ABSTRACT

QUINTANILLA BERJON, VERONICA. Fuel Loads, Prescribed Fire and Fire Effects in Longleaf Ecosystems: Analysis of Fuel Consumption and Mortality. A Case Study in the Calloway Forest Preserve, NC. (Under the direction of Dr. Joseph Roise, Dr. Glenn Catts and Dr. Heather Cheshire).

Land managers involved in longleaf restoration are increasingly using fire as management tool to restore and maintain this highly diverse and endangered fire dependent ecosystem. However, to achieve restoration goals it is necessary to better understand the relationships between stand conditions, fuel loadings, fire behavior, fire effects and ecosystem responses. This information would help to plan accordingly to reach short and long term management goals and avoid undesired fire effects (longleaf mortality).

In this case study, detailed analysis of pre, during and post burn conditions were conducted in a mature longleaf-wiregrass stand in the Calloway Forest Preserve (NC). Before burning a fuel loading inventory was conducted using two different fuel sampling methods, planar intersect (PI) and biomass collection destructive sampling. Estimates from both methods were compared for five different fuel types. Fire conditions and fire behavior were recorded and related with fire intensities and fire effects. Fuel consumption turned out to be higher than expected in the burn plan and an equation to predict forest floor depth removal was developed for future prediction. Fire intensity was found highly variable and hotter than expected. Fire severity effects analyzed in the overstory pointed to no direct association between percentage of crown scorched and tree mortality. Longleaf seedling mortality was found to be related with fire temperature and height; especially in seedlings between 0.3 and 1.5 m height and a mortality predictive model based on these variables was developed. Finally, a review of burn objectives and accomplishments was conducted and management recommendations based on fire effects were developed.

Fuel Loads, Prescribed Fire and Fire Effects in Longleaf Ecosystems: Analysis of Fuel Consumption and Mortality. A Case Study in the Calloway Forest Preserve, NC

by
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DEDICATION

I dedicate this thesis to my husband and close friends, who provided me with nothing but support and encouragement throughout this journey into the scientific word in a second language.

BIOGRAPHY

Veronica Quintanilla Berjon was born in a small town in Leon, Spain. She completed a Technical Engineering Degree in Forestry at the University of Leon (Spain) and a Forest Engineering Degree at the University of Lleida (Spain). As part of her B.S. thesis project, Veronica made an academic exchange with the University of Chapingo (Mexico), where she started developing her interest in wildland fire topics and focused her thesis research in the Evaluation of Forest Fuels through Geographic Information Systems (GIS).

Throughout her career Veronica has been closely involved with numerous Non-Profit Organizations focused in natural conservation and rural development and she loves working in sustainable community development. She is passionate about wildland fire and before moving to the United States to pursue her M.S. at North Carolina State University, she worked as a firefighter in a helitack crew in the North of Spain. She is planning to keep travelling and discovering new countries, cultures and languages while she continues working with wildland fire management and researching fire ecology and fire effects.

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CHAPTER 1: EVALUATION OF TWO FUEL SAMPLING TECHNIQUES FOR ESTIMATING SURFACE FUEL LOADING IN LONGLEAF ECOSYSTEMS.

ABSTRACT

Land managers are increasingly applying fire as a management tool and using fuel models as baselines for developing their fire prescriptions. However, fuel models do not capture the particularities of the stand being burned and therefore specific fuel sampling programs should be used to more accurately estimate fuel loads. This information would help to plan accordingly to reach short and long term management goals and avoid undesired fire effects (mortality). In this study, I tested two different fuel sampling methods, planar intersect (PI) and biomass collection destructive sampling, to obtain loading values for five different fuel types (litter, duff, wiregrass, fine woody debris (FWD) and course woody debris (CWD)) in a mature longleaf-wiregrass stand in the Calloway Forest Preserve, North Carolina. For each fuel type and total fuel load, I compared the differences in loads and the precision and limitations between methods. Results showed that total load estimates by the two methods were not significantly different before and after the burn; however, the individual estimations by fuel type had significant differences when computing coarse woody materials (CWM) before the burn and for all fuel types after the burn. The biomass collection sampling was rated as the more precise for horizontally continuous fuels (litter and duff) while the planar intersect had better estimates for fuels with patchy or irregular distribution (wiregrass and CWM).

Key words: fuel sampling, fuel loading, planar intersect, biomass collection, longleaf.

INTRODUCTION

In an effort to restore fire-dependent ecosystems and reduce hazardous fuel loads, forest managers are increasingly applying prescribed burning as management tool. Analysis, diagnosis and detailed planning are needed for every area where burning is contemplated. The fire prescription should include the amount of fuel, weather conditions and desired intensity of the burn, what will determine the firing technique and ignition pattern to use to meet the burn's objectives (Waldrop and Goodrick 2012). Fire weather conditions can be accurately monitored and fire techniques selected; however, fuel loadings cannot be chosen. Therefore, the ultimate management goals success depends on the appropriateness of the inventory and the knowledge and precision of the fuel loadings (Laverty and Williams 2000).

Although the forest floor may contain a large proportion of a site's biomass in many Southeastern ecosystems (Ottmar et al. 2007; Riccardi et al. 2007), generally there is no time or resources to adequately perform field work to characterize this mass. Several fire practitioners use their expertise or seek guidance in wildland fuel classifications (models) to help predict fire behavior and model fire severity effects (Anderson 1982; Lutes et al. 2009). However, these types of models, although useful, cannot capture the particularities and conditions of the stand being burned. Even under the same vegetation conditions, fuel loads can be highly variable in their distribution (within a plot or across the forest) due to the burn history and management activities of the forest (raking, treatments with herbicides, conservation of endangered species, etc). Due to this variability and the important role of fuels in fire behavior, developing an appropriate fuel inventorying and monitoring system is important to evaluate the fire effects and ecosystem's response, as well as the success of the short and long term specific management goals.

Designing an appropriate inventory, sample size and fuel-sampling protocol that accurately and efficiently assesses fuel loads is complicated. It requires a good knowledge of the different sampling methods as well as of the variables needed to meet monitoring goals (Keane and Gray 2013; Sikkink and Keane 2008). Sikkink and Keane (2008) and Catchpole and Wheeler (1992) conducted extensive comparisons between different sampling techniques to estimate fuel loadings and concluded that every method has strengths and weaknesses and therefore the selection of the most appropriate one is going to be a tradeoff between accurate results, resources and management objectives.

In this study, considering the resources available and the management objectives of the Calloway Forest, I conducted a fuel loading inventory using 2 sampling techniques: the planar intersect method (Brown 1971; 1974) and a biomass destructive sampling method. The overall objectives were (a) to compare both sampling techniques' precision in estimating fuel loadings, (b) to determine if their load estimations were significantly different, (c) to discuss their application benefits and limitations; and (d) to make recommendations for possible fuel sampling inventories to help monitoring fire effects and ecosystem responses in the area of study.

MATERIALS AND METHODS

Study Area

Calloway Forest

The study area is part of the Calloway Forest Preserve (2,837 acres), which is located within the threatened longleaf pine-wiregrass (*Pinus palustris - Aristida stricta*) ecosystem of the Sandhills region in Hoke County, North Carolina (Figure 1). Its northeastern portion is adjacent to Fort Bragg and is considered a critical area for the recovery of the Sandhills Red-cockaded woodpecker (*Picoides borealis*) (RCW) population. Since 2002, this forest has been owned and managed by The Nature Conservancy (TNC), a non-profit organization working around the world to protect ecologically important lands and waters for nature and people.

From the late 1980s to 2001 the Calloway Forest was primarily managed for pine straw production. In order to increase and facilitate straw harvest, oaks were cleared and herbicides (aerial application of Velpar ULW) were used extensively to prevent stump-sprouting. In addition, some timber was harvested in 50-100 acre clear cuts and fire activities were suppressed throughout the property. These greatly disrupted the structure of the longleaf pine-wiregrass ecosystem and reduced understory species' diversity (Calloway Forest Management Plan, unpublished 2012).

The area has a temperate climate with warm summers and cool winters. It receives an average yearly rainfall of 120 cm (47 inches) fairly well-distributed throughout the year (Southeast Regional Climate Center 2007). It is characterized by rolling hills with elevation ranging from 43 m (200 ft) to 150 m (500 ft) and predominantly porous sandy soils (Hudson 1984).

The Calloway Preserve includes 7 natural communities (Schafale and Weakley 1990). The upland portions of the forest contain a mosaic of Longleaf pine-Scrub Oak communities. Most of the area has an intact canopy of mature longleaf pine (*Pinus palustris*), established around 1920 with smaller pockets of younger stands replanted during the last 25 years. Turkey oak (*Quercus laevis*), is present in varying densities across the property, but is most prevalent at higher locations. At other locations dominant shrub species include bluejack oak (*Q. incana*), dwarf post oak (*Q. margaretta*) and blackjack oak (*Q. marilandica*). In the northeastern part of the property there are fewer scrub oaks and a higher density of legumes, which are indicative of Mesic Pine Savannas. Sandhills Streamhead Swamp and Streamhead Pocosin communities intermingle along the edges of the creeks and drainages that dissect the uplands. Pockets of Atlantic White Cedar (*Chamaecyparis thyoides*) are also present within the swamps and pocosins although they are not dominant and occupy the understory. Throughout side slopes of the uplands, there are also patches of fire suppressed, overgrown Sandhill Seeps.

These natural communities support a diverse array of wildlife, including rare and endangered species as red-cockaded woodpecker (*Picoides borealis*), bachman's Sparrow (*Aimophila aestivalis*), eastern Fox Squirrel (*Sciurus niger*), coachwhip snake (*Masticophis flagellum*) and michaux's sumac (*Rhus michauxii*) among others (Schafale and Weakley 1990).

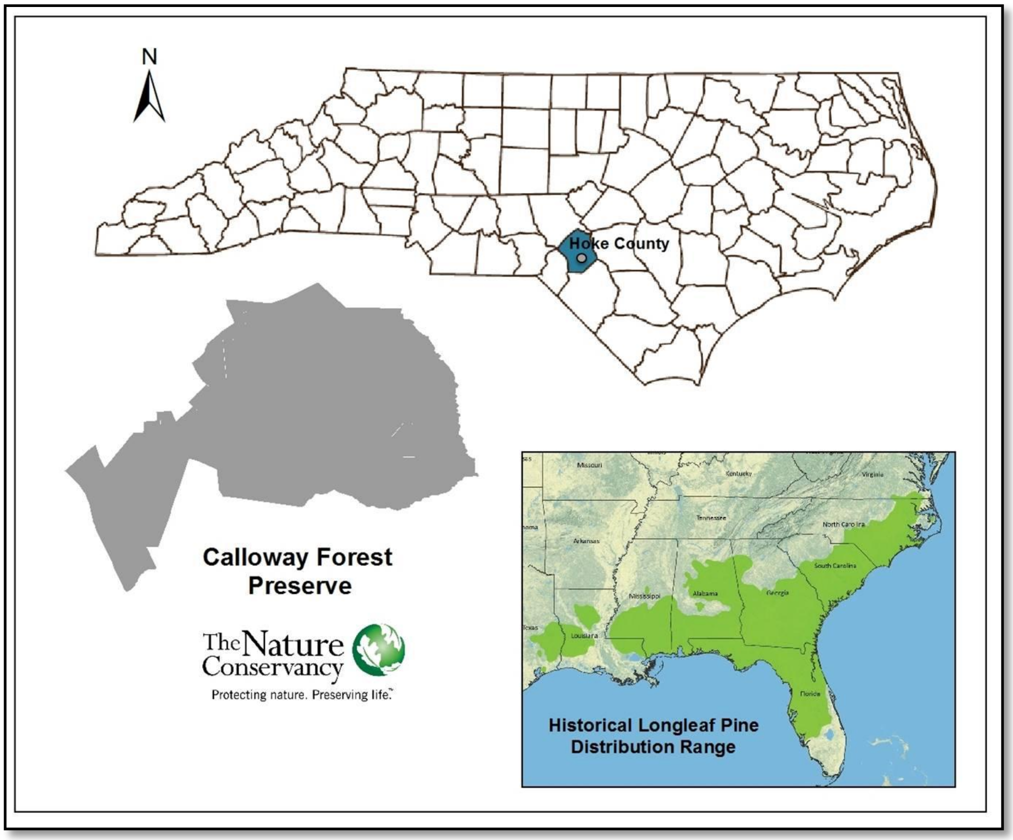

Figure 1: Calloway Forest Preserve location (Hoke County, NC) accompanied by historical longleaf pine distribution range.

Burn Unit fuels general description

The experimental burn was conducted in the natural longleaf portion of Burn Unit 27 (169 acres) (Figure 2). The area is a relatively uniform, open even-aged stand of mature longleaf pine savanna, established in 1921 (Calloway Forest Management Plan, 2012). The density of the stand varies in basal area from 40-110 ft^2/acre, with trees ranging in size from 25 – 56 cm (10”- 22”) diameter-at-breast-height (DBH). Due to management history of the forest, there was little hardwood understory. Groundcover was also sparse; however, native wiregrass (*Aristida stricta)* persisted, varying in coverage from about 5-50%.

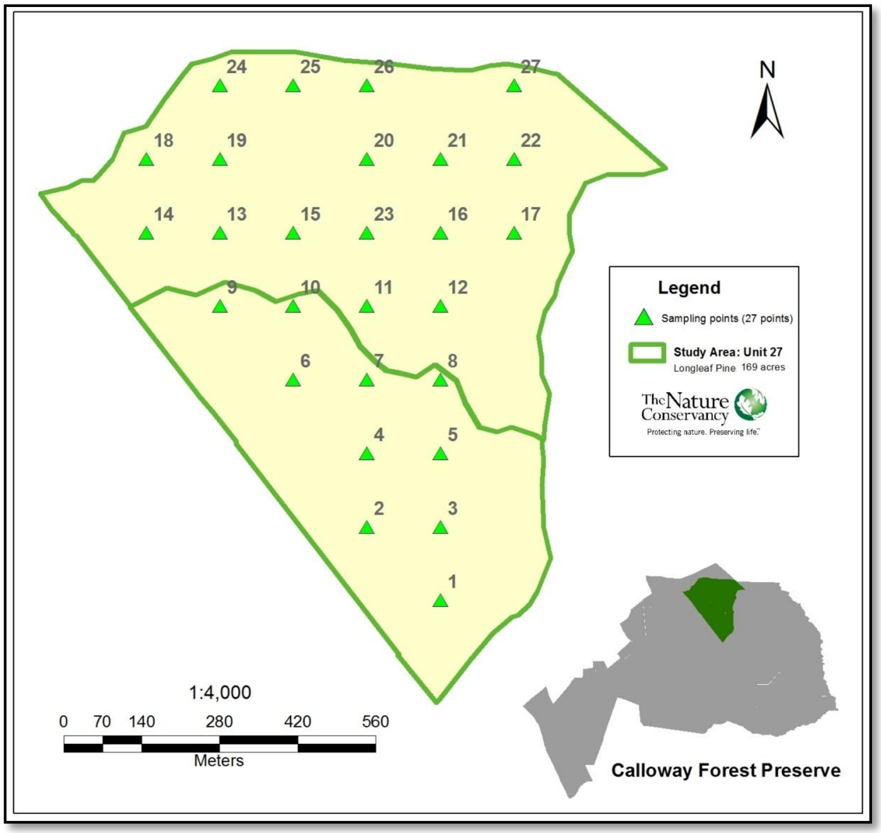

Figure 2: Study area (Burn Unit 27) with sampling points at Calloway Forest Preserve (grey), forest owned by The Nature Conservancy (TNC).

The majority of the surface fuels (main carrier of the fire) were longleaf pine litter (1-h fuels) and wiregrass (both live and cured). In general, duff accumulations were not big but still larger than expected due to the unit fire regime and type of soil. Some 10-h and 100-h fine woody debris was present; however, they were few and sparse. Snags and 1000-h coarse woody debris in different decompositions stages were also scattered. Some live shrubs and hardwoods, mainly turkey oak (*Quercus laevis*), were also present, especially in the northeast portion of the unit; however, due to the time of the year (dormant season), they did not have leaves. For the same reason, small quantity of herbaceous cover was observed. Neither the CWM nor the shrubs or herbaceous were active components carrying the fire.

Figure 3: Overview of general fuel types and distributions in burn Unit 27 at Calloway Forest.

In the last 11 years, the unit has been managed with frequent low intensity prescribed burns (every 2-3 years). Burn History: April 2003, April 2006, February 2008, March 2011 and March 2014 (TNC, personal communication 2015).

Analysis procedures

Fuel load definitions

In this study, 5 fuel types were sampled for estimating fuel loads: litter, duff, wiregrass, fine woody debris (FWD) and coarse woody debris (CWD). There is some controversy in the literature when referring to litter and duff definitions (Chojnacky et al.

2009); therefore, to avoid confusion while collecting the samples and interpreting the results, the fuel types in this study are defined as:

- *Litter*: top layer of the forest floor composed of loose debris of small diameter dead twigs, fruits, bark, recently fallen needles, dead matted grass and leaves that are little altered by decomposition. It is referred to as the L (litter) layer or as the Oi horizon in U.S. soil taxonomy (Ottmar and Andreu 2007; Reardon 2007) (Table 1).
- *Duff*: partially decomposed material above the mineral soil and beneath the litter layer. It is often referred to as the F (fermentation) and H (humus) layer or as the Oe (upper duff) and Oa (lower duff) horizons in U.S. soil taxonomy (Ottmar and Andreu 2007; Reardon 2007). In this study, both duff layers were collected together as one unique duff layer.

Table 1: Canadian and U.S soil taxonomy description correspondent to litter and duff definitions (lower & upper) (Reardon 2007).

Canadian System of Soil Classification (1998)	**U.S. Soil Survey (1975)**	**U.S. Soil Survey (2006)**	**Characteristics of organic material**
L	O1	Oi	Slightly decomposed and the original plant structure is recognizable
F	O1 or O2	Oe	Increasingly decomposed but the original plant structure is recognizable
H	O2	Oa	Highly decomposed and the original plant structure is unrecognizable

- *FWD*: woody pieces, not attached to live trees, with a diameter smaller than 7.62 cm (3 inches) at the point of intersection with the sampling transect (Woodall and Monleon 2008). They are divided in 3 time lag or diameter classes, which are related with the number of hours needed to dry enough to reach 63% of the difference between the initial moisture content and the equilibrium moisture content. (Pyne et al. 1996).

