Project Title: Characterization of Masticated Fuelbeds and Fuel Treatment Effectiveness in Southeastern US Pine Ecosystems.

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I. Abstract

Mechanical fuels treatments are being widely used in fire prone ecosystems where fuel loading poses a hazard, yet little research 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 prescribed 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 mowed treatments may have resulted from combustion of the compact surface fuels beneath the shrub layer. Although temperature and humidity at the shrub level were minimally impacted, 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, observed reduction in saw palmetto may alter future groundcover, as slight increases in grass cover were observed. The fast recovery of understory vegetation and generally low impact to ecosystem attributes suggest resiliency of these pine flatwoods following mechanical treatments. However, their effectiveness at reducing fire hazard is likely short-lived. Treatment regimes that utilize prescribed burning to reduce post-mastication fuels will require special attention to treatment timing in order to ensure surface litter consumption, while minimizing potential impacts to the overstory.

II. Background and Purpose

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 evolved under frequent and relatively low intensity fire regimes. 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 in the tree canopy stratum, the understory and midstory vegetation, and as downed woody and foliar 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) is burned often enough that large quantities are not accumulated between fires. The plants that thrive in these ecosystems are typically adapted to the frequent 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. In addition, fuel biomass can accumulate to such levels that 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 hazards for the health and safety of human populations. It is often difficult, however, to maintain highly frequent fire cycles over large areas due to logistical constraints, especially in the wildland-urban-interface (WUI). In areas where significant fuel buildup has occurred, reintroducing fire could pose a risk to the public or cause 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 over 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 can 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 employed across the 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 consists 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 other methods, such as roller-chopping (Watts and Tanner 2006), that use weighted drums pulled behind ground equipment to push over and chop understory vegetation, typically causing soil damage in the process. Mastication largely impacts understory vegetation with relatively minimal impact to ground fuels, soils, or overstory trees (Kobziar et al. 2009).

Mastication treatments are being used in several shrub and forest ecosystems across the US, yet most 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 loading results from treatments where total fuel mass is not reduced, but only rearranged into more-compacted, 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 comprehensively described post-treatment fuel characteristics, evaluated fuel dynamics over time, or determined treatment effectiveness for 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., and *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 2-7 years, with sprouting shrub species being the dominant fuel driving fire behavior. Fire management in this ecosystem requires burning at least every five years 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. Additionally, their potential ecological impacts, with or without follow-up burning, has not been assessed. The uniqueness of this ecosystem regarding its fuel characteristics and environment (Hough and Albini 1978, McNab et al. 1978) is likely to result in a unique fuel environment when masticated.

Assessing impacts of mastication on the fuel environment, elucidating fire behavior in masticated fuelbeds, determining treatment efficacy in reducing fire hazard, and quantifying important ecological impacts together provide a holistic evaluation of the management tool. In order to more fully understand mastication as a fuels treatment option in palmetto/gallberry pine flatwoods of the southeastern US, the objectives of this study 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 improve our understanding of mastication as a fuels treatment option in palmetto/gallberry pine flatwoods, as well as expand exiting assessments of the efficacy of the management tool.

III. Study Description and Location

The Osceola National Forest (ONF) in northern peninsular Florida, USA, encompasses 81,000 ha in parts of Columbia, Baker, Bradford, and Hamilton counties. The terrain is generally flat with underlying marine deposited sandy soils. The climate is characterized by hot, humid summers with mild winters and the majority of precipitation occurring during summer months from thunderstorms. Dominant vegetation communities in the ONF include mesic and hydric pine flatwoods with intermittent cypress-hardwood swamps. Fuel characterizations were conducted in naturally regenerated stands of mature longleaf/slash pine flatwoods that were either burned five years prior to the study, or had not burned in at least 11 years, as well as in pine plantations. Fire behavior and ecological effects studies were conducted in mature flatwoods stands that had not burned in >11 years.

