated, adding surface fuels may result in increased ignitability of duff and potential overstory mortality. Burning in drier conditions to increase surface fuel consumption, a likely objective during prescribed burning in masticated stands, could pose a hazard to overstory trees if duff moisture is also low. Burning when surface fuels created from mastication are dry enough for consumption, but when duff is moist enough to limit damage to trees may be key to successful fuels management using these treatment regimes. Bulk density increases observed following treatments, immediately and one-year following, may mean that fuels will be even more difficult to consume as time since treatment increases. This, along with shrub recovery, both indicate that follow-up burning in these treatments should be conducted early to sufficiently reduce fuel loading and increase fire control. Developing treatment regimes so that treatment timing will enhance meeting management objectives will be important.

Mastication had minor effects on the ecological attributes assessed with this research. Vegetation communities were little affected by treatments, except that saw palmetto reduction was evidenced. Shrubs that vigorously sprout following burning may resprout following mastication because meristematic tissues and underground carbohydrate reserves are not destroyed. Apical meristems in saw palmetto, however, are embedded in the above-ground stem and while they are typically not damaged during burning, thus continuing to produce new fronds, they may be damaged by masticators during treatments. Understory or groundcover vegetation communities may change over time with a loss of palmetto cover, however only little evidence of increases in grass cover were observed here. Continued monitoring may reveal potential changes. Impacts of treatments on microclimate was minor, but treatment influences over fuel moisture indicated that loss of shrub cover may have enhanced drying of surface fuels. While increased fuel bulk density should provide a mulching effect, drier surface fuels in masticated sites may actually increase ignition probability. Consumption of surface fuels may be aided by such an effect, however the risk of wildfire could be also enhanced. Moisture content in living shrub foliage wasn't influenced by mastication alone, however burning in masticated sites resulted in shrubs with higher moisture content compared to sites burned that had not been previously masticated. Differences were likely due to reduced shrub cover, especially saw palmetto, and less competition for resources.

Whether mastication is conducted as a stand-alone treatment or followed up by prescribed burning, palmetto/gallberry pine flatwoods seem to recover quickly following treatments. Treatment effectiveness is likely not to last long without follow up burning. While concerns regarding potential impacts to overstory trees during burning in these treatments will need to be considered, it appears that such treatments will likely have minor ecological impacts if conducted in a manner to minimize potential long duration surface heating. Considerations regarding treatment timing and conditions for follow-up burning will need to be taken into account to minimize such impacts and meet management objectives. Palmetto/gallberry pine flatwoods are unique in their post-mastication fuel environment and provide additional insight into the effects and efficacy of mastication treatments as a whole.

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BIOGRAPHICAL SKETCH

Jesse Kreye was born in 1974 in Mora, Minnesota and subsequently raised in the North Star state. He graduated from Hinckley-Finlayson High School in 1993. He served in the U.S. Navy as an aircraft firefighter aboard the U.S.S. Enterprise. Jesse received a Bachelor of Science in forestry in 2005 and a Master of Science in natural resources, with a minor in biometrics, in 2008 from Humboldt State University. He received his Ph.D. in forest resources and conservation in 2012 from the University of Florida. He has worked for the Minnesota Department of Natural Resources in fire suppression and the U.S.D.A Forest Service in fire management, silviculture, and wildlife management. Jesse was also a lecturer in the Department of Forestry and Wildland Resources at Humboldt State University.