  - 1-h time lag fuels – particles with diameters <0.64 cm (<0.25 inches) in diameter.
  - 10-h fuels – particles between 0.64 and 2.54 cm (0.25–1.00 inches) in diameter.
  - 100-h fuels – particles between 2.54 and 7.62 cm (1–3 inches) in diameter.

- *CWD*: downed pieces of wood with a minimum small-end diameter of at least 7.62 cm (>3 inches). This class includes all logs and is also known as 1000-h time lag fuels.

  **CWM*: The sum of the FWD and CWD will be named coarse woody material (CWM) in future references in this study.

- *Wiregrass* (*Aristida stricta)*: Grass from the Poaceae family, common in this kind of longleaf ecosystem.

**Other live*: Other live fuels, including nonwoody herbaceous plants and woody shrubs were collected and separated from the rest when clipping vegetation in the biomass sampling.

Fuel load measurements

Surface and ground fuels were sampled before (January and February, 2014) and within one week from the prescribed burn (April, 2014). In the interim between the first inventory, the burn accomplishment and the post burn inventory, a couple of bad weather episodes happened resulting in increased amounts of branches (FWD) on the ground than those accounted for in the first inventory.

The field inventory was performed following two different methods:

1. *Planar Intersect (PI) method (Brown 1971; 1974).*

The planar intersect method is a variation of the line transect method that uses sampling planes instead of lines. It was originally introduced by Warren and Olsen (1964), made applicable to measure CWD by Van Wagner (1968) and adapted for sampling fine and coarse woody debris in forests by Brown (1971; 1974). It estimates volume rather than weight and biomass is calculated based on geometry and density characteristics. This method is commonly used in many inventories, research and monitoring programs because it is relatively fast, simple and cheap (Catchpole and Wheeler 1992; Chojnacky et al. 2004; Sikkink and Keane 2008; Woodall and Monleon 2006).

In this inventory, three 15.24 m (50 feet) transects were established and sampled at each plot. The first transect was located at a random azimuth and the other two were established 120° apart from each other. A total of 81 fuels transects were installed and marked for easy location in post-burn re-measurements. Total duff and litter depths (in inches) were measured at 4 points along each transect. FWD and CWD were sampled at different levels based on their time lag or fuel size class. 1-h and 10-h fuels were sampled (count) from 0 to 1.83 m (6 ft) along the transect, 100-h fuels from 0 to 3.66 m (12 ft); 1000-h fuels were separated into solid (S) and rotten (R) categories and sampled (measuring individual diameter) in the whole transect length. Wiregrass was measured as inches of grass intercepting the transect and afterwards computed to percentage coverage. The same procedure was followed for other live herbaceous and shrubs.

2. *Biomass samples collection.*

Destructive sampling is the most accurate method to estimate biomass at a specific sampling point (Catchpole and Wheeler 1992). However, to collect and process biomass samples requires significant amounts of time and money; therefore, this type of technique is not normally used when monitoring for management purposes.

In this study, one biomass sample was collected at each of the 27 plots using a 0.63 x 0.63 m (2.06 x 2.06 ft) plastic PVC pipe frame. The frame was randomly located at 7.6 m (25 ft) from the center of the plot (bearing recorded) and all the dead and live fuels from duff to 2 m (6.5 ft) above ground were clipped and collected separately by fuel type. Samples were weighed wet, placed in paper bags and oven-dried 5-7 days to a constant weight in a forced-air oven at 60-70°C (140-160°F). While drying, 3-5 bags were randomly selected and weighed every day to monitor changes in mass characteristics. When the dry weight was constant, samples were removed one-by-one from the oven and weighed as fast as possible to avoid changes in mass due to ambient humidity.

Because these were destructive samples, they were collected at 2 different random locations before and after the burn.

Fuel loading calculations

1. *Planar Intersect (PI) method (Brown 1971; 1974).*

Litter and Duff

To estimate the litter and duff loadings, measures of the depth of the layers were taken and published bulk density values were used to convert depth measurements to mass following the expression:

$$\text{Litter or Duff} = D \times \rho \times F \qquad (1)$$

Where D is the material depth (inches), ρ is the material bulk density (tons/acre/inch) and F is a conversion factor from tons/acre to Mg/ha (2.24170231).

Depth (D): measurements (inches) were taken at four points per transect, 3 transects per plot; therefore, mean depth plot values were based on 12 samples.

Bulk density (ρ): The PI method is simple to apply; however, there are some difficulties related with the bulk density of the fuels that are important to consider. First of all, bulk densities are not constant among forest types, age classes or locations; and are highly variable depending on weather conditions and time of the year. Secondly, values of the bulk densities of litter and duff are not available for all forest types. Many of the litter and duff density values published for North American species were limited to western forest types or species (Woodall and Williams 2005). Woodall and Monleon (2008) provided density values for Forest Inventory and Analysis (FIA) by forest type groups, including longleaf, based on the FIA’s phase 3 inventory (O'Neill et al. 2005); however, these constants are subject to revisions and the authors strongly recommend using local or regional values if available. After an experimental study conducted at the Savannah River Site (SC) (Maier et al. 2004), Parresol et al. (2005; 2006) published some bulk density conversion factors (tons/acre/inch) for Atlantic Coastal Plain forest, including mean bulk density conversion factors for longleaf (age > 20 years). The influence of stand age, basal area, site index and fire history were integrated when analyzing fuel components to develop the conversion factors; and therefore, they were considered the most appropriate to calculate litter and duff fuel loading for this study (Table 2).

Table 2: Atlantic Coastal Plain Longleaf bulk density conversion factors (tons/acre/inch) (Parresol et al. 2005).

	Litter layer			Duff layer		
	Mean	Std Dev	Std Error	Mean	Std Dev	Std Error
Longleaf (> 20 years)	2.4723	1.4165	0.151	7.531	3.4158	0.441

Fine woody debris (FWD) and coarse woody debris (CWD)

The coarse woody debris subcomponents were converted to biomass using formulas from Brown (1974). These formulas are design to compute biomass in tons/acre so the values were transformed a posteriori to Mg/ha (2.24170231).

$$\mathrm{FWD} = \frac{11.64 \times \mathrm{n} \times \mathrm{d}^2 \times \mathrm{s} \times \mathrm{a} \times \mathrm{c}}{\mathrm{L}} \qquad (2)$$

$$\mathrm{CWD} = \frac{11.64 \times \sum \mathrm{d}^2 \times \mathrm{s} \times \mathrm{a} \times \mathrm{c}}{\mathrm{L}} \qquad (3)$$

Where **11.64** is a conversion factor used to transform inch-ft to tons/acre (Van Wagner 1968), **n** is number of particles tallied in each size class along a line transect, **d** is the squared average quadratic mean diameter for the FWD size classes and the sum of squared measured diameter for CWD, **s** is wood specific gravity, **a** is the non horizontal angle correction factor included to adjust the probability of selection (because not all small branches lie flat on the ground), **c** is the “slope correction factor for converting weight/ac on a slope basis to a horizontal basis”, and **L** is the transect length in ft.

In his handbook publication, Brown (1974) proposed values for all these variables; however, they were estimated for western species and it would be inappropriate to use all of them for longleaf estimates. This is especially true for mean quadratic diameters and wood density. Previous research has shown that there are significant differences between the mean diameter in different species and time lag classes; therefore, appropriate specie values should be used (Anderson 1978; Harmon et al. 2008; Woodall and Monleon 2006; Woodall and Monleon 2010). This is also true in fuel wood density between different species, rot classes, and size classes (Van Wagtendonk et al. 1996). Woodall and Lutes (2005) showed that using inadequate density values can cause 5 % variation in biomass estimates. On the other hand, although decomposition is almost absent on western ecosystems, it plays an important role in the south, reducing wood density and accelerating the availability of the fuels (Harmon et al. 2008). Therefore, an adequate combination of initial density and decay factors should be chosen when determining specific gravity for each time lag class.

Table 3: Values used to transform inventory values (counts and volumes) to biomass (weight) following Brown's (1974) equations.

Size class (cm)	**d^2**		**s**	**a**	**c**	**L**	
	cm	(inches)				m	(ft)
0 - 0.64	-0.05	(0.020)	0.648	1.13	1	1.83	(6)
0.64 - 2.54	-0.58	(0.230)	0.680	1.13	1	1.83	(6)
2.54 - 7.62	-7.28	(2.866)	0.646	1.13	1	3.66	(12)
> 7.62 + sound	NA	NA	0.346	1.00	1	15.24	(50)
> 7.62 + rotten	NA	NA	0.204	1.00	1	15.24	(50)

For this study, the values shown in Table 3 were used. Longleaf average quadratic mean diameter values for 10-h and 100- hours were taken from the Woodall and Monleon (2010) and had a value of 1.22 cm and 4.30 cm respectively. After personal communications with Woodall, the 1-h value was established as 0.36 cm (Woodall and Monleon 2008). Appropriate, specific density values were found in Harmon et al. (2008). For FWDs, specific densities were obtained as a combination of wood density for each size class and an appropriate density reduction factor. For CWD, density reduction factors where estimated as mean values of decay class 1 & 2 (for solid = 0.346 g/cm3) and 3, 4 &5 for rotten (0.204 g/cm3) (Harmon et al. 2008). Average slope was below 5% for all 27 plots and therefore, the slope correction factor was 1 for all calculations ($c=\sqrt{1+(\%\ \text{slope}\div 100)^2}$). The only values found in the literature for non-horizontal correction factors were those proposed for Brown (1974) for western species (FWD= 1.13, CWD= 1).

Wiregrass

Wiregrass estimates were based on regression equations for Western species developed by Mitchell et al. (1987) to transform grass percentage cover into fuel loading:

$$\text{Grass (Mg/ha)} = \frac{9.0058 \times \text{Pct cover}}{100} \tag{4}$$

Where *Pct cover* is the horizontal projection of live or dead wiregrass cover intercepting the line transect (%).

2. Biomass samples collection

The individual oven dry mass of litter, duff, wiregrass, FWD, CWD and other live fuels collected at each plot was divided by the area of the sampling square and multiplied by a conversion factor to transform them to the landscape scale (Mg/ha).

$$\text{Biomass (Mg/ha)} = \frac{\text{Dry weight (g)}}{\text{sampling area}} \times 0.11861 \tag{5}$$

Where dry weight (g) is the weight of the dry sample minus the bag weight (g), sampling area= 4.2436 ft² and $0.11861 = \frac{0.000001102\ \text{Mg}}{0.0000229568\ \text{acres}} \times \frac{1\ \text{acre}}{0.404686\ \text{ha}}$.

Ash content estimation (subsample)

Because upper (Oe) and lower (Oa) duff layers were collected together, while processing the duff samples, large amounts of sand were observed mixed with the organic material and this significantly increased the weight of the sample. To separate them and account for the extra weight added by ash content, a sub-experiment was performed in the duff samples. All dry duff samples were sieved (4 mm size), and divided in two categories:

1. *Duff > 4 mm*: bigger materials, decomposing but with a more recognizable plant structure. This layer was a mixed of upper duff (Oe) and what some researchers are beginning to call "residual fuel" (old fuel that was not consumed in the last fire, but might not be necessarily duff yet) (Robertson, personal correspondence 2014).
2. *Duff < 4 mm*: materials that hypothetically should be part of the lower duff layer (Oa) where the majority of the ash content is normally concentrated.

Samples < 4mm were re-dried to a constant weight, then a subsample was collected, placed in a previously weighed porcelain dish, re-weighed and placed in a Lindberg muffle furnace at 440 °C (±40°C) until the specimen was completely ashed (around 24 hours). At that point, the dish was allowed to cool in a desiccator for 2 minutes and weighed. The mineral/ash content was determined as:

$$\text{Ash content (\%)} = (\text{Ash mass x } 100) / \text{dry sample weight (g)} \qquad (6)$$

Then, ash content percentage was subtracted from the < 4mm duff sample to estimate the new weight. Total duff loading was calculated as:

$$\text{Total Duff (g)} = \text{duff} > 4\text{mm (g)} + (\text{duff} < 4\text{mm - \% ash content) (g)} \qquad (7)$$

Data Analysis

Statistical analyses were performed using InfoStat version 2014p, Jump Pro 11.2, R 2.15.3 and SAS Enterprise Guide 6.1. For all analyses, the confidence level was 95%.

Fuel loading distribution

To understand the characteristics and distribution of fuel loadings at the unit level, some basic graphics and analysis were performed for each collection method. In addition, to better visualize the relationships between the different fuel loading types (variables) before and after the burn and the 27 sampling plots, a principal components analysis (PCA) (biplot) was carried out to find a new set of linear variables not correlated that would help explain the structure of variation and to analyze the join relations between observations and variables. The analysis was conducted with InfoStat version 2014p (free statistical software).

To complement the analysis, maps of the spatial fuel load distributions for both methods were developed using Inverse Distance Weighting (IDW) interpolation in Arc Map 10.2. Since the data available were not enough to make reliable correlations, this procedure was conducted only to help visualize distributions of the variables (high/low) and may not adequately represent values at any unmeasured locations. The 3 nearest sample points were used to perform interpolations at unmeasured locations, and output cell size was 5 meters.

Fuel loading: comparison between estimation methods

Preliminary statistical analysis showed that the majority of fuel types did not follow a normal distribution for either of the collection methods. In addition, an F test of homogeneity of variances was conducted to compare the variability between both methods. The test applied a Satterthwaite’s correction (significance level of 5%) for heterogeneous variances and results showed that variances were not equal in four (out of 6) fuel types. Due to the non-normal distribution of the data, the heterogeneous variances and the small sample size (n=27), it was decided that a non-parametric approach would be the most appropriate to analyze the data. Therefore, a bootstrapping (with replacement) was conducted to determine if the two methods were significantly different in their mean estimations, independently of their distribution characteristics.

Bootstrap is a fast method to overcome limitations due to small sample sizes or unknown distributions. It was introduced by Efron (1979) as a way for approximating the sampling distribution of a statistic using data from the sample study as a "surrogate population" (Singh and Xie 2008). The procedure consists in taking a "bootstrap" sample from the original sample and calculate the bootstrap statistics (mean, SD, etc). These steps are repeated many times to create a bootstrap distribution; then, after defining a confidence level (usually 95%), the bootstrap confidence interval is estimated by the cutoff values for the middle 95% of the bootstrap distribution. This method has been widely used to construct confidence intervals and, although still controversial, also to conduct hypothesis testing (Martin 2007).

Using Jump Pro 11.2, a bootstrap with replacement of the mean values (n=1,000) was performed for each fuel type. Then, a summary statistics of bootstrapping was generated as well as the bootstrapping Confidence Limits (percentile method, α=0.05). To determine if the mean values of both methods were significantly different for each fuel type, the bootstrap confidence limits at 95% were compared. If they overlapped, the methods were not significantly different. To complement the result, a test statistic and p-value were also calculated. Although, it is possible to estimate them following a simple bootstrap procedure, it was decided to perform a Mann-Whitney U-test instead, to compare results obtained with both approaches.

The Mann-Whitney U-test is the non-parametric counterpart of the t-test for two samples, so it does not assume normality or equal variances. It is used to test whether two independent samples of observations are drawn from the same distributions based on the ranked distributions. The analysis was conducted with InfoStat version 2014p (α=0.05).

When both methods disagreed in their results (post burn duff load), a more traditional approach was followed. First, a log transformation was performed to correct for non-normality and then a t-test was conducted to test the significance.

RESULTS

Fuel loading estimations and distributions

Fuel load estimates were calculated by fuel type for both sampling inventory methods at the plot level (detailed information in appendices B & C). Then, values were extrapolated at the landscape level (Mg/ha) to compute basic summary statistics for the unit and to visualize the spatial fuel load distribution.

At the unit level, pre-burn average total fuel loadings for the biomass sampling ranged from 8.64 to 36.67 Mg/ha with a mean value of 21.31 Mg/ha (9.51 ton/ac), while average values from the PI method ranged between 8.07 and 52.56 Mg/ha with an mean value of 24.11 Mg/ha (10.76 ton/ac) (Table 4).

Table 4: Estimated fuel loadings in Mg/ha (values in tons/acre in parenthesis) for fuel type and sampling method (n=27) before the prescribed burn.

Burn Status: Pre Burn

		Fuel loadings Mg/ha (ton/ac)							
Method	**Fuel Type**	**Mean**		**S.E.**	**Var**	**Min.**		**Max.**	
Biomass Collection	Litter	11.53	(5.15)	0.67	12.02	4.33	(1.93)	17.51	(7.81)
	Duff	7.50	(3.35)	1.19	38.26	1.48	(0.66)	22.44	(10.01)
	Wiregrass	1.05	(0.47)	0.31	2.53	0	(0)	5.4	(2.41)
	CWM	0.85	(0.38)	0.3	2.38	0	(0)	6.37	(2.84)
	Other	0.38	(0.17)	0.16		0	(0)	3.33	(1.49)
	Total Fuel	**21.31**	**(9.51)**	**1.37**	**50.76**	**8.64**	**(3.85)**	**36.67**	**(16.36)**
Planar Intersect	Litter	11.93	(5.32)	1.12	33.72	3.88	(1.73)	25.49	(11.37)
	Duff	9.50	(4.24)	1.27	43.67	1.69	(0.75)	25.32	(11.29)
	Wiregrass	0.21	(0.09)	0.03	0.02	0.01	(0.004)	0.60	(0.27)
	CWM	2.48	(1.11)	0.62	10.48	0	(0)	14.32	(6.39)
	Other	0	(0)	0		0	(0)	0	
	Total Fuel	**24.11**	**(10.76)**	**2.02**	**11.44**	**8.07**	**(3.60)**	**52.56**	**(23.45)**

Table 5: Estimated fuel loadings in Mg/ha (values in tons/acre in parenthesis) for fuel type and sampling method (n=27) after the prescribed burn.