Fuels Characterization

Fuels were characterized within two mowing treatments in the southwestern portion of the ONF. One, a large contiguous area (500 ha) adjacent to Interstate 10, referred here as the 'areal' treatment, and the other, a 100 m wide, 6 km long buffer treatment (60 ha) adjacent to privately owned pine plantations. 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).

Surface fuels including fine woody debris (1h, 10h, 100h), litter, and duff were destructively sampled from 32 1×1 m quadrats (Fig. 1) allocated to 16 plots (2 quadrats plot^{-1}) randomly located in the areal treatment just after mowing treatment. Litter and duff depths were measured at 4 locations within each quadrat and all surface fuels were removed and transported to the lab, sorted, oven-dried, weighed, and biomass (Mg ha^{-1}) calculated for each quadrat, by fuel class. Woody fuels were subsequently sorted into fractured or non-fractured particles, according to Kane et al. (2009), where fractured particles are those in which ≥50% of particle length is visibly fractured. Bulk density was calculated for each quadrat, by fuel class.

Trees, shrubs, and surface fuels were non-destructively sampled prior to mowing and again at 2, 8, 16, and 24 months following treatment in both the areal and buffer sites. Sampling occurred within the 16 plots described above in the areal treatment (Fig. 1a) and within 27 plots systematically located in the buffer (Fig. 1b). Plot allocation in the buffer was weighted according to the area each stand type accounted (mature N=12, mature/burned N=9, plantation N=6). Within each plot, trees ≥2.5cm diameter at breast height (DBH) were measured for height, crown base height (CBH), and DBH. Trees <2.5cm DBH and shrubs ≥0.5 m tall were all measured for basal diameter and height within two 1×4m belt transects. Woody shrub biomass, by species, was estimated using published allometric equations. Saw palmetto biomass was estimated using an allometric equation developed in this study from 40 palmetto fronds selected from 40 individual palmetto shrubs. Woody surface fuels (1,10,100,1000h) were tallied and litter and duff depths measured within 4, randomly oriented, 10m long transects. Biomass of woody surface fuels were estimated using the planer intercept method (Brown 1971) and published fuel characteristics from palmetto/gallberry site nearby (Hough and Albini 1978). Pretreatment litter and duff biomass was estimated from measured depths using published bulk density values (LLP09 fuel model, Ottmar and Vihnanek 2000). Post treatment litter and duff biomass was estimated using equations developed from destructive sampling in the areal site.