Burn Status: Post Burn

		Fuel loadings Mg/ha (ton/ac)							
Sampling Method	**Fuel Type**	**Mean**		**S.E.**	**Var**	**Min.**		**Max.**	
Biomass Collection	Litter	3.32	(1.48)	0.28	2.15	1.23	(0.55)	7.17	(3.20)
	Duff	5.4	(2.41)	0.9	21.73	0	(0)	22.72	(10.14)
	Wiregrass	0	(0)	0	-	0	(0)	0	(0)
	CWM	0.48	(0.21)	0.09	0.2	0	(0)	1.65	(0.74)
	Other	0	(0)	0	-	0	(0)	0	(0)
	Total Fuel	**9.2**	**(4.10)**	**1.11**	**33.07**	**1.29**	**(0.58)**	**29.12**	**(12.99)**
Planar Intersect	Litter	0.73	(0.33)	0.07	0.15	0.14	(0.06)	1.52	(0.68)
	Duff	3.27	(1.46)	0.49	6.49	0	(0)	8.02	(3.58)
	Wiregrass	0	(0)	0	-	0	(0)	0	(0)
	CWM	2.77	(1.24)	0.55	8.27	0	(0)	13.65	(6.09)
	Other	0	(0)	0	-	0	(0)	0	(0)
	Total Fuel	**6.79**	**(3.03)**	**0.89**	**21.36**	**0.57**	**(0.25)**	**20.99**	**(9.36)**

Post-burn fuel loadings range values were 1.29 to 29.12 Mg/ha with a mean value of 9.2 Mg/ha (4.10 ton/ac) for the biomass sampling and 0.57 to 20.99 Mg/ha with a mean value of 6.79 Mg/ha (3.03 ton/ac) for the PI (Table 5). Pre and post total fuel load mean estimations were very similar in the two methods. A larger range was detected in the PI method which reported slightly higher values for the pre-burn loadings (2.8 Mg/ha) and slightly lower with the post-burn estimates.

When breaking total fuel loading into individual fuel types, larger variations in the estimations and distribution of the components were observed. Before the burn, the major fuel load components were litter (approximately 50% of the total) and duff. CWM estimations were very different between methods ranging from 0 to 6.37 Mg/ha in the biomass sampling to 0-14.32 Mg/ha in the PI method. A similar but reverse situation happened with the wiregrass with values ranging from 0-5.4 Mg/ha (2.41 ton/ac) in the biomass sampling method and from 0-0.6 Mg/ha (0.27 ton/ac) in the PI (Figure 4).

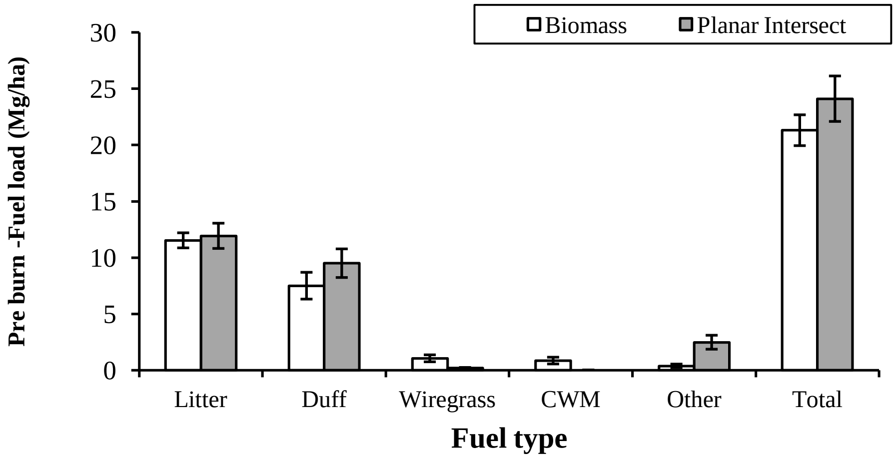

Figure 4: Pre burn mean fuel loads (Mg/ha) and SE by fuel type and method of estimation.

After the burn, larger variations between estimates by method were observed with consistent smaller consumptions reported by the biomass collection method. Although both agreed that duff was the higher fuel type left, the estimates reported were very different. The biomass method reported a smaller consumption with 5.4 Mg/ha (2.4 ton/ac) left while the PI estimated 3.27 Mg/ha (1.46 ton/ac). A similar situation was observed in litter values but with even bigger differences. According to the biomass method, CWM were reduced to half after the burn, while PI reported an increase of 0.3 Mg/ha (0.13 ton/ac) after the event. This big discrepancy between methods might be due to the sample size of the biomass collection (too small to capture a representative fraction of the CWM distribution across the landscape) and the fact that biomass samples were collected at different spots before and after burning, while PI measurements were performed at the same locations. Wiregrass was reported as totally consumed in both methods (Figure 5).

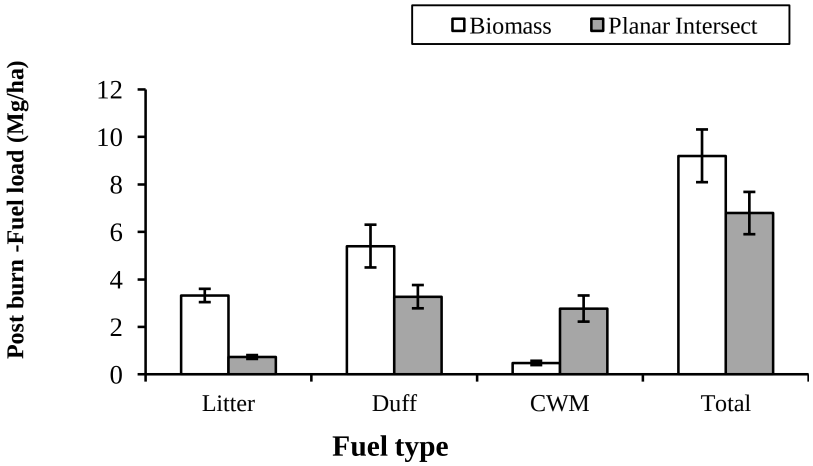

Figure 5: Post burn mean fuel load (Mg/ha) and SE divided by fuel type and method of estimation.

The biplot graphic (Figure 6) obtained from the Principal Component Analysis (PCA) was able to explain 65% of the total variability in the observations with two axes or components (PC1-PC2).

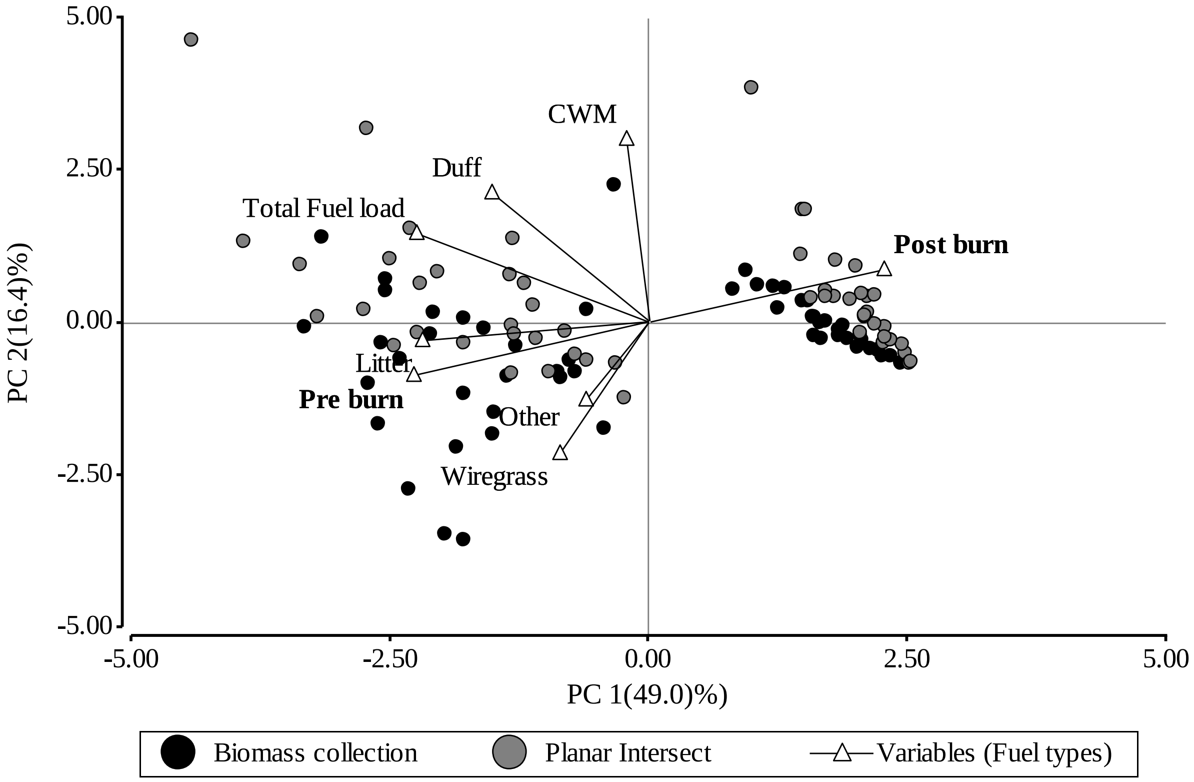

Figure 6: Biplot obtained from Principal Component Analysis (PCA) of fuel loading observations and variables in the 27 sampling plots before and after the burn. Principal components 1 and 2 are able to represent 65.4% of the variation between samples.

As expected, both methods had less dispersion in estimations after the burn and their values were lower than pre burn measurements. The first component (PC1) separated pre and post values from the other variables (180° angle, strongly negatively correlated) showing that the greater variability between loads was found when comparing estimations before and after the burn. Although all pre burn observations for both methods showed a larger dispersion, the PI method seems to have a bigger variability and some outliers that are also evident in the post burn observations (plots 4 and 5). The biplot confirmed a strong positive relationship between total fuel load and litter/duff and a small correlation with the other fuel types before the burn, especially with the CWM. This corresponds with a good representation of the observed fuel distribution and abundances in the unit.

In general, pre burn fuel load distribution maps showed that both collection methods yield higher average loads in the center and northwest portions of the unit; however, several differences arose between them (Figure 7). The biomass collection method suggested larger fuel loads in plots 7, 11, 12, 14 & 23, while PI pointed to plots 5, 6, 8, 12, 14, 18 & 23 as the plots with higher accumulations. In the case of plot 6 differences were due to CWM loads, with 14.32 Mg/ha (6.4 ton/acre) estimated by the PI and 0.17 Mg/ha (90.07 ton/acre) by the biomass collection. In plot 8 the discrepancy was observed in duff loads (PI 25.3 Mg/ha (11.3 ton/acre), biomass collection 4.36 Mg/ha (1.9 ton/acre)) and in plot 12 in wiregrass (PI0.4 Mg/ha (0.2 ton/acre) and biomass collection 2.75 Mg/ha (1.2 ton/acre)).

Post burn spatial fuel load distributions for the two methods showed higher fuel loads after burning in the same places where accumulations were larger before the burn, with the exception of the northeast area (plots 17, 22 & 27) (Figure 8). In this portion consumption seemed to be lower, maybe because that was the point where ignition started in the morning (with lower temperatures and higher RH %) and fire intensity was lower. Due to the variable fire behavior, consumption patterns are different across the unit and particularities can be found at each plot (see appendix C for detailed information).

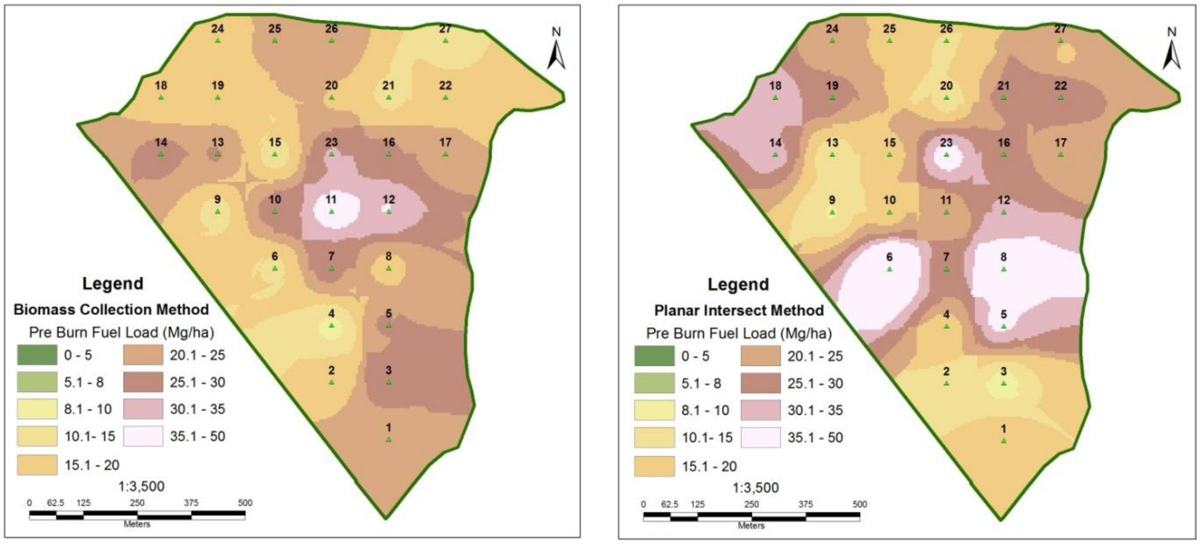

Figure 7: Maps of pre-burn fuel load estimates (Mg/ha) using biomass collection (left) and planar intersect (right) methods.

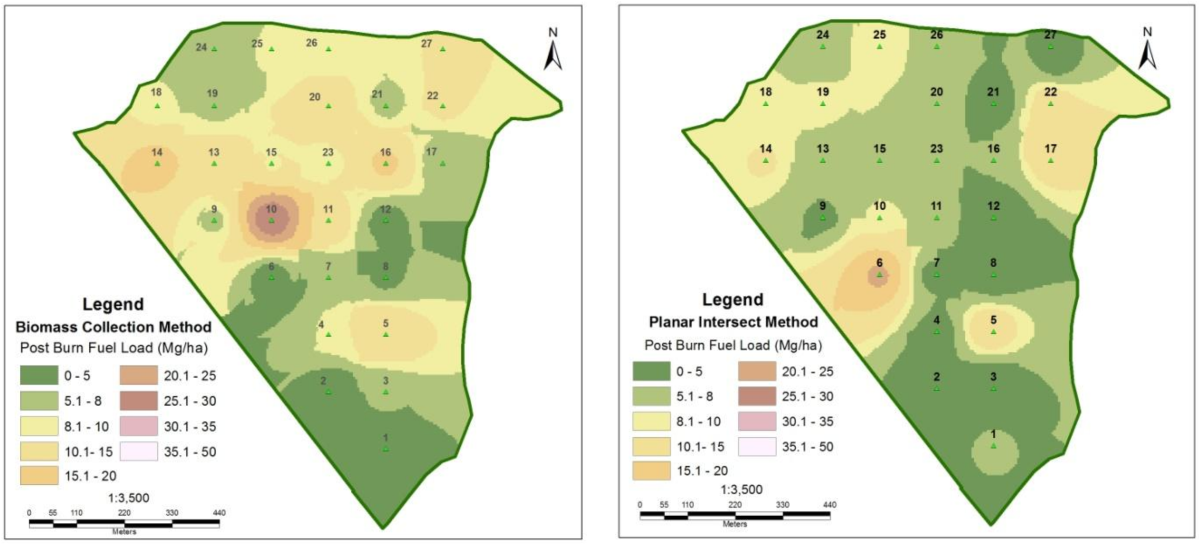

Figure 8: Maps of post-burn fuel load estimates (Mg/ha) using biomass collection (left) and planar intersect (right) methods

Fuel loading: comparison between estimation methods

A comparison between means (and SD) before and after the burn was performed to visualize central tendencies and variability (Figure 9).

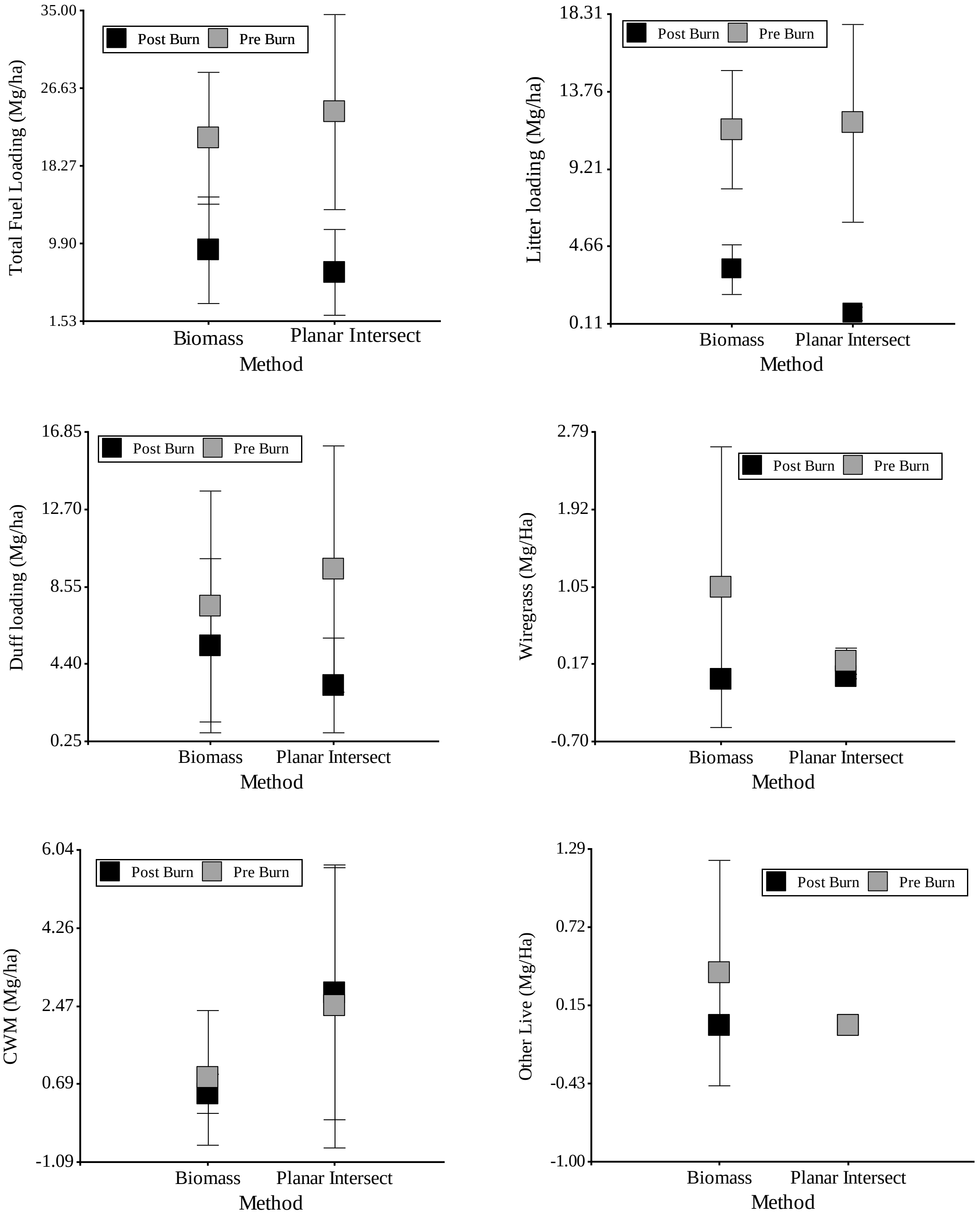

Figure 9: Comparison of mean total fuel load estimations and SD by collection method and fuel type before and after burning.

These graphs help visualizing mean estimations and SD for both methods and all fuel types; however, conclusions cannot be drawn directly from their interpretation due to the non-normal distribution of the data and the small sample size.

Bootstrapping was conducted to overcome the small sample size and unknown distribution. The bootstrapping confidence intervals for the fuel types collected before the burn overlapped in litter, duff, wiregrass and total fuel estimates; therefore, I concluded that with a 95% confidence level, both PI and biomass estimates were not significantly different for pre burn estimations of these fuels (Table 6). However, CWM confidence intervals did not overlap and therefore the techniques were significantly different in this case. A comparison was not possible for other live fuels since none were collected with the Planar Intercept method.

Table 6: Bootstrap summary statistics for all fuel types present before the burn. CL=95% Bootstrap Confidence intervals (α=0.05), n=27, re-sampling size=1,000 Samples marked in red are significantly different.

Burn status: Pre burn

	Estimation Method							
	Biomass collection				Planar Intersect			
Fuel Type	**Mean**	**Std Dev**	**CL Lower**	**CL Upper**	**Mean**	**Std Dev**	**CL Lower**	**CL Upper**
Litter	11.510	0.666	10.203	12.803	11.916	1.075	9.874	14.040
Duff	7.506	1.189	5.374	10.116	9.492	1.244	7.316	12.068
Wiregrass	1.049	0.293	0.514	1.644	0.208	0.026	0.158	0.262
CWM	0.844	0.289	0.336	1.379	2.488	0.612	1.469	3.781
Other	0.387	0.155	0.125	0.732	-	-	-	-
Total Fuel	21.313	1.314	18.722	24.137	24.108	2.022	20.286	28.143

Confidence intervals of the fuel loading values collected after the burn overlapped in duff and total load estimations but neither in litter or CWM (Table 7). Therefore, with a 95% confidence level, I concluded that the methods were not significantly different for duff and total fuel loading post burn estimations while they were significantly different for the rest of the fuel type's estimations.

On the other hand, the difference in size between confidence intervals by method (before the burn) were systematically larger in the PI method, suggesting that the variance of estimating using this method was larger than that resulting from using the Biomass method. That was not true for estimations after the burn, but it is possible this is due to the small amount of fuels left after the burn.

Table 7: Bootstrap summary statistics for all fuel types present after the burn. CL=95% Bootstrap Confidence intervals (α=0.05), n=27, re-sampling size=1,000. Samples marked in red are significantly different.

Burn status: Post burn

	Estimation Method							
	Biomass collection				**Planar Intersect**			
Fuel Type	**Mean**	**Std Dev**	**CL Lower**	**CL Upper**	**Mean**	**Std Dev**	**CL Lower**	**CL Upper**
Litter	3.320	0.273	2.817	3.884	0.723	0.073	0.585	0.869
Duff	5.371	0.867	3.894	7.205	3.303	0.479	2.449	4.231
CWM	0.475	0.084	0.317	0.640	2.766	0.546	1.799	3.921
Total Fuel	9.228	1.109	7.179	11.621	6.804	0.881	5.004	8.632

The Wilcoxon-Mann-Whitney test results agreed with all the conclusions obtained in the previous analysis except post burn duff. Total fuel loads did not show any significant difference when comparing the loads before and after the burn (pre-burn p-value= 0.5856, post-burn p-value=0.0933) (Table 8). However, when analyzing the different fuel components individually before the burn, the test confirmed that litter, duff and wiregrass load estimates were not significantly different while CWM estimations were significantly different in both methods (p-value= 0.0103). In this case, duff estimations after the burn were significantly different between methods (p-value= 0.0475). These results differed with the conclusion obtained with the bootstrapping confidence limits; therefore a third testing (t-test) was performed following a more traditional approach. The t-test results (p-value= 0.0267) agreed with the Wilcoxon-Mann-Whitney and I concluded that both methods were significantly different for post burn duff observations.

Table 8: Wilcoxon-Mann-Whitney U test for significant difference between fuel types collected with two different methods. Methods: Biomass collection=1, Planar Intersect=2, n=27. W=standardized version of the statistic W based on the asymptotic distribution of the same.

Burn Status	Variable	Mean(1)	Mean(2)	SD(1)	SD(2)	Var(1)	Var(2)	W	p(2 tails)
Pre Burn	**Litter**	11.53	11.93	3.47	5.81	12.02	33.72	774	0.5856
	Duff	7.5	9.5	6.19	6.61	38.26	43.67	639	0.0730
	Wiregrass	1.05	0.21	1.59	0.15	2.53	0.02	701	0.4679
	CWM	0.85	2.48	1.54	3.24	2.38	10.48	595	0.0103
	Other	0.38	0	0.83	0	0.68	0	877.5	0.0006
	Total Fuel	21.31	24.11	7.12	10.51	50.76	110.44	691	0.3729
Pos Burn	**Litter**	3.32	0.73	1.47	0.39	2.15	0.15	1097	<0.0001
	Duff	5.4	3.27	4.66	2.55	21.73	6.49	857	0.0475
	CWM	0.48	2.77	0.45	2.88	0.2	8.27	469	<0.0001
	Total Fuel	9.2	6.79	5.75	4.62	33.07	21.36	839.5	0.0933

Variance values for both methods were also included in the summary statistics. The high values of the mean variances suggested an over dispersion in all scenarios and pointed to PI as the method with more variability and therefore less precise.

DISCUSSION

This study indicates that pre bun total fuel loading estimates at burn unit 27 in the Calloway Forest have a mean value between 21.31 and 24.11 Mg/ha (9.51-10.76 ton/acre) depending on the estimation method. At a first glance, these values appeared to be high compared with a recent fuel study conducted in the same area (Strand et al. 2013). However, a deeper analysis of the differences revealed that inventory design, fuel definitions and measurements were different between studies, especially in duff loadings, and therefore, the outputs are not comparable. Additional literature reviewed showed that estimations were not inconsistent with other values found in similar ecosystems with the higher loadings coming from the litter and duff components (Evans 2012; Lashley 2014; Robertson 2014; Scholl and Waldrop 1999); 54-49 % and 39-39%, respectively in this study.

Annual litterfall in longleaf pine stands older than 20 years has been estimated to be about 4.8 Mg/ha (2.14 ton /acre) (Gresham 1982; Roise et al 1991), which corresponds with litter loads found after 3 years in the study area (11.5 Mg/ha (5.1 ton/acre)). In addition to this load, it is important to consider the litter decay rates and presence of unburned litter from the last burn (Bale 2009). When modeling litter accumulation rates after a fire (Olson 1963), fire behavior (Behave plus software) or fire effects (FOFEM & Consume software), total combustion of the litter mass is assumed, but this only occurs in the most intensive fires. The burn management of this unit during the last 11 years has been based on frequent low intensity fires and therefore, it is expected to have litter left unburned from the last fire. On the other hand, burns had been conducted in the dormant season, with relative high moisture and ash content in the duff layer, especially in the lower duff, that would translate in low smoldering consumption rates of the organic matter (Garlough and Keyes 2011). This is congruent with the results observed, where around half of the available duff was left unburned (3 to 5 Mg/ha (1.5-2.5 ton/acre)). Hence, amount of duff in the unit, although not expected to be high, will build up in past “old” unburned litter and influence the new litter accumulations, decay conditions, variable relative humidity and ash content of the proper duff layer. Considering these factors, previous research and that both methods yielded close estimates; I consider the overall fuel loadings estimates in this study to be a representation of the fuel mass, with some errors and limitations due to sampling mistakes and personal bias. However, I recommend treating the duff load estimations with caution, since measurements related to them have higher uncertainty and inaccuracy.

Comparison between biomass collection and planar intersect (PI) estimates showed that the two methods were not significantly different when estimating total fuel loadings before (p-value = 0.3729) and after burning (p-value = 0.0933) but they had significant differences in estimations of individual fuel types. Previous research has showed that the biomass collection method is the most precise when estimating continuous fuel loads; however, its precision decreases as the spatial variation of the fuels increases (Catchpole and Wheeler 1992). This is consistent with the results of this comparison, with the biomass estimates being more precise (smaller variance) when estimating continuous fuels.

When analyzing litter loads, pre burn results showed that the two methods' mean values were close, what suggests that they have similar estimation capabilities when measuring horizontally continuous fuels. However, ultimately, the precision of the PI estimation is going to depend on how appropriate the bulk density is for transforming the field data into mass estimations (Harmon et al. 2008; Keane and Gray 2013; Parresol et al. 2006; Woodall and Monleon 2006). In this case, the similarity between results points to the bulk density conversion factor proposed by Parresol et al. (2006) as appropriate for the area.

Differences between duff load estimations before and after burning were 2 Mg/ha (0.89 ton/acre), with the highest value reported by the PI method. This difference almost corresponds with the amount of ash content subtracted from the biomass samples in the laboratory. When measuring duff depths in the field following PI method, it was observed that at some point lower duff and sand were mixed; however, to mark that limit in a consistent way was complicated and ultimately depended on the field technicians. Similarly than with litter, total depth was transformed to biomass by multiplying the value by a bulk density conversion factor (Parresol et al. 2006); which means that a minimum depth overestimation can yield a huge increase of the load at the landscape level. For example, knowing that the duff bulk density conversion factor is 7.5310 tons/acre/inch, 1 tenth of an inch mistake (0.1") will result in 0.75 ton/acre or 1.69 Mg/ha overestimation at the landscape level. Therefore, when considering duff load estimates, some level of uncertainty should be taken into account due to inaccuracy in depth measurements and % of ash content.

Wiregrass estimates before the burn were not significantly different between methods; however, both sampling methods had significant limitations and it is suggested to review these values in future work. Some authors have pointed out that when collecting biomass samples, the precision of the estimates obtained from the sampling decreases as the spatial variation of the vegetation increases (Catchpole and Wheeler 1992). Wiregrass naturally distributes in a patchy pattern and giving the sampling size and limitations of the method, it is probable that the error in generalizing to a large area could have been substantial. The line intersect areal percentage coverage measured in the 3 transects from the PI method captured this variability; nevertheless, since height values of the grass were not measured, it was not possible to find adequate equations to transform those percentages into mass. Equations developed for western species were used (Mitchell et al. 1987) and therefore, estimations might not reflect the reality of the unit.

A similar problem might be reflected in the CWM estimations of the biomass method. The distribution and abundance of these types of fuels was better captured with the sampling design of the PI. In fact, Brown's method is used in many established fuel sampling protocols as the most appropriate for sampling CWM (Lutes et al. 2006; National Park Service 2003; Sikkink and Keane 2008; Woodall and Monleon 2008; Woodall and Williams 2005). An extensive literature review was conducted to find the appropriate quadratic diameters (Woodall and Monleon 2010), density and decay classes (Woodall and Monleon 2008; Woodall and Williams 2005) to convert the field data into mass values and therefore, I recommend their use for future work related with longleaf.

Post burn fuel load estimates for both methods corroborated previous statements and pointed to some interesting variability due to the natural dynamics of the ecosystem. Between inventories and after the fire, several bad weather episodes (snow, wind and rain) happened, altering the amount and distribution of the fuels. This was observed in the post burn inventory where unburned litter had been washed away by a storm the night after the burn. Both methods estimates reflect this episode but in a different way. The biomass sample was able to capture a bigger representation of the floor and therefore areas where fuels had been washed away were complemented with "extra" accumulations of litter. On the contrary, the PI method is based on measurements at specific points that, if affected by the water, might not have had any litter at all. This scenario agrees with the results of the estimations with

3.32 Mg/ha reported for the biomass collection and 0.73 Mg/ha by the PI. Evidence of alterations due to weather were also evident in the CWM (PI method), which estimates were higher after the burn than before (2.7 vs. 2.4 Mg/ha).

A deeper analysis of both sampling techniques and estimates has shown that even though total fuel loading estimates with both methods might not be significantly different; each method has different precision, strengths and weaknesses. It is important to consider that every method requires a different amount of money, time, equipment and training; these considerations might be the ultimate constraint when making a decision from a management point of view. In general the biomass sampling method is more precise, but it is more expensive and requires more time and training. Conversely, the PI method is less precise, but more economical and faster. To choose one method over the other in a fuel sampling monitoring program, will involve important tradeoffs between precision, time, money, training, scale, and effectiveness (Sikkink and Keane 2008) and the decision should be driven by the management goals and resources.

CONCLUSIONS AND MANAGEMENT RECOMENDATIONS

- Differences in total fuel load found among the two methods tested in this study are not large enough to say that they are significantly different; but, there are significant differences in terms of individual fuel types estimations, adequacy of the method and sampling efficiency related with cost, time and resources. Agreeing with Sikkink and Keane (2008) recommendations, I suggest land managers establish an acceptable precision for their sampling programs and select a sampling method based on their management goals, concerns, constraints, resources and desired short and long term fire effects.

- I also advise the consideration of the individual management necessities at both the unit and the landscape level to determine if different (or combined) methods might be appropriate to capture the fuel variability and particularities that are important to reach the desired fire effects. For example, if the goal is to reintroduce fire in a long unburned longleaf stand, specific measurements related to duff loadings and moisture should be considered when sampling. This detailed information of the particular characteristics of the stand will help planning how to conduct the burn to avoid undesired effects such as mortality in the overstory (Hood 2010; Kreye et al. 2014; Varner et al. 2007) . However, this deeper analysis might not be necessary in stands that have been frequently burned.
- Once a method has been implemented, I do not recommend changing plot sizes, number or locations just to save time or money (Sikkink and Keane 2008). The sampling method should not be changed either; although concrete measurements (such as duff moisture) can be included for a specific periods, basic measurement should not be altered. Changes on these factors will affect the long term monitoring effects and will end up in a waste of effort; therefore, I recommend to plan carefully and to consider the long term management goals and constraints before jumping into the field.
- Fuel inventories should be conducted as close as possible to the actual burn season to avoid big changes in loads, especially in living vegetation. If the inventory is performed in the dormant season but the prescribed burn will be conducted in the growing season, changes in the understory loads should be taken into account. This is especially important

in the South; where highly flammable species (for ex. gallberry (*Ilex coriacea*)) might be present increasing significantly the fire intensity.

- I do not recommend using the biomass collection method since it is too time-consuming, expensive and not practical from a management point of view (Catchpole and Wheeler 1992). I suggest that the planar intersect technique is used with Brown's equations to transform volume into mass. For longleaf, I recommend the variables selected in this study since they are suggested by recent research (Parresol et al. 2006; Woodall and Monleon 2010; Woodall and Monleon 2008; Woodall and Williams 2005). Although, it would be advisable to estimate a bulk density value for litter and duff specific for the Calloway Forest, the increase in precision might not justify the expenses; especially considering the error associated with variability at each unit and time of the year.
- When inventorying herbs, grasses, shrubs and other live fuels, I suggest the line intersect method (% cover) with the inclusion of the height measurement that will help transform values to biomass using the appropriate equations for southern ecosystems. If type of vegetation is also monitored for biodiversity purposes, the requirements can be different and a more detailed method might be needed. Time of the year for conducting the inventory should be planned accordingly.
- Finally, I recommend exploring additional sampling techniques when high precision might not be needed and particular constraints are not present. For example, Ottmar et al. (2000; 2003) successfully used stereo photo series and web-based digital photo series (2007) developed for longleaf communities in the Southeast.

CHAPTER 2: PRESCRIBED FIRE AND FIRE EFFECTS IN LONGLEAF ECOSYSTEMS: FUEL CONSUMPTION AND MORTALITY. A CASE STUDY IN THE CALLOWAY FOREST

ABSTRACT

Land managers involved in longleaf restoration use fire as a primary management tool to restore and maintain this highly diverse and endangered fire dependent ecosystem. However, to achieve restoration goals it is necessary to better understand the relationships between stand conditions, fire behavior, fire effects and ecosystem responses. In this empirical study, a detailed analysis of fuel and stand conditions was conducted before executing a prescribed burn. Then, fire conditions and fire behavior were recorded and correlated with fire intensities and fire effects. Fuel consumption turned out to be higher than expected in the burn plan and an equation to predict future forest floor depth removal was developed. Fire intensity was found highly variable and with higher temperature. Fire severity effects analyzed in the overstory pointed to no direct association between percentage of crown scorched and tree mortality. Longleaf seedlings mortality was found to be related to fire temperature and height, with higher mortality percentages observed in seedlings between 0.3 and 1.5 m tall; and a predictive model based on these variables was developed. Finally, a review of burn objectives and accomplishments was conducted and management recommendations based on fire effects were developed.

Key words: longleaf, fire behavior, intensity, severity, effects, consumption, temperature, height, seedling mortality, crown scorch.

INTRODUCTION

Longleaf pine (*Pinus palustris* Mill.) ecosystems were once one of the most extensive forest ecosystems in North America, dominating 92 million acres throughout the southeastern United States at the time of European settlement (Frost 1993). They are among the most species-rich plant communities outside the tropics (Peet and Allard 1993), containing several endemic, rare and endangered plants (Walker 1998) and key wildlife such as red-cockaded woodpecker (RCW). However, due to human exploitation and fire exclusion, they have become the third most endangered ecosystem in the United States (Noss et al. 1995) with a current extension of about 3.4 million acres (America's Longleaf Org. 2015).