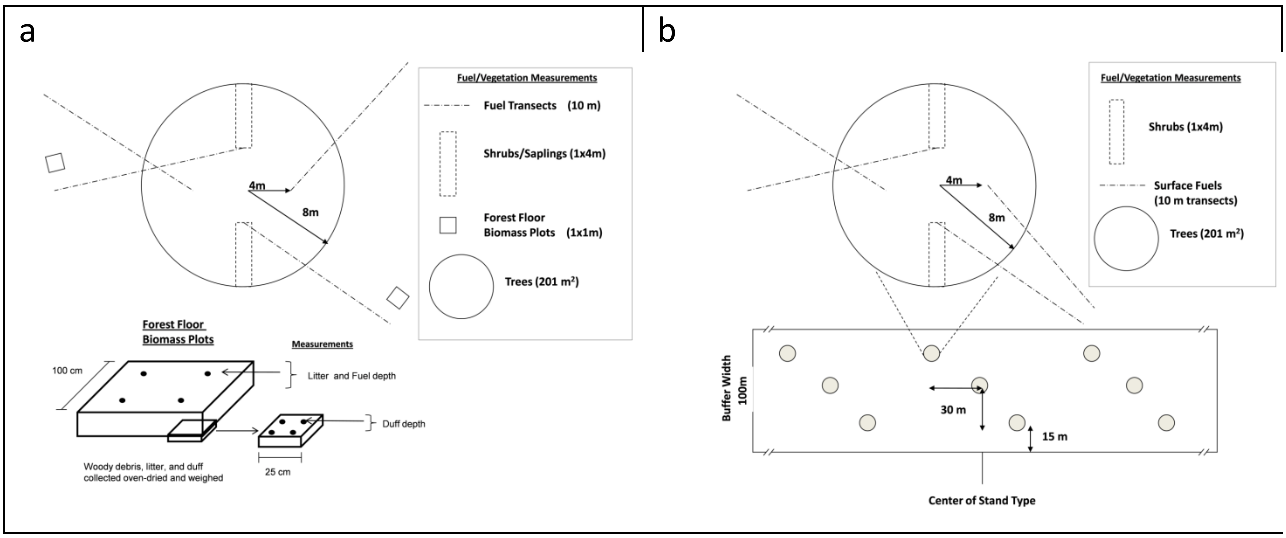

Figure1. Fuel and vegetation sampling plot designs in the areal (a) and buffer (b) mowing sites.

Mean, range, and standard deviation were reported for all fuelbed characteristics measured from destructive sampling in the areal site. 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 in the areal site using a repeated measures analysis of variance (ANOVA) with plot as the subject. In the buffer all the above characteristics were compared between stand types (mature, mature/burned, plantation) and across time since treatment (TST) using a 2-way repeated measures ANOVA, with TST as the within-subject variable and each plot as the subject. Assumptions of normality and equal variance were tested with the Shipiro-Wilk and Modified-Levene Tests, respectively, and Tukey-Kramer post-hoc comparison of means used when differences occurred.

Fire Behavior and Effects Studies

Two studies were conducted to evaluate fire behavior in masticated fuels. First, a laboratory-scale experiment was used to determine the effects of fuel loading and moisture content on fire behavior. Second, a field-scale experiment was employed to compare fire behavior and effects between mowed and unmowed sites, and to subsequently evaluate key ecological effects of mastication and mastication followed by burning.

For the laboratory-scale experiment, mowed surface fuels (excluding 1000h) were collected from the areal treatment site, 2-3 weeks after mowing, transported to the lab, and oven-dried at 50°C for 7-10 days. Eighteen circular fuelbeds (4m diam.) were created from the collected fuel and manipulated to achieve a 3x2 factorial experimental design, replicated 3 times, with 3 fuel loading treatments (10, 20, and 30 $Mg \cdot ha^{-1}$) and 2 fuel moisture content (FMC) treatments (low 9% and moderate 13%). Fuelbeds were tamped to achieve bulk densities similar to field-observations and averaged 6, 9, and 12 cm deep for the 10, 20, and 30 $Mg \cdot ha^{-1}$ treatments, respectively. Fuelbeds were created in a flat field with all grass removed down to the soil (fine sandy Grossarenic Paleudults) surface.

Fuelbeds were burned, using strip head fire, under warm (28-34˚C), moderately dry (46-63% RH), and light wind (0.3-1.8 $m \cdot s^{-1}$) conditions and each burn video recorded. Flame heights were visually estimated at 6 equidistant locations, from height poles placed in the fuelbeds, and rate of spread (ROS) calculated, for each burn. Surface temperatures were recorded from 3 Type K thermocouple probes equidistantly arranged perpendicular to the anticipated fire front. Soil temperatures were recorded from three 30-AWG Type K thermocouple wires inserted at 2, 5, and 8 cm beneath the fuelbed surface (center of the fuelbed). Fuel consumption was estimated from depth reduction measurements from 4 litter pins. Flame length was derived by dividing the average flame height from each burn by the sine of the average flame angle. Fireline intensity ($kJ\ m^{-1}\ s^{-1}$) was estimated for each burn as ROS × percent consumption × fuel load × fuel heat content (19,678 $kJ\ kg^{-1}$). Flame length, ROS, consumption, fireline intensity, maximum surface temperatures, and duration of lethal heating (≥60˚C) were compared across fuel load and FMC treatments (main effects and interactions) using a general linear model analysis of variance. To evaluate soil heating we tested main effects and interactions of fuel loading and FMC on soil temperatures across the 3 soil depths. Assumptions of normality and equal variance were validated using the Shipiro-Wilk Test and the Modified-Levene Equal Variance Test, respectively, and the Tukey-Kramer Test was used to determine differences amongst fuel loading. Temperature, RH, and wind speed (measured during each burn) were compared across all treatments and tested as covariates in all analyses to account for potential differences in weather conditions.