Longleaf pine forests are one of the most fire-dependent communities in the U.S. (Henderson 2006) and therefore, fire is a requisite for its regeneration and perpetuation. Historically, frequent lightning and anthropogenic fires had maintained this ecosystem (Van Lear et al. 2005) whose structure and biodiversity was really affected by the fire exclusion policy in the 20th century. In the absence of frequent low-intensity fires, less fire adapted species invaded and replaced these communities (Ware et al. 1993), fuels started accumulating in the forest floor (Wade et al. 2000) and natural regeneration became harder due to the heavy grass and litter accumulations (Kush et al.2004; Provencher et al. 2001).

Recognizing the ecological and economic importance of these ecosystems, state, federal and private organizations such as The Nature Conservancy are promoting education, research and restoration of longleaf forests (Henderson 2006). Land managers involved in restoration of these habitats are using fire as a primary management tool. The success of this restoration depends on a balance of frequent small-scale disturbances to reduce fuel accumulations, lower competition and preparation of seedbeds for regeneration (Varner III and Kush 2004). To archive these restoration goals in longleaf ecosystems, it is necessary to understand the relationships between stand conditions, fire behavior, fire effects and ecosystem responses.

However, under apparently similar fuel and weather conditions, it is not unusual to have different fire behaviors, with unexpected high intensities, resulting in undesired fire severity and fire effects in the forest floor and on stand structure and composition. In April 2013, a prescribed burn was conducted in a naturally regenerated longleaf-wiregrass stand (24 ha, 58 acres) at the Crowley/Bowling Preserve, Sandhills, NC, owned by The Nature Conservancy (TNC). Weather was inside prescription guidelines and stand conditions and fuel loads seemed similar to other units burned within the area. Nonetheless, while burning, fire intensity was unexpectedly extreme and resulted in high fire severity effects that led to 85% tree mortality within 6 months. This unexpected result highlighted our lack of understanding of the interactions between fire behavior and fire effects, and pointed to the need to be able to measure whether prescribed burns are achieving the desired management objectives. The present case study was born based on that need, as an experimental way to refine our understanding of fuel load and weather interactions with fire behavior and resulting fire effects in longleaf ecosystems.

In open longleaf savannas, fire behavior and effects are closely linked to the characteristics of the forest floor fuels. Litter and duff can represent the majority of these fuels (Bale 2009; Waldrop and Goodrick 2012). In addition, wiregrass ground cover plays and important roll, carrying the fire and affecting the distribution and characteristics of the litter layer (Bale 2009; Hendricks et al. 2002). The structure created by grasses traps the longleaf needles beneath the canopy but above the soil surface hampering their decomposition (Hendricks et al. 2002), decreasing their moisture and increasing the oxygen availability between needles (Bale 2009; Wahlenberg 1946). Litter usually has low moisture contents, low bulk density, high volatile content, and high surface area fuels that help carry the fire and support flaming combustion fronts of high intensity but short duration (Fonda 2001; Hendricks et al. 2002).

The duff layer also plays an important role in fire effects, especially in temperate coniferous forests where duff tends to have patchy distributions and accumulates near the base of trees (Hille and Den Ouden 2005; Hood 2010; Varner et al. 2005; Varner 2005). The duff layer is characterized by high bulk density, abundant fungus, many fine roots and high moisture contents. Due to this, it burns relatively independent of wind direction and at very slow rates (smoldering) (Byram 1959; Miyanishi 2001; Nelson 2001; Varner 2005). That is commonly associated with elevated fire severity and undesired fire effects including soil damage, plant mortality, alteration of stand structure and species composition and noxious smoke emissions beside others (Hungerford et al. 1995; Ryan and Frandsen 1991; Varner 2005). Therefore, to better understand fire effects, it is necessary to know fuel load characteristics and availability because they will affect ignition and combustion, resulting in a mosaic of consumption and effects distributed across the burn unit.

Fuel consumption is an important first order fire effect (Reinhardt et al. 2001) since it is the source of the heat produced by the fire. It is directly related with fire intensity and depends on fuel availability (amount and moisture content). Previous research has confirmed a strong association between fuel consumption and moisture content, especially in duff (Ferguson et al. 2002; Goodrick et al. 2010; Hough 1978; Ottmar and Andreu 2007). Research has also shown the influence of weather conditions (Ferguson et al. 2002; Goodrick et al. 2010) and fire behavior (Kauffman and Martin 1989; Waldrop et al. 2004) on consumption. On the other hand, smoldering combustion is directly related with fire effects in the forest floor (Kauffman and Martin 1989), while fuel consumption in the flaming front is more associated with fireline intensity (Alexander 1982) and severity in the overstory (Alexander and Cruz 2012).

Relationships between fire intensity and fire severity in the overstory have been widely studied (Alexander and Cruz 2012; Regelbrugge and Conard 1993; Rothermel and Deeming 1980). Percentage of crown scorched has been shown to be a good predictor of post-fire tree mortality in several species (Borchert et al. 2002; Fowler and Sieg 2004; Kobziar et al. 2006; Ryan and Reinhardt 1988) and it is used as a predictive variable in modeling software such as FOFEM (Lutes 2014). However, due to the high tolerance of longleaf pine to fire (Hood 2010; Outcalt and Foltz 2004), it seems that crown scorch is not a good indicator of longleaf mortality (Wang et al. 2007) if bud kill is kept to a minimum (Wade and Johansen 1986), which is easier to achieve when prescribed fires are conducted during the dormant season (Sparks et al. 2002). Recent research also points to other variables such as relative humidity or environmental conditions (Goodrick et al. 2010), duff moisture (Ferguson et al. 2002; Varner et al. 2007), root mortality (Otrosina et al. 2002), burn season (Sparks et al. 2002) and external factors such as bark beetles (Campbell et al. 2008; Evans

2012; Sullivan et al. 2003) as more closely tied to mortality than fire severity effects in the canopy.

Not only mortality in the mature longleaf trees is important; mortality patterns in longleaf seedlings and saplings should also be taken into account since they are a key component for the long-term sustainability of the ecosystem (McGuire et al. 2001). Nevertheless, regeneration response to prescribed fire has rarely been evaluated. Although longleaf pine seedlings are extremely adapted to fire in the grass stage, once they are well established (Croker and Boyer 1975), they can still die. Few recent studies have studied the dynamics between prescribed fire and silviculture (Mitchell et al. 2006) and the possible links between fuel loadings, fire intensity and seedlings mortality (Gagnon et al. 2010; Knapp et al. unpublished 2014). However, these relationships are still unclear and more studies are needed to contribute expanding knowledge on this topic. For this reason, one objective of this case study is to analyze the relationships between mortality, seedling size and fire temperatures to further understand their dynamics and associations.

Considering all these factors and fire interdependencies, as well as the burn objectives for the experimental area, the overall objective for this case study is to analyze relationships between fire behavior and fire effects on (a) fuel consumption and (b) mortality in longleaf overstory and regeneration (seedlings); and to (c) assess the degree of fulfillment of the objectives established in the burn plan.

MATERIALS AND METHODS

Study Area

Calloway Forest: management goals

The study area is part of the Calloway Forest Preserve (2,837 acres), which is located within the threatened longleaf pine - wiregrass (*Pinus palustris* - *Aristida stricta*) ecosystem of the Sandhills region in Hoke County, North Carolina. Its northeastern portion limit is adjacent to Fort Bragg and is considered a critical area for the recovery of the Sandhills Red-cockaded woodpecker (*Picoides borealis*) (RCW) population (Schafale and Cantrell 1996). Since 2002, it has been owned and managed by The Nature Conservancy (TNC). From the late 1980s to 2001 the Calloway Forest was primarily managed for pine straw production and herbicides (aerial application of Velpar ULW) were used extensively to prevent stump-sprouting. During this period, fire activities were suppressed throughout the property, which greatly disrupted the structure of the longleaf pine - wiregrass ecosystem and reduced understory species diversity.

The mission of TNC is to preserve plants, animals and natural communities that represent the diversity of life on Earth by protecting the lands and waters they need to survive. In order to achieve this mission at the Calloway, TNC developed two main management goals for the forest: to maintain the viability of the existing RCW groups and expand the population as much as possible and to maintain, enhance, and/or restore the health of the natural communities and their full component of native species. To accomplish this, specific objectives were established, including the implementation of a prescribed burn program to support regular fire that is essential to longleaf pine - wiregrass ecosystems. The overall prescribed burn goal is to reintroduce fire with regular growing-season burns (approximately every 3 years) in order to mimic natural lightning and anthropogenic fire disturbance processes. Prescribed fire will help control hardwoods, spur flowering and propagation of wiregrass and other native, fire-dependent groundcover species, as well as open-up overgrown seeps and help the development of heterogeneous, multi-aged, old growth longleaf stands (Calloway Forest Management Plan, unpublished 2012).

Unit 27: Fire management and general burn objectives

The experimental unit (27) located in the eastern portion of the preserve is an even-aged stand of mature longleaf pine established around 1930. The unit is divided into 2 zones: a natural, relatively open longleaf-wiregrass savanna around 70-80 years old in the west portion (169 acres), where this study was conducted, and a longleaf plantation about 24 years old (53 acres) (Figure 10). Since 2003, the unit has been managed with prescribed fires every 2-3 years. The burns were conducted in April 2003, April 2006, February 2008, and March 2011. The overall fire management goal is to restore and maintain an uneven-aged longleaf pine savanna with wiregrass understory and patches of turkey oak to be suitable as forage habitat for Red-Cockaded Woodpeckers (RCW). General burn objectives for Unit 27 as specified in the Prescribed Burn Plan (TNC, unpublished 2013) were:

1. Provide for safety of fire crew and public.
2. Top kill 50% of the hardwood mid-story (DBH< 3").
3. Reduce fuel load by 50% or 1 inch in the 2 inches fine fuel layer.
4. Maintain flame lengths below 4-5 ft to minimize crown scorch and tree stress.

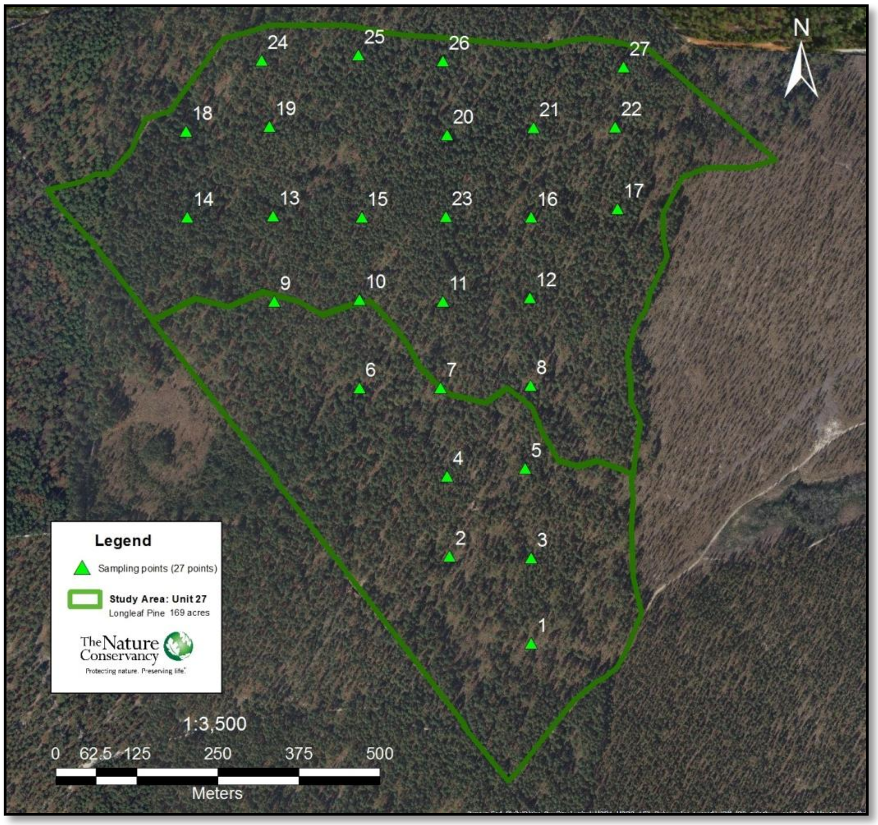

Figure 10: Study area limits with sampling points (n=27) and vegetation cover overview.

Field data collection and analysis procedures

Plot Establishment

Using a stratified random design based on visual density differences, a grid with 39 plots was created across the unit. Twenty-seven points were randomly selected from the total and their UTM coordinates were generated for field work. Minimum distance from roads was set to 50 ft. The procedure was performed using ArcMap 10.2 software.

Pre burn sampling inventory

The pre burn sampling inventory lasted from January 17 to February 6, 2014. At each plot, GPS coordinates, aspect, elevation and slope were recorded. For future monitoring, the center of the plot was permanently marked and 5 pictures were taken at 6.1 m (20 ft) from the center: 4 towards the cardinal points and 1 facing the tree canopy (appendix A).

Fuel load measurements

Five different surface and ground fuels were sampled: litter, duff, wiregrass, fine woody debris (FWD) and coarse woody debris (CWD). Two different methods were followed (for detailed information review Chapter 1, Fuel load measurements section, page 10 of this document).

1. *Planar Intersect (PI) method (Brown 1971; 1974):* Three 15.24 m (50 feet) transects were established and sampled at each plot. The first transect was located at a random azimuth and the other two were established 120° apart from each other. A total of 81 fuels transects were installed and marked for easy location in post-burn re-measurements. Duff and litter depths were measured in inches at 4 points along each transect (314 samples in the unit). FWD and CWD were sampled at different levels based on their time lag or fuel size class. 1-h and 10-h fuels were sampled (count) from 0 to 1.83 m (6 ft), 100-h fuels from 0 to 3.66 m (12 ft) and 1000-h fuels were separated into solid (S) and rotten (R) categories and sampled (measuring individual diameter) over the whole transect length. Wiregrass was measured as inches of grass intercepting the transect and afterwards computed to percentage coverage.
2. *Biomass sample collection (destructive sampling):* One biomass sample was collected at each plot using a 0.63 x 063 m (2.06 x 2.06 ft) plastic PVC pipe frame. The frame was randomly located at 7.6 m (25 ft) from the center of the plot (bearing recorded) and all the fuels from duff to 2 m (6.5 ft) above ground were clipped and collected separately by

fuel type. Samples were weighed wet, placed in paper bags and oven-dried (5-7 days) to a constant weight in a forced-air oven at 60-70°C (140-160°F), then re-weighed.

Understory measurements

Understory cover data were collected using the Line Intercept (LI) method along the same 15.2 m (50 ft) transects established to measure fuel loads. Along each transect, cover intercept was recorded to estimate percentage cover by life form (evergreen shrubs, deciduous shrubs, grass/grass-like, moss/lichen, ferns, other herbs/forbs, vines, boulder and bare ground). Individual species were identified when possible.

Overstory measurements

Data were collected for all trees with Diameter at Breast Height (DBH) ≥ 5.08 cm (2 inches) within a 1/10th acre (405 m^2) fixed radius plots. Tree species, DBH, height, crown class (dominant, codominant, intermediate, overtopped or suppressed), live status (live or dead) and damage code were recorded for all trees. Each tree was tagged and a map drawn with each location for future reference.

Regeneration measurements

Seedling tree data were collected for all species with DBH< 5.08 cm (2 inches) within a 1/100th (36.8 m^2) or 1/50th acre (73.6 m^2) fixed radius plots. All the individuals within the plot were tallied and data collection was divided by species, stem origin (resprout (R) or single (S)) and stem height class (Table 9).

Table 9: Height class codes for seedling trees (National Park Service 2003). Height was measured from the ground level to the highest point of growth of the tree.

Height class code					
1	< 0.15 m (0.5 ft)	**4**	0.62 - 0.92 m (2.1 - 3 ft)	**7**	2.74 - 3.66 m (9.1 - 12 ft)
2	0.15 - 0.31 m (0.5 - 1 ft)	**5**	0.92 - 1.83 m (3.1 - 6 ft)	**8**	3.66 - 4.57 m (12.1 - 15 ft)
3	0.31 - 0.62 m (1.1 - 2 ft)	**6**	1.83 - 2.74 m (6.1 - 9 ft)	**9**	4.57 - 5.49 m (15.1 - 18 ft)

Fire behavior observations and data collection (ROS, weather, moisture)

The prescribed burn was conducted in March 27, 2014. A test fire was started in 11:00 am at the northeast corner and firing finished at 16:30 pm in the southwest corner.

Fuel moisture measurements

Before the burn, litter (10-h), duff, wiregrass and 100-h fuel samples were collected at 3 points to estimate fuel moisture of the main carriers of the fire (Figure 11). Samples were collected following the Pollet et al. (2007) field guide, placed in a sealable bag, weighed in the field and stored in a cooler. During the burn, 5 additional litter samples were collected inside the unit at the same plot where fire behavior was recorded (2, 7, 12, 17 & 22). On the next day, all samples were placed in paper bags and dried to a constant weight in a forced-air oven at 60-70 °C (140-160 °F). Dry weight was recorded and fuel moisture estimated as (Zahn and Henson 2011):

$$\text{Moisture content } (\%) = \frac{\text{wet weight of sample} - \text{dry weight of sample}}{\text{dry sample weight}} \times 100 \qquad (8)$$

In addition, three ponderosa pine fuel moisture sticks placed in the units 2 weeks before, were weighed before the burn and used to estimate 10-h fuels moisture:

$$\text{10-h fuel moisture } (\%) = \text{wet weight (g)} - \text{moisture stick dry weight (g)} \qquad (9)$$

Where moisture stick dry weight is equal to 100 g.