For field-scale experiments, 2 ha treatments (mow, mow+burn, burn only, and controls) were each replicated 3 times for a total of twelve 2 ha treatments. Mowing (mow and mow+burn) was conducted in Aug 2010, using a front-mounted mowing head on a Gyro-Trac, and burning (mow+burn and burn only) was conducted in Feb 2011 using strip-head-fire technique under mild weather conditions. To evaluate fire behavior and immediate fire effects, flame lengths and rates of spread were observed in 3 plot locations within each treatment during burning and fuel consumption and fire effects to trees (scorch and basal char) were quantified just after burns. Fire behavior and immediate fire effects were compared between mowed and unmowed treatments. To evaluate the overall effects of mowing and mowing followed by burning, fuels, vegetation, micrometeorology, and soil nutrients were compared across all treatments (mow, mow+burn, burn only, controls) following treatments. Fuels and vegetation (overstory, understory, shrubs, and groundcover) were quantified before and after treatments and again at one and two years following treatment. Air temperature and relative humidity (1 m above ground) and soil temperature were recorded continuously started at 2 months post mowing to 11 months following burning. Moisture contents of surface litter and live shrub foliage were measured every 3 to 4 weeks from 4 months post-burning to one year post burning. Soil nutrients were sampled from all treatments just prior to burning and again 1 yr following burning. Decomposition rates of masticated debris (litter, 1h, and 10h) were estimated within decomposition bags placed in both mow and control sites, with rates compared between treated and non-treated sites.

IV. Key Findings

Fuels Characterizations

Mowing in pine flatwoods sufficiently reduced shrub and small tree biomass, but converted it all into dense surface fuels that were dominated by foliar biomass. The relationship between litter loads and depths were sufficient to use as a predictor of litter biomass in these sites. Since shrubs dominated the understory prior to treatment, tree basal area was not significantly affected. In a mature pine site that hadn't burned in >10 yrs, mowed surface fuels (litter and fine wood) ranged from 9.6 to 35.6 Mg ha^{-1}, but with shallow fuel depths, ranging from 4 to 8 cm. Bulk density of these surface fuels were not only dense, but had additionally increased within the year following treatments.

Surface fuels created by mowing also differed across stand types (plantations, recently burned mature sites, and mature sites that hadn't burned in >10 yrs), likely attributed to differences in pre-mowing shrub and small tree biomass. In all stand types shrub regrowth was rapid following treatments and total fuel loading had actually increased in plantations within 16 months after treatment. Large diameter surface fuels were almost non-existent prior to mowing and were still rare following treatments; increases in 1000h fuels were most prevalent in plantations. Detailed results can be found in Kreye et al. (In Press) and Budny et al. (2013).