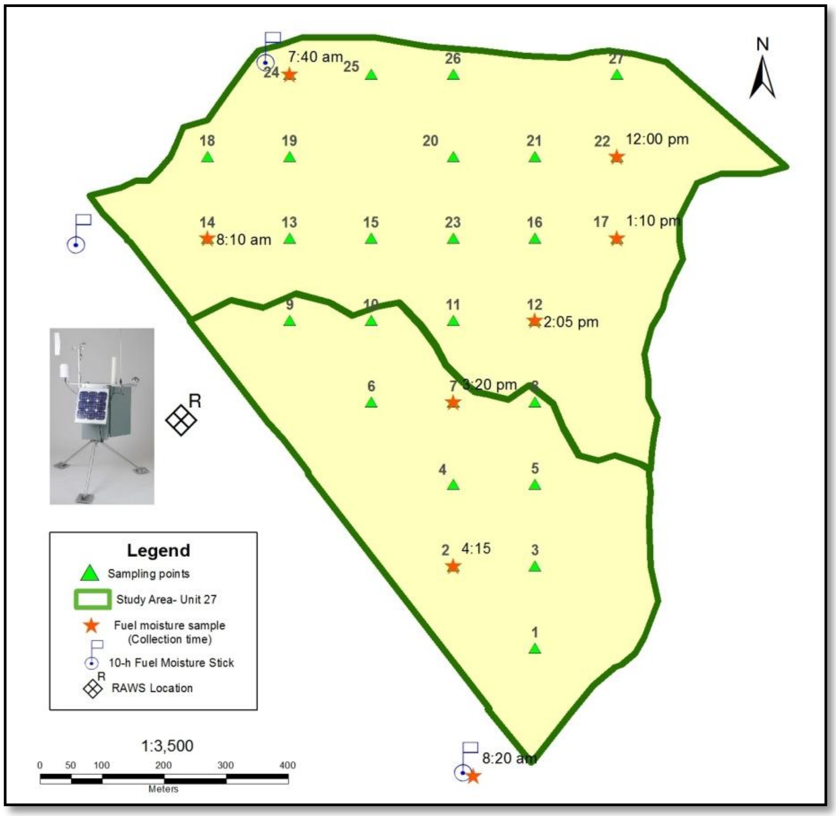

Figure 11: RAWS station and fuel moisture samples location and time of collection before and during the burn.

Fire Weather

A FTS Quick Deploy Remote Automatic Weather Station (RAWS) was installed in an adjacent open area of from the unit (Figure 11) and used to record fire weather data (wind speed and direction, temperature, % RH and dead fine fuel moisture and temperature) by the minute from 6:30 am to 5:00 pm. In addition, on site fire weather measurements were conducted by the hour (11:15 am to 4:30 pm) with a portable weather kit (psychrometer, anemometer and Kestrel 3000).

Maximum fire temperature

To record maximum fire temperature during the burn, aluminum tags painted with heat sensitive paints (Tempilaq®, Tempil Inc., Elk Grove Village, Illinois) were installed at the center of each plot. These types of paints are designed to melt and change color when the rated temperature is reached. They are an inexpensive alternative to thermocouple probes or Hobo data loggers and previous research has showed that, although with limitations, they are useful in evaluating fire effects on vegetation, (Iverson et al. 2004; Kennard et al. 2005; Rebbeck et al. 2006).

The aluminum tags (2.5 x 7 cm) were painted with 4/5 heat sensitive paints ranging from 93°C (200°F) to 454°C (850°F) in 10°C (50°F) increments. Then they were covered with an aluminum tag attached with a paper clip to protect the paint from weather and soot accumulations that might complicate their post fire readability and interpretation (Strand et al. 2013). The painted tags were installed on a rebar located at the center of the plot at 8 different heights: from 0 to 2.13 m in 0.31 m increments (0-7 ft, 1 ft increments). Three tags per height were necessary to cover the temperature range (Figure 12).

After burning, visible interpretation of the paints (melted or not) was conducted to estimate the maximum temperature for each group of tags at the different heights.

Figure 12: On right, rebar with tags painted with heat sensitive paints and located at 8 different heights, from ground level to 2.13 m. On the left, 1.52 m pole installed at 3.05 m from rebar to estimate (ROS) and (FH).

Fire rate of spread (ROS), flame height (FH) and flame length (FL)

Fire ROS, FH and FL were estimated at several locations (Figure 13) following 2 different methods:

1. *Fixed transects*: Before the burn, 3 fixed transects were marked in the north, west and southwest portions of the unit. Each transect had 12 trees marked with a white dot on the trunk and a pink flag along the road indicating approximate location of the tree. Distance between selected trees was measured. During the burn, a 3 person team, visually inspected and collected fire behavior data at each transect: fire direction of spread, time of spread between trees and approximate FH and FL.
2. *Fire internal behavior:* Inside the unit, a 2 person team visually inspected and recorded fire behavior at 8 plots with a Go-Pro Hero 3 and a Sony HD Camcorder digital camera. Minutes before the fire reached the plot, 2 or 4 aluminum poles (1.52 m tall) were located at 3.05 m (10 ft) from the rebar marking the center of the plot and at a right angle from

the prescribed fire ignition lines. Then, the flaming front was recorded when moving from one point to the next.

In both cases, ROS was determined as the time needed for the flaming front to move from one known point to another, divided by the distance between them. In transects observations, FH estimations were based on visual interpretation and agreement of the team. However, in the interior plots where recordings were available, estimations of FH and FL were done by using measurements performed with digital techniques.

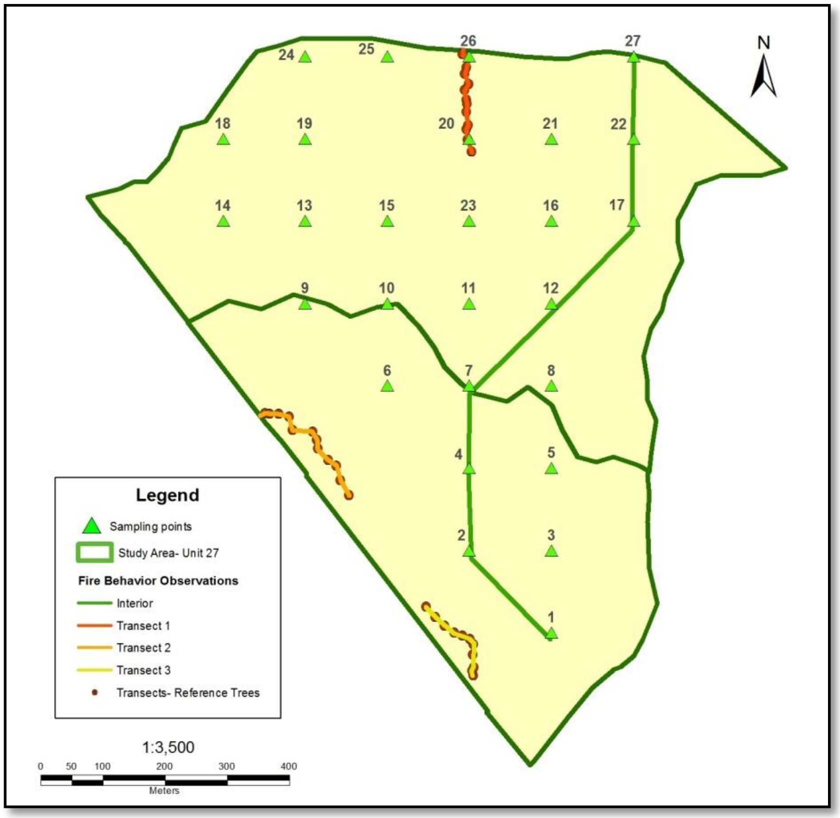

Figure 13: Rate of spread (ROS), flame height (FH) and flame length (FL) observations across the unit (Fixed transects and interior observations location).

Post burn sampling

Post burn sampling inventory had two phases. The first part was focused on quantitative and qualitative fire severity measurements. It was conducted as soon as possible after the burn to capture fire effects in all strata with minimal external disturbances (April 2 and 9, 2014). However, it is important to mention that immediately after the burn there was a storm and it rained for 3 days. Three months after the burn, a second inventory was conducted to record mortality in seedlings/saplings and to look for new signs of mortality in adult trees. This sampling was conducted in the middle of the growing season (June 20-23, 2014) when it was easier to discern live from dead seedlings.

Fire severity assessment (categorical)

A categorical visual assessment of fire severity was conducted within 7 days after the burn following the National Park Service Fire Monitoring protocol (2003). This procedure uses a coding matrix developed by Ryan and Noste (1985) which is based on 5 levels of change in the organic substrate and plan survival (5-Unburned, 1-Heavily burn). Fire severity was assessed at the macro plot level at each forest strata.

Fuel load measurements

In the substrate, fuel loads were re-measured and burn severity ratings were determined at the same points where litter and duff depth were measured. Surface and ground (duff) fuels were sampled and converted to fuel loads (weight) following the same 2 methods used in the pre burn inventory. In the PI method, measurements were conducted at the same location; however, due to the destructive characteristics of the sampling, post burn biomass samples had to be collected at a different location. As in the pre burn inventory, location was determined using a constant distance to the center of the plot (7.62 m) and a random bearing.

Understory measurements

Understory measurements were performed along the same 50 ft (15.2 m) transects. All grasses and herbs were totally consumed during the burn, as were a majority of the small woody shrubs.

Overstory measurements

Data were collected for the same trees marked in the pre burn inventory (1/10th acre (405 m^2) fixed radius plots). Tree live code (Live, Dead, Resprouting, Consumed/Down, Broken) was recorded and a careful inspection for fire and beetle damage was conducted. Then, three quantitative measurements of tree fire severity were recorded:

1. *Char (bole) height*: defined as height of the highest point of bole blackening on the uphill face of the tree (Regelbrugge and Conard 1993).
2. *Maximum scorch height*: defined by Albini (1976) as maximum height, measured vertically from the base of the tree to the height in the tree crown at which needles have survived the fire.
3. *Percentage of crown scorched:* defined as the portion of a tree's foliage (%) that has been killed by heat during a fire (Hood 2007).

Several authors have pointed to these severity effects in the overstory as good indicators of fire intensity (Alexander 1982; Alexander and Cruz 2012; Pomp et al. 2008; Rothermel and Deeming 1980) as well as good variables to model or predict tree mortality (Dixon et al. 1984; Lutes 2014; Wang et al. 2007). Therefore, it was considered especially important to measure them for analyzing first order fire effects related to mortality, as well as for use in future research to asses possible secondary effects as delayed mortality.

Regeneration measurements

Seedling tree data were collected as a count of individuals (tally) for all live tree species < 2 inches DBH within the same fixed radius plots. Again, all individuals within the plot were tallied and data collection was divided by species, stem origin (resprout (R) or single (S)) and stem height class. Due to the fire resistant characteristics of longleaf, especially in the grass stage, this part of the inventory was conducted at the end of June, when it was easier to discern live from dead seedlings (Figure 14).

Figure 14: Live and dead longleaf seedlings observed in the burn unit 3 months after burning (June 2014).

Data analysis

Fuel loads and fire effects in the forest floor: fuel consumption

Fuel loading estimations

A detailed description of procedures for fuel loading estimations for both collection methods is included in Chapter 1, Fuel loading calculations section, page 12.

Fuel loading distribution vs. tree density

Previous research has pointed out that factors such as stand basal area and stand structure can produce differences in the quantity and distribution of yearly litter fall across the landscape (Lashley 2014; Parresol et al. 2006). To analyze these possible connections, basic linear regression and correlation analysis were performed to test associations between variables that could predict linear patterns of fuel distribution related with tree density. A second analysis including duff (the origin and quantity of which is directly related with litter and fire regime) and total load (litter + duff) was run. The analysis was performed at a plot level, using basal area (BA) (m^2/ha) as a measure of density and the Spearman coefficient (nonparametric measure of association based on ranks) for the correlation analysis. The hypothesis tested was H_o= there is not a linear correlation between fuel load and BA (α=0.05).

To complement the analysis, maps of the spatial BA, litter and duff depth distributions were developed using Inverse Distance Weighting (IDW) interpolation in Arc Map 10.2. Since the data available were not enough to make reliable correlations, this procedure was conducted only to help visualize distributions of the variables (high/low) and may not adequately represent values at any unmeasured locations. The 3 nearest sample points were used to perform interpolations at unmeasured locations, and output cell size was 5 meters.

Fuel consumption and forest floor depth removal

Previous research has confirmed the strong association between fuel consumption and moisture content, especially in duff (Ferguson et al. 2002; Goodrick et al. 2010; Hough 1978; Ottmar and Andreu 2007), and the influence of weather conditions (Ferguson et al. 2002; Goodrick et al. 2010) and fire behavior (Kauffman and Martin 1989; Waldrop et al. 2004) in consumption. However, due to the reduced scope of this study, there was not enough information to analyze relationships between fuel consumption and these variables. Hence, fuel consumption regression analysis was conducted using pre and post burn fuel loadings, as well as forest floor depths, which have also been shown to be highly correlated with fuel consumption in longleaf ecosystems (Wang et al. 2007).

At the plot level, fuel consumption was calculated (total and by fuel type) as the difference between fuel load before and after the burn for each collection method. Then, mean values and associated errors were estimated to extrapolate consumption at the landscape level. A comparison between measured forest floor removal after burning and removal estimated with the equation developed by Wang et al. (2007) for longleaf forest floor depth removal was conducted to test the precision of the model and its applicability to Calloway Forest:

$$\mathrm{Y}\ (\mathrm{mm}) = -9.939 + 0.896\mathrm{X} - \frac{29.582}{\mathrm{X}} \qquad (10)$$

Where Y is forest floor depth removed and X is forest floor depth before burn (mm).

Besides this comparison, using the 324 litter and duff depth measurements taken with the PI method, an equation for predicting forest floor removal after burning based on pre burn fuel loadings was developed using simple linear regression (standard least squares), for the Calloway Forest.

Fire behavior and fire effects in overstory and regeneration

Fire intensity and fire severity in the overstory

Basic data analyses were conducted to visualize fire severity signs in the overstory (char height, maximum bole scorch height and percentage of crown scorched). A correlation analysis was performed looking for relationships among these severity variables, especially between maximum scorch height and % scorched crown, which have been increasingly used in tree mortality probability models (Alexander and Cruz 2012; Kobziar et al. 2006). Since there was no mortality observed in the overstory 9 months after burning when the last field visit for this project was performed, it was not possible to test for associations between fire severity and fire effects (mortality) in this stratum.

Scatter plots were used to graphically examine relationships for linearity, as well as potential nonlinear relationships between fire intensity (fireline intensity and maximum temperature), scorch height and % crown scorched. Following graphical examination, simple linear correlation and regression analyses were performed to test associations between both bole scorch measures (percentage and height, dependent variables) and fire intensity (independent variable) for all plots.

Fire effects in regeneration: seedlings mortality

The temperature for instantaneous (< 1 second) plant tissue death for longleaf has been defined to be 70 °C (158 °F) (Wade and Johansen 1986), slightly higher than the general value for less fire resistant species (60 °C, 140 °F) (Wright 1970). When analyzing relationships between mortality and temperature, residence time or length of exposure is also important because lower temperatures can cause death when the contact lasts longer. For example 55°C (131 °F) with 5 minutes exposure can cause mortality. In this case study, information on residence time was not available and analyses of mortality were based only on temperature. This limitation should be taken into account when interpreting the results.

Longleaf seedlings mortality, fuel consumption and maximum temperature at the unit level

Linear regression exploration was performed to understand relationships between total mortality (independently of seedling height class), maximum temperature and total fuel consumption by plot. Also, a nonparametric correlation analysis (Spearman) was conducted to explore possible association between variables (H_o= there is not a linear correlation between variables (α=0.05)).

Analysis of longleaf seedlings mortality by height class and max. temperature at each height

Longleaf seedlings mortality data available were based on a count (# live seedlings before the burn – # live seedlings after the burn) by height class group (1 to 7).

At each plot, maximum temperature measured at different heights from 0-1.8 m (0-7 ft) was also available. Based on the premise that temperature will have different effects on seedlings depending on the amount of heat reaching the terminal bud, seedlings mortality (by height class) and temperature were matched by similitude in heights (Table 10). As a result, total mortality was classified as a count of dead seedlings at each height that maximum temperature was recorded.

Several statistic analyses were performed to test relationships between seedling mortality (dependent variable), height and temperature (independent variables). Then, a mortality model was developed to predict longleaf seedlings mortality based on these variables.

Table 10: Correspondence between seedling height class, seedling height and height where maximum temperatures were recorded.

Seedling Height class code	Seedling height (m)	Height Temperature recorded (m)
1	< 0.15	0
2	0.15 - 0.31	0.3
3	0.31 - 0.62	0.6
4	0.62 - 0.92	0.9
5	0.92 - 1.83	1.2
6	1.83 - 2.74	1.5
7	2.74 - 3.66	1.8

In ecological studies, mortality data (binomial or binary) usually follows a non-normal distribution with heterogeneous variance (Bolker et al. 2009). Simple linear regression and ANOVA models have limitations for analyzing these data. Generalized linear models (GLM) are a better non-parametric approach to work with the mortality information available (Piza 2012). Therefore, after testing different options, a Negative Binomial Regression Model was chosen. This type of model is designed to analyze count data and is appropriate for aggregated events. It can be considered as a generalization of a Poisson regression; however, unlike Poisson, negative binomial regression does not assume equal mean and variance of the dependent variable and corrects for over-dispersion in the data; therefore it is more appropriate for the data available (Pedan 2001).

I modeled the effect of seedling height and temperature as predictors of seedling survival (mortality) after prescribed fire. The probability of mortality (π) was modeled with a generalized linear mixed model (Eq.11), using a logit (canonical) link function:

$$\eta ij = \mathrm{Log}\left(\frac{\pi}{1-\pi}\right) = \beta_0 + \beta_1(\mathrm{Hi}) + \beta_2(\mathrm{Tj}) + \beta_3(\mathrm{HTij}) + \varepsilon ij \qquad (11)$$

Where **ηij** is the link function [g(μ)] of mortality of the jth temperature in the ith height. It is observed as the ratio of the events and trials: **e/t**, with **e** being seedlings mortality and **t** being seedlings before burning; **g(μ)** is the log transformation between the observed data and the log data; **$\mathrm{Log}(\frac{\pi}{1-\pi})$** is the logit value or log of odds of mortality, which is the ratio of the probability of the outcome (mortality) to the probability of no outcome; **π** is probability of mortality, **β_o** is the intercept, **β_1** is the coefficient for height, **β_2** is the coefficient for temperature, **β_3** is the coefficient for the interaction between height and temperature and **$\varepsilon ijkl$** is the error term $\varepsilon ijkl \sim N(0, \sigma^2\varepsilon)$.

The analysis was conducted using SAS Enterprise 6.1 software (SAS Institute Inc. 2014) GLIMMIX procedure (proc GLIMMIX, binomial distribution, logit link function). The parameters on the logit scale were transformed to a probability scale using the inverse link function in the GLIMMIX procedure.