Fire Behavior and Fire Effects

From small-scale burning experiments, both fuel moisture and fuel loads influenced flame lengths and fire intensity, with drier fuels burning with taller flames and greater intensity, as expected, and fuel load steadily increasing flame lengths, but intensity only being less in the lowest of the fuel loads (10 Mg ha^{-1}). Rate of fire spread was influenced by moisture, with drier fuels burning faster, but was unaffected by fuel loads. Consumption was not influenced by treatments, but was high (>90%) across all laboratory burns. Average surface temperatures, ranging from almost 300 to 500 °C, and the long durations of lethal heating (>60 °C), ranging from almost 10 to 20 min, each steadily increased with fuel loading. Soil temperatures, however, never exceeded 60 °C, even as shallow as 2 cm and with soil moistures all being very dry. Nonetheless, soils did heat up more when surface fuels were burned under a drier moisture content and when fuel loads were high. Soil temperatures when 20 or 30 Mg ha^{-1} of mowed debris was burned exceeded those when only 10 Mg ha^{-1} of fuel was burned, but with no difference between the 2 higher fuel loads, reflecting a similar effect of fuel load on fireline intensity, the measure of energy output that likely influences soil heating. Detailed results of this study can be found in Kreye et al. (2013).

During field-scale burning, sites that were previously mowed burned with shorter average flame lengths (1.1 m) than sites that were unmowed (3.3 m), however flame lengths were more correlated with the recovering shrubs in these sites that with the amount of surface fuel created from the treatments conducted just 6 months prior to burning. Rate of fire spread did not differ between treatments, but conditions were mild (17-24 °C, 47-62% humidity, and <5 km h^{-1} winds). Percent litter consumption was high across all these burns (>80%), with no difference between treatments, but since mowed sites had higher pre-burn surface fuel, prior to burning more surface biomass was consumed in the mowed (10.6 Mg ha^{-1}) versus unmowed sites (7.6 Mg ha^{-1}). Litter moisture content was actually lower in the mowed sites (12%) versus the unmowed sites (18%) on the day of the burns. Percent crown scorch on trees varied from 0-100% on an individual tree basis, but when averaged on a plot basis did not differ between treatments. Basal charring, however, was marginally greater in sites that were not previously mowed. One year following burns, almost all of the 116 trees examined had survived except for two small-diameter pines in the burn only treatments. When observed fire behavior was compared to modeled fire behavior, using the BehavePlus fire modeling system (Andrews et al., 2008), average model error rates for flame lengths were similar between mowed and unmowed sites (~45%), however error rates of rate of spread were higher in mowed (66%) versus unmowed (53%) sites and error rates of fireline intensity were much higher in mowed (89%) versus unmowed (23%) sites. Detailed results can be found in Kreye (2012).

Ecological Effects of Mowing and Burning

No treatments (mow, burn only, or mow+burn) influenced the overstory in the mature pine flatwoods sites. Tree density, basal area, and quadratic mean diameter didn't differ between any of the treatments or the controls immediately following mowing, just after burning, or 1 yr following burning. Shrub density, however, was lower in the mowed sites soon after treatment, but when burns were implemented 6 months after mowing, shrub density had already recovered in the mow only sites, even though they were reduced in burn only and mow+burn sites. In contrast, saw palmetto density, although reduced by burning also, was still lower in the mow only sites versus controls at the time of burning. One year after burns, shrub density did not differ across any treatments, but saw palmetto density and cover were both lower in the previously mowed sites (mow and mow+burn) compared to the unmowed sites (burn only and control). At this stage, both saw palmetto density and cover did not differ between mow only and mow+burn sites, nor did it differ between burn only and control sites, indicating that mowing reduced saw palmetto, but burning, either alone or following mowing, had no effect.

Species richness of just shrubs and trees were only lower in burned sites (burn only and mow+burn) just after burning, with no differences one year later. Species richness of all groundcover plants also did not differ across any treatments 1 yr following burning. Groundcover, not including shrubs >50cm in height, was dominated by litter across all treatments regardless of sampling period. Small shrubs accounted for most of the remaining cover across treatments except in the burned sites just after burning where there was more bare ground. Vines, herbs, and grasses were rare across treatments, but there was some marginal evidence of increased grass cover in mow only and mow+burn sites one year following burning, but variation was quite high.

For up to six months following the August 2010 mowing treatments, and prior to burns, relative humidity (RH) was lower in the mowed versus un-mowed sites, however air temperatures did not differ among any treatments prior to burning. Following the February 2011 burning treatments, RH did not differ among treatments during the March to August growing season, however air temperatures were lower in the mow+burn sites versus controls, except during March. Between September and January 2011, 13 to 17 months following mowing and 7 to 11 months after burning, no differences were detected in air temperature or RH among all fuels treatments. Soil temperatures did not differ between treatments prior to burning, however after the burns, growing season (Mar-Aug) soil temperatures consistently ranked highest to lowest across mow+burn, burn only, mow only, and controls, respectively. In September, 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.

Litter and live shrub foliar moisture content differed between treatments up to about a year following the February burns, however it depended on what time of year it was. During the growing season (Jun-Aug) litter was wettest in the controls (13%), followed by mow only (10%), and then driest (7%) in the burn only and mow+burn sites, which did not differ. This trend generally occurred throughout the remainder of the calendar year, however during the wettest months (Sep-Dec), differences between treatments were the most pronounced and mow+burn treatments were actually drier than burn only treatments during this period. Live shrub foliar moisture, the primary driver of fire behavior in flatwoods, were higher in the burned sites (burn only and mow+burn) compared to the mow only and control sites, mow+burn sites having the highest moisture content of all, from about Jun to Sep, but after that differences aren't as apparent.

The only differences detected in soil properties or nutrient content was that exchangeable K within 0-5 cm was lower in mow+burn treatments compared to controls prior to burning and that base saturation of H within 0-5 cm was lower in burn only treatments compared to controls one yr following burns. There was no effect of mowing, burning, or mowing followed by burning in a suite of soil properties that we assessed.

Decomposition rates of masticated debris (placed in decomposition bags) did not differ when located within mowed and unmowed sites. 74% of litter and 82% of 1h woody fuels remained after one year of decomposition. And 81% of 10h woody fuels remained after 10 months of decomposition. Detailed results of this work can be found in Kreye (2012).

V. Management Implications

Fuel Characterization

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 recovered to pre-treatment levels in as little as 16 months. Treatment effectiveness in this system may be short-lived due to this expedited recovery of shrub biomass, compounding 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. 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. 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. 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. 2010). 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.

Fire Behavior and Fire Effects

From small-scale burning experiments, results show the effects of fuel load and moisture content on the burning behavior of these unique fuels and the heating potential they may incur when burned. 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).

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 need to be considered when evaluating the ecological effects of these treatments. 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. The impacts of treatments on microclimate were minor, but treatment influences on 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.

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.

VI. Relationship to other recent findings and ongoing work on this topic

Surface fuelbeds following mowing in these palmetto/gallberry pine flatwoods were dominated by foliar litter, with a lower component 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). 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). 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.

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 in the laboratory studies conducted 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. 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 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. Higher woody fuel loading in these other studies likely contributed to the higher surface temperatures and much higher soil temperatures during burning, likely 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.

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. The field-scale experiments 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, a potential effect that may occur in other treated sites where shrubs resprout following treatment. Knapp et al. (2011) stated that moisture and burn patterns (heading vs. backing) were responsible for differences in fire behavior, not fuel loads, in masticated sites in California pine forests. Also, Kobziar et al. (2009) reported that variation in fire behavior was influenced by spatial heterogeneity of heavy surface debris and herbaceous ground cover as well as ignition patterns in pine plantations of California. Studies comparing actual fire behavior between treated and untreated sites are very rare. Besides this study, Bradley et al. (2006) showed that fire behavior was actually exacerbated by mastication treatments. 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, 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.