RESULTS

Fuel loads

Fuel loading estimations

Pre burn fuel loadings were 21.31 Mg/ha (9.51 ton/ac) for the biomass sampling method and 24.11 Mg/ha (10.76 ton/ac) for the planar intersect. Corresponding post burn fuel loadings were 9.2 Mg/ha (4.10 ton/ac) and 6.79 Mg/ha (3.03 ton/ac), respectively. For detailed information about calculations and fuel type distributions review Chapter 1, Fuel loading estimations and distributions section, page 20 of this document.

Fuel loading distribution vs. Basal Area (BA)

Average basal area (BA) across the unit was 18 m²/ha (78 ft²/ac), with values ranging from 5 m²/ha (22 ft²/ac) at plot 3 to 30 m²/ha (132 ft²/ac) at plot 24 (Table 11).

Table 11: Summary table with mean, minimum and maximum values for fuel loading depths and tree density across the study unit.

	Density (BA)		**Litter depth**		**Duff depth**		**Litter & Duff**	
	m²/ha	ft²/ac	mm	in	mm	in	mm	in
Avg.	17.92	78.03	54.66	2.15	14.30	0.56	68.96	2.71
Min.	5.01	21.81	17.78	0.70	2.54	0.10	20.32	0.80
Max	30.21	131.58	116.84	4.60	38.10	1.50	154.94	6.10

The highest tree density was observed at the northwest part of the unit (Figure 15), in plots 14, 18, 24 & 25 with an average value approximately 28 m²/ha (121 ft²/ac). High litter depth was also recorded in this area (Figure 16); however, measured duff depth was relatively low compared with the center-east portion (plots 5, 8 & 12). Plots located in the south (1 & 3) had low BA accompanied by low litter and duff depths.

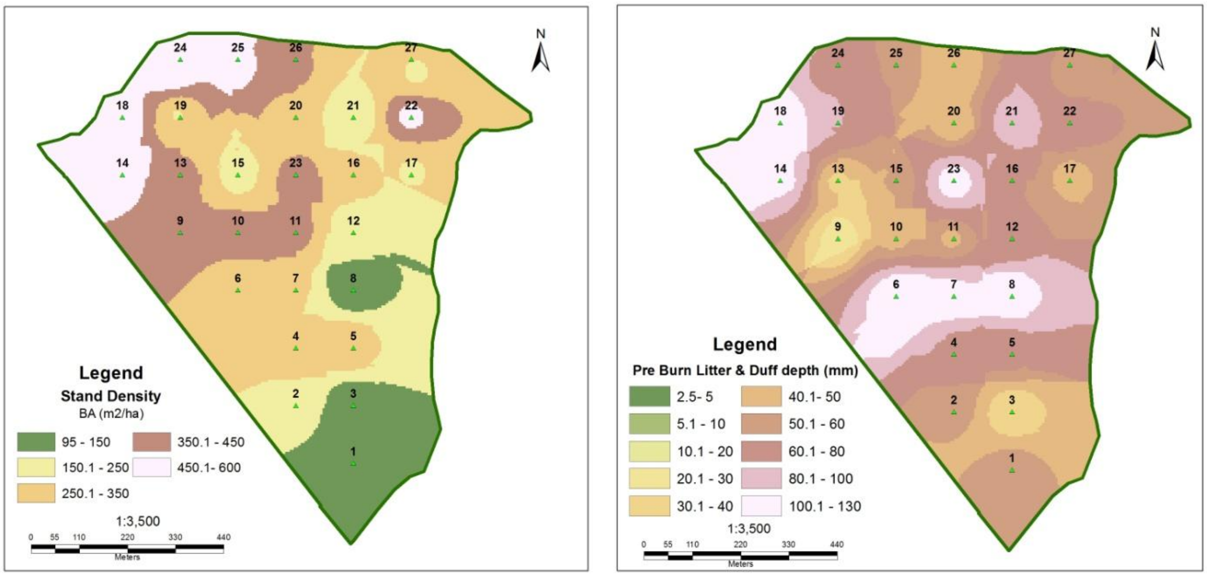

Figure 15: Maps of Basal Area (BA) (m²/ha) (left) and pre-burn litter + duff depth (mm) (right) distribution across the study area.

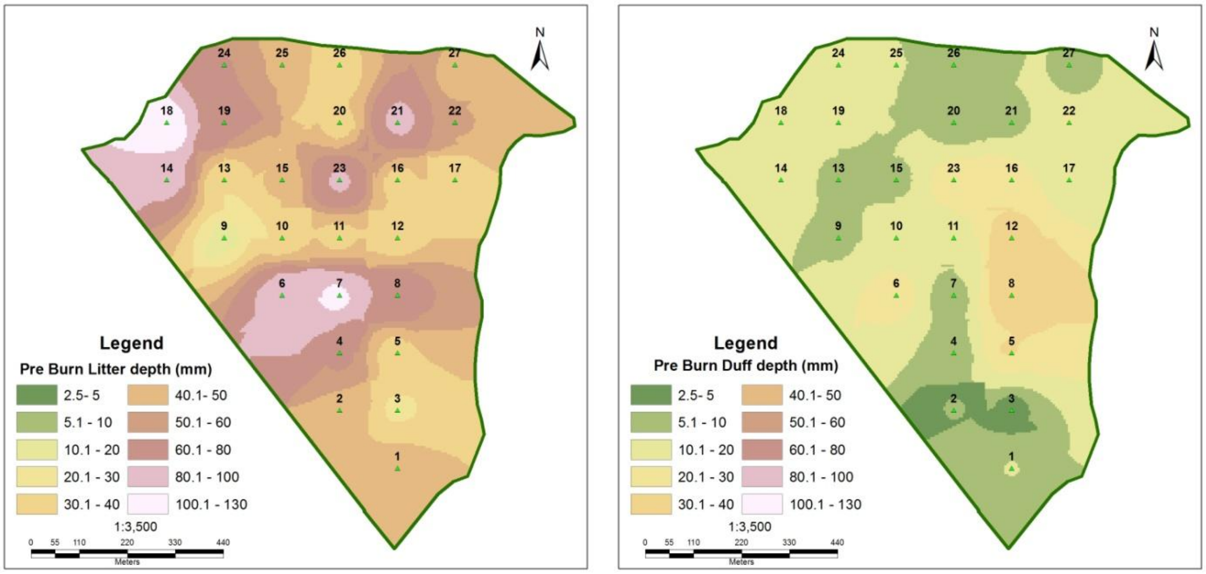

Figure 16: Maps of pre-burn litter depth (mm) (right) and pre-burn duff depth (mm) (left) distribution across the study area.

Average litter depth was 55 mm (2.2 in) with values ranging between 18 and 117 mm (0.7 - 4.6 in). Deeper depths were recorded in the northwest (plots 14 & 18) and around the center of the unit (plots 6, 7 & 8). Nevertheless, the highest duff depths (38 mm (1.5 in)) were not observed here but in the east side of the unit (plots 5, 8 & 12) where lowers elevations were recorded.

Preliminary linear regression analysis pointed to lack of a relationship between forest floor fuels estimated with both estimation methods and tree density (BA). Spearman correlation analysis (Table 12) confirmed that there was not a significant linear association between fuel loading types and BA, although some weak correlations were displayed. The test was performed separately for the 2 methods of estimation. For biomass collection estimates, a small positive correlation was found between litter and BA (0.34); however, it was not found to be significant enough to reject the null hypothesis (Prob>|ρ| =0.08). Duff and total load estimates were not found to be significantly related to BA either (Prob>|ρ|=0.69 and =0.42, respectively). The same results occurred with estimates from the PI method, although in this case the biggest correlation was observed between duff and BA (0.20), no fuel loading variables were found to be significantly related to BA.

Although previous research has shown that tree density influences litter distributions (Bale 2009), with the information available in this study, a higher tree density does not necessarily mean higher litter or duff accumulation.

Table 12: Spearman correlation coefficients between tree density (basal area (m²/ha)) and pre burn forest floor fuel loads (litter, duff, litter & duff) by estimation method.

Matrix interpretation: Correlation coefficients between variables are below the main diagonal (1.00) and the probability associated with the null hypothesis test of correlation (Prob>|ρ|< 0.05) are above the main diagonal.

Method: Planar Intercept

Spearman correlation: Coefficients\probabilities

		Fuel loading (Mg/ha)		
	Density (BA)	**Litter load**	**Duff load**	**Total Load**
Density (BA)	1.00	0.68	0.33	0.56
Litter load	0.08	1.00	0.39	5.90E-05
Duff load	0.20	0.17	1.00	3.60E-06
Total Load	0.12	0.69	0.76	1.00

Method: Biomass collection

Spearman correlation: Coefficients\probabilities

		Fuel loading in Mg/ha		
	Density (BA)	**Litter Biomass**	**Duff Biomass**	**Total Biomass**
Density (BA)	1.00	0.08	0.69	0.42
Litter Biomass	0.34	1.00	0.16	2.30E-03
Duff Biomass	0.08	0.28	1.00	6.50E-06
Total Biomass	0.16	0.60	0.88	1.00

Fire weather

Weather collected on site with RAWS from 6:38 am to 5:07 pm (air temperature, fine fuels temperature, RH, dead fine fuels moisture content and wind speed) helped with analysis of the daily pattern and interactions between weather components during the day of the burn (Figure 17). Low temperatures (-4°C, 24 °F) and high RH (80%) were observed in the early morning from 6:30 to 8:00 am with 2-3 km/h winds coming from the north-northwest. By 9:30 am temperature was around 4°C (48 °F), RH had dropped to 28 % and wind was switching to the south-southeast. Fine dead fuel moisture content (FDM %) oscillated between 6 and 9 % with lower values around 5:00 pm.

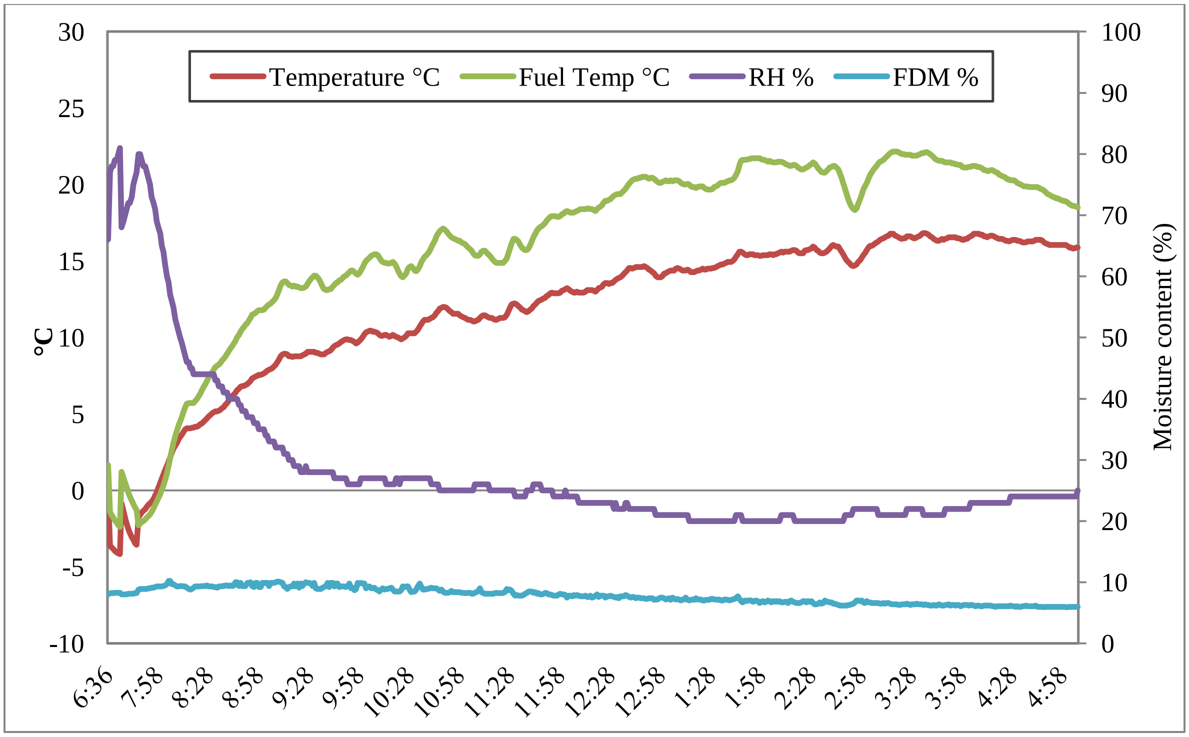

Figure 17: Atmospheric & fine dead fuel temperatures (°C) and RH (%) recorded by RAWS the day of the burn. Station was located in an adjacent unit west of unit 27.

During the burn (11:00 am to 4:30 pm), fire weather collected by the RAWS station recorded an average temperature of 14.7 °C (58.4 °F) with a maximum temperature of 16.8 °C (62.3 °F) reached at 3:30 pm (Figure 18). Average wind speed was 9.5 km/h (5.9 mph) mostly from the southeast. Mean relative humidity (RH) was 22 % reaching minimum values of 20% between 1:15 and 3:00 pm. Fine dead fuels moisture (FDM) had a mean value of 7% varying between 9 to 6%, with minimum values after 1:45 pm. Weather inside the unit was collected with a portable weather kit about every hour. Estimations obtained with the kit were slightly different from those from the RAWS station due to precision of instruments and variability in location of the data collector (Figure 19). Larger differences were observed in wind speed (kit 3-4 km/h less) and RH % (kit 5-12 % above) since the RAWS station was located in an open area while in-situ measurements were taken inside the unit (canopy cover). Considering general conditions during that day, weather kit wind measurement at 14:30 pm and RH% at 15:30 might be due to human error when collecting data.

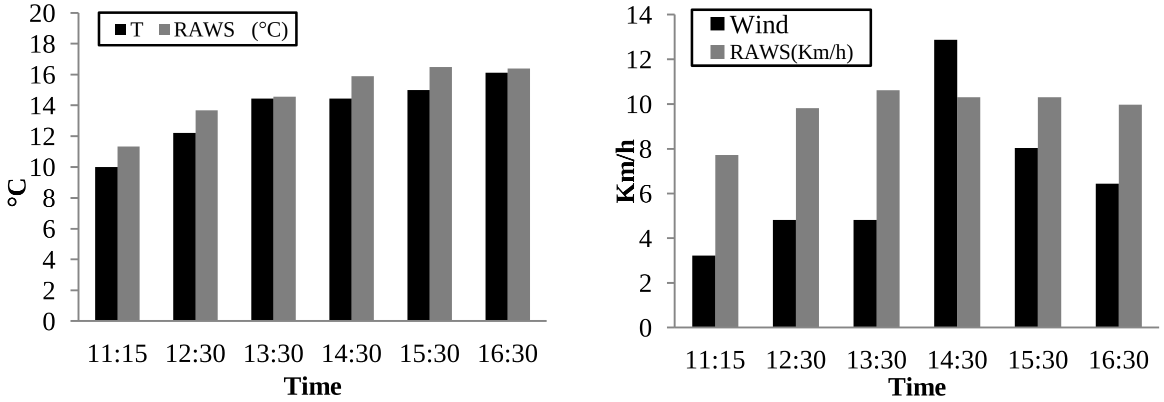

Figure 18: Temperature (°C) and wind speed (Km/h) collected from 11:15 am to 4:30 pm with portable weather kit (black) and RAWS (grey) during prescribed burn

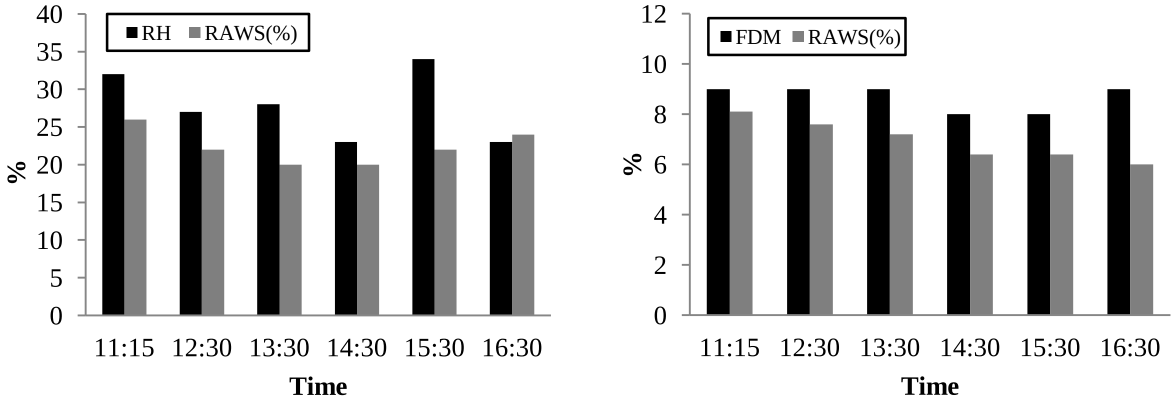

Figure 19: RH (%) and fine dead fuels moisture (FDM) (%) collected from 11:15 am to 4:30 pm with portable weather kit (black) and RAWS (grey) during prescribed burn.

Fire behavior, fire intensity and maximum temperature

Average rate of spread (ROS) observed in the north and northwest portions was 8.91 m/min (0.49 ft/s) while in the east-interior ROS was 5.67 m/min (0.31 ft/s). In general, ROS increased after 1:30 pm, when lower RH% and FDM% were recorded (Table 13).

Observed mean flame height (FH) was between 0.7 and 0.9 m (2.3-2.9 ft), ranging from 0.4 m (1.2 ft) to 1.22 m (4 ft). Flame length (FL) in the north-northwest transects was about 1.42 m (4.7 ft), while FL measured with digital techniques using recorded videos was 0.42 m lower.

Table 13: Average rates of spread (ROS), flame heights (FH) and flame lengths (FL) observed and recorded at different locations during the burn. Transect 1 was located in the north of the unit while transects 2 & 3 were in the west. Interior behavior was recorded from the northeast to the southeast (from plot 27 to 1).

			ROS		**FH**		**FL**	
Transect	**Plot #**	**Time**	**(m/min)**	**(ft/s)**	**(m)**	**(ft)**	**(m)**	**(ft)**
1	26	12:00	5.53	0.30	0.74	2.4	1.35	4.4
1	20	13:00	16.17	0.88	0.65	2.1	1.14	3.8
2	close to 6	14:30	6.80	0.37	1.10	3.6	1.95	6.4
2	close to 6	15:30	8.14	0.44	1.09	3.6	1.42	4.7
3	Btw 2-1	16:30	7.92	0.43	0.88	2.9	1.25	4.1
		Avg.	**8.91**	**0.49**	**0.89**	**2.93**	**1.42**	**4.67**

			ROS		**FH**		**FL**	
Transect	**Plot #**	**Time**	**(m/min)**	**(ft/s)**	**(m)**	**(ft)**	**(m)**	**(ft)**
Interior	27	11:49	5.19	0.28	0.5	1.7	0.9	2.8
Interior	Close 27	12:00	2.65	0.14	0.6	2.0	0.8	2.5
Interior	Btw 27-22	12:15	2.93	0.16	0.61	2.00	0.76	2.50
Interior	22	12:33	2.64	0.14	0.38	1.25	0.53	1.75
Interior	17	13:33	3.28	0.18	0.71	2.33	1.07	3.50
Interior	12	14:26	14.28	0.78	0.76	2.50	1.30	4.25
Interior	7	15:24	5.99	0.33	0.97	3.17	1.27	4.17
Interior	4	15:50	6.44	0.35	0.73	2.40	1.07	3.50
Interior	1	16:39	7.62	0.42	1.22	4.00	1.52	5.00
		Avg.	**5.67**	**0.31**	**0.72**	**2.37**	**1.02**	**3.33**

Assuming little to no wind, and using equations based on the relationship between flame intensity and size proposed by Byram (1959), mean fireline intensity in the east side of the burn was 298 kW/m (FL = 1.02 m) while in the north-northwest fire intensity reached 588 kW/m (FL=1.42 m) with a maximum of 1111 kW/m (Table 14).

Table 14: Fireline intensity calculations based on Byram's equations for flame length (FL).Transects 1, 2 and 3 were located in northwest portion of the unit, while interior observations were on the east and south areas.

Transect #	Location	Time	Avg. ROS m/s	Avg. FL (m)	Fireline Intensity (FL) (Kw/m)
1	26	12:00	0.09	1.35	499
1	20	13:00	0.27	1.14	347
2	close to 6	14:30	0.11	1.95	1111
2	close to 6	15:30	0.14	1.42	559
3	Btw 2-1	16:30	0.13	1.25	422
		Avg.	**0.15**	**1.42**	**588**
Interior	27	11:49	0.09	0.9	189
Interior	Close 27	12:00	0.04	0.8	144
Interior	Btw 27-22	12:15	0.05	0.76	144
Interior	22	12:33	0.04	0.53	66
Interior	17	13:33	0.05	1.07	299
Interior	12	14:26	0.24	1.30	456
Interior	7	15:24	0.10	1.27	437
Interior	4	15:50	0.11	1.07	299
Interior	1	16:39	0.13	1.52	649
		Avg.	**0.09**	**1.02**	**298**

Generally, low intensity surface fires are less than 550 kW/m. and those above 4000 kW/m are considered as high intensity, although this varies according to fire tolerance of the species (Alexander 1982). According to this, fireline intensities observed during the burn agreed with expected low intensity values for this type of ecosystem.

For this study, fire temperature was defined as the maximum temperature recorded by the paints at each plot and height due to exposure to flames and heat during the burn. Higher values were found at the ground level (in all plots but four: 3, 7, 10 & 16), with a median temperature of 371 °C (700 °F), ranging from 93 to 454 °C (200-850 °F) (Table 15).

Table 15: Maximum temperature (°C) vertical profile recorded at each plot from ground level to 7ft.

		Temperature (°C)			
Height (ft)	**n**	**Mean**	**Median**	**Min.**	**Max.**
0	27	337	371	93	454
1	27	229	177	121	371
2	25	164	149	93	316
3	20	143	149	121	232
4	16	140	149	93	232
5	12	126	121	93	149
6	9	121	121	93	149
7	1	121	121	121	121

Previous research in longleaf ecosystems, has pointed to low intensity burns having a peak temperature around 225 °C and 400 °C for high intensity burns (Knapp, personal communication 2014). General mean observations in the unit agreed with temperatures characteristic of low intensity burns; however, at the ground level, mean temperatures recorded were closer to 400 °C than 250 °C indicating the fire had higher fire intensity than expected. When analyzing maximum individual temperature distributions at the plot level, it was easier to identify areas where higher temperatures were reached (Figure 20). These visual differences suggest a big variability in fire behavior that might be a consequence of fuel availability, burn pattern, slightly different weather conditions or other reasons;

however, with the information available no clear relationship has been found between any of these variables and temperature differences.

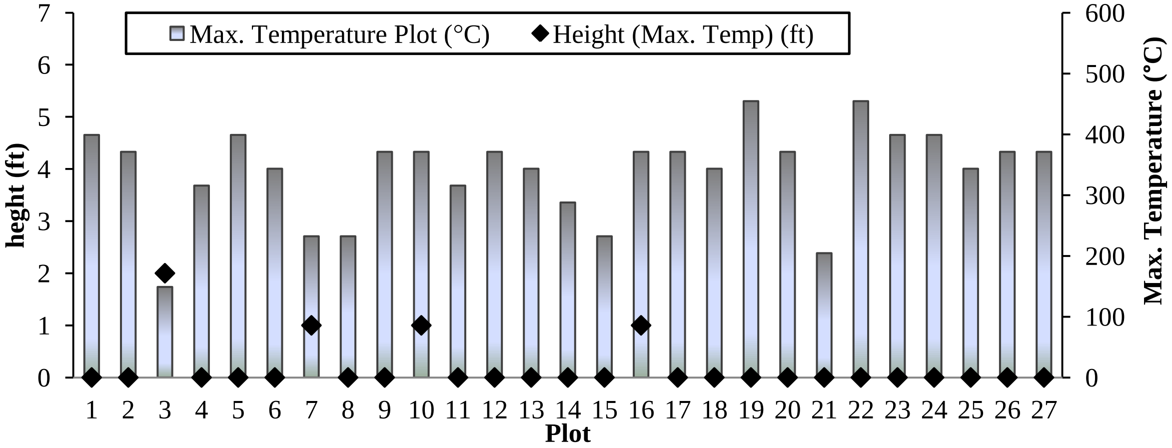

Figure 20: Maximum temperature (°C) recorded at each plot accompanied by height where it was reached.

Fire effects: fuel consumption and mortality

Fire effects in the forest floor: fuel consumption and forest floor depth removal

Fuel load consumption estimates were calculated at the unit and plot level (n=27) for each one of the fuel types and methods. At the unit level, Table 16 shows that the biomass collection method estimated a total fuel consumption of 12.1 Mg/ha (5.4 ton/ac) while the estimate obtained with PI method was 17.3 Mg/ha (7.73 ton/acre), 5 Mg/ha higher (2.3 ton/ac). A similar pattern was repeated with the litter and duff consumption predictions, with the PI estimating consistently higher values (Figure 21).Wiregrass consumption estimates were higher in the biomass method and they seem closer to what was observed in the field. Finally, CWM consumption estimates in the PI method were negative, showing an increase of the loading after burning due to wind storms that took place between the pre burn inventory and the burn. Wiregrass aboveground parts were completely consumed during the burn so fuel consumption was estimated as 100% of the pre burn load for both methods.

Table 16: Summary statistics of fuel consumption at the Unit level by sampling method (Biomass collection and Planar Intersect), n=27.

	Fuel consumption in Mg/ha (ton/ac)							
Sampling Method	**Fuel Type**	**Mean**	**S.D.**	**S.E.**	**Min.**		**Max.**	
Biomass Collection	Litter	8.21 (3.66)	3.54	0.68	0.32	(0.14)	14.48	(6.46)
	Duff	2.1 (0.94)	6.49	1.25	-9.98	(-4.45)	20.4	(9.10)
	Wiregrass	1.05 (0.47)	1.59	0.31	0	(0)	5.4	(2.41)
	CWM	0.37 (0.17)	1.69	0.32	-1.01	(-0.45)	5.96	(2.66)
	Other	0.38 (0.17)	0.83	0.16	0	(0)	3.33	(1.49)
	Total	**12.1 (5.40)**	**7.62**	**1.47**	**-1.32**	**(-0.59)**	**31.59**	**(14.09)**
Planar Intersect	Litter	11.2 (5.00)	5.79	1.11	3.19	(1.42)	24.11	(10.76)
	Duff	6.24 (2.78)	6.65	1.28	-0.42	(-0.19)	25.32	(11.29)
	Wiregrass	0.18 (0.08)	0.13	0.03	0.01	(0)	0.52	(0.23)
	CWM	-0.29 (0.13)	1.41	0.27	-4.23	(-1.89)	3.55	(1.58)
	Total	**17.3 (7.73)**	**9.19**	**1.77**	**5.36**	**(2.39)**	**40.89**	**(18.24)**

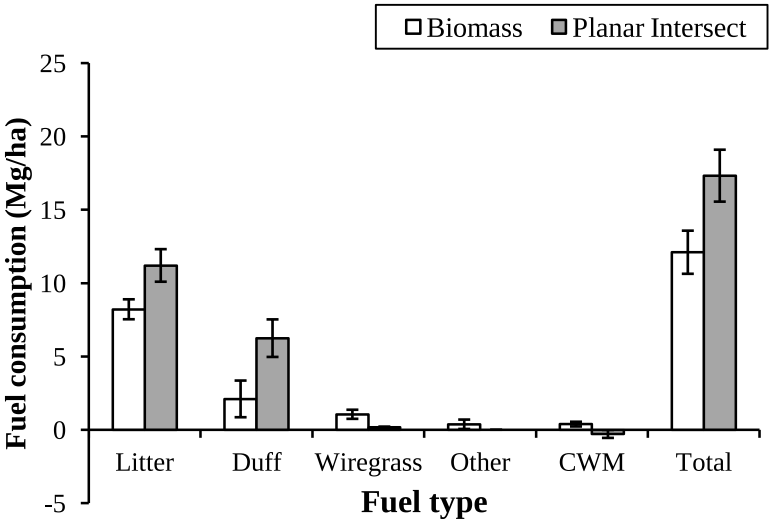

Figure 21: Fuel consumption mean estimates (Mg/ha) and standard errors by fuel type and method of estimation (Biomass collection and Planar Intersect).

When estimating and analyzing the consumption data at a plot level, some problems related with the biomass sampling design arose. Since this sampling was based on a destructive method, pre and post samples were collected at different points. Due to this spatial difference when collecting fuel loads before and after the burn, in some cases the loadings were higher after the burn than before, which resulted in negative fuel consumption values. Because of this limitation, it was necessary to adopt the fuel consumption values (with the wiregrass exception) estimated with the PI method for farther analysis related to fuel consumption. Wiregrass consumption values were taken from the biomass samples since calculations for PI were done with equations created for other western species; therefore, biomass estimations were considered more appropriate.

Mean depth (n=324) before the burn was 54.7 mm (2.2") for litter and 14.7 (0.6") for duff. Forest floor depth was defined as the sum of litter and duff depth (69 mm). Post burn depths were 3.3 (0.1") mm and 4.9 (0.2") mm yielding a total of 8.2 mm. Therefore, observed forest floor removal after the burn was 60.7 mm (2.4"). Using the equation proposed by Wang et al (2007) to improve fire effects predictions with FOFEM for longleaf, mean estimation of forest floor depth removal was 51.3 mm (2.02"). The estimations differed by 9.4 mm (0.4"), with more consumption in our measurement-than in the prediction.

Using field litter and duff depth measurement, a simple equation for predicting fire effects on the depth of the forest floor was developed (Figure 22).

$$\text{Y (mm)} = -7.234036 + 0.9812809\text{X} \tag{12}$$

Where Y is forest floor depth removed (mm) and X is forest floor depth before the burn (mm).

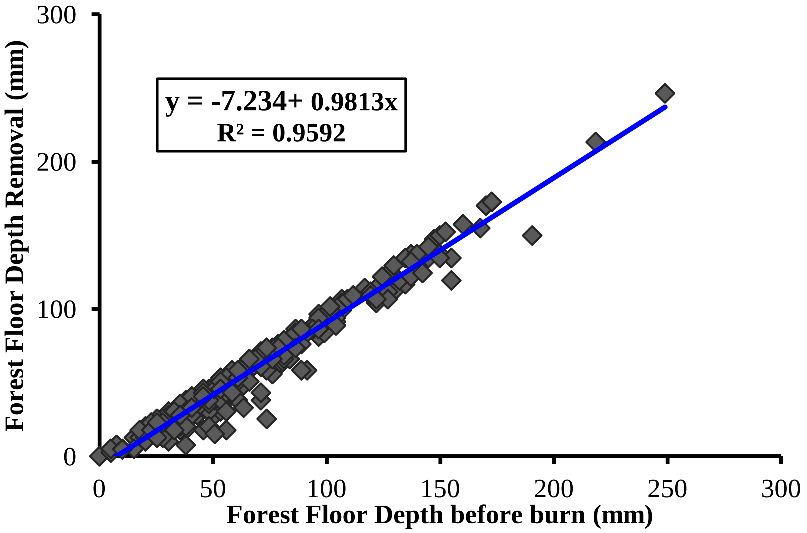

Figure 22: Simple lineal regression model to predict forest floor depth removal after a prescribed fire based of pre burn fuel depths (Unit 27 at Calloway Forest) (n=324).

Table 17: Parameter estimates and Analysis of Variance tables of forest floor depth removal model. (R^2=0.9592, n=324, FFBB: Forest floor before burn (mm))

Term	Estimate	Std Error	t Ratio	Prob>|t|
Intercept	-7.234036	0.850217	-8.51	<.0001
FFBB (mm)	0.9812809	0.01128	86.99	<.0001

Source	DF	Mean Square	F Ratio
Model	1	465172	7567.616
Error	322	61	**Prob > F**
C. Total	323	-	<.0001

The coefficient of determination of the model (R^2) was very high, pointing to pre burn forest floor depths as good predictors of depth removal (Table 17). There was not enough information to include other variables such as fuel moisture in the analysis to compare the appropriateness of different models. Therefore, this information should be interpreted with caution since several research papers have pointed to moisture content as highly correlated with duff consumption (Brown et al. 1985; Ferguson et al. 2002; Goodrick et al. 2010; Hood 2010).

Fire behavior and fire effects in overstory

Char height, maximum bole scorch height and percentage of crown scorched

At the unit level, mean char height was 5 m, maximum scorch height was 13 m (range from 0-27 m) and % of crown scorched was 35% (median=20%, range from 0-100) (Table 18). Across the unit, 24 trees had 100% of the crown scorched and 46 out of 214 had above 85%. All of them were alive 9 months after the burn.

Table 18: Fire severity in the overstory. Summary statistics by tree (n=214)

Variable	Mean	Median	S.E.	Min.	Max.
Height (m)	21	22	0	4	31
Char height (m)	5	5	0	0	14
Max. Scorch height (m)	13	16	1	0	27
% Scorch crown	35	20	3	0	100

Fire severity values at the unit level failed to display the variability associated with fire behavior and fuel consumption at each plot and tree. Differences in fire severity effects in the canopy are more evident in Figure 23, where plots 11, 17 and 24 display the highest values of % of crown scorched and scorch height, while plots 15, 22, 25 and 27 are the smallest in both variables. On the other hand, plots 13 and 19 have high scorch height but unexpectedly low % of crown scorched. This highlights variability in fire behavior and suggests that the relationship between scorch height and % of crown scorched might not be straightforward, with many other factors such as tree high, canopy closure, fuel bed high and weather variations playing an important role.

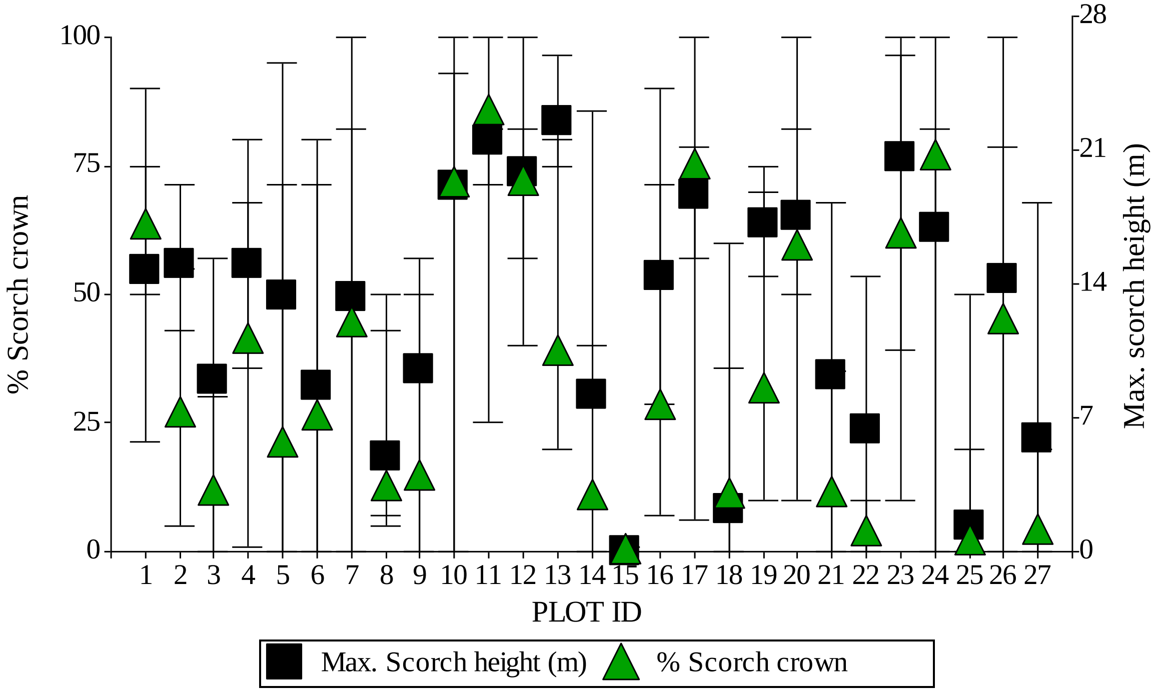

Figure 23: Mean percentage of crown scorched and maximum scorch height (m) with minimum and maximum values displayed at each plot in the burn unit.

A cluster of high fire severity effects was observed in the central-east part of the unit, with high percentages of crown scorched (Figure 25), in plots 10, 11, 12, 17 & 23; high scorch height in plots 11, 12 & 23; and taller char heights in plots 12, 17 & 23 (Figure 24). However, high fuel consumptions