The immediate ecological effects mowing in this study were short-lived, suggesting that this ecosystem may recover quickly from such treatments, although long-term effects are unknown. The shrub vegetation stratum 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). Forbs 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). If saw palmetto were to continue to decline with these treatments, especially if treatments are used repeatedly, herbaceous cover might increase. 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. Instead they observed reduced dominance in saw palmetto and slightly increased importance of forbs and grasses. 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. When including all plant species into groundcover richness, however, marginal evidence in this study suggests that mowing increased species richness one year following treatment, yet burning alone did not. 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 (Kane et al. 2010). 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 mastication had no effect on overall diversity. Increased cover of forbs and grasses in masticated pinyon-juniper woodlands has been reported, but with 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. Longer term studies are needed to assess whether the minor differences observed in this study are persistent or ephemeral.

Decomposition of mowed residues may be an important factor regarding fuel dynamics in these treatments. Decomposition rates of surface litter here were slightly higher than that observed in pine plantations in the region (Gholz et al. 1985). The 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. 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.

Soils nutrients were generally unaffected by mowing treatments or prescribed burning. 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 this study. 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. 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.

VII. Future Work Needed

Mechanical mastication treatments are being widely implemented across the US, however much more research is need to understand the effectiveness of these treatments at mitigating fire hazard while meeting ecological goals across the many ecosystems and regions in which treatments are being employed. Additional research in this area should include:

- Further characterizing masticated fuels and their dynamics in other ecosystems where they are being employed;
- Determining the spatial heterogeneity of fuels within masticated sites;
- Evaluate the long-term efficacy of treatments at mitigating fire behavior by continuing to study sites that have been treated and where initial data exist;
- Quantify the effects of the emergent fuelbed properties in these unique fuels that influence important fire behavior metrics such as flame lengths, fire intensity, rates of spread, and heating;
- Determine the desired burning conditions in masticated sites where desired surface fuel consumption is accomplished while minimizing deleterious effects to the overstory;
- Determine the long-term ecological effects of mastication on moisture dynamics, soil nutrients, vegetation, and carbon sequestration;
- Evaluate smoke production and emissions from the burning of masticated debris; and
- Evaluate the long-term effects of mastication and burning in various treatment combinations over time.

VIII. Deliverables Cross-Walk

Proposed	Delivered	Status
Initial Workshop	2 initial workshops with Forest Service personnel	Completed
Annual Progress Reports for JFSP	Yearly	Completed
Presentation at Scientific Conferences	1) 4 oral presentations at national or international scientific conferences. 2) 4 oral presentations at local and regional meetings and a	1) Completed 2) Completed

	university seminar. 3) 3 poster presentations at scientific meetings	 3) Completed
PhD Dissertation	Jesse Kreye	Completed
Peer Reviewed publication	Kreye, Kobziar et al. *Immediate and short-term response of understory fuels following mechanical mastication in a pine flatwoods site of Florida, USA.* (Forest Ecology and Management)	*In Press*
Meeting with USFS Fire Managers (Local Workshop)	Results and Demonstration Site Planning	Completed, August 2013
Regional Workshop	SFE collaborative knowledge transfer workshop	Completed, September 2011
Peer Reviewed Publication	1) Kreye, Kobziar et al. 2013 *Effects of fuel load and moisture content on fire behaviour and heating in masticated litter-dominated fuels* (Int. J. Wildland Fire) 2) Kreye, Kobziar et al. *Altered fire behavior and effects following mastication in pine flatwoods ecosystems* (manuscript) 3) Brewer et al. *Fire behavior in masticated fuels: a review* (For. Ecol. Manage.)	1) Completed 2) *In progress* 3) *Accepted* with revisions (also associated with other JFSP projects)
Peer Reviewed Publication	Kreye et al. *Ecological effects of mechanical fuel treatments and prescribe burning on vegetation, microclimate, and soils in pine flatwoods ecosystems of Florida, USA.* (manuscript)	*In progress*
Photo Series Guide	Fuel Treatments in Pine Flatwoods: Photo Series Guide	Available on-line Dec. 1, 2013 (Southernfireexchange.org) and *In Press*
Final JFSP Report	JFSP Project ID 10-1-01-16	Submitted Nov. 1, 2013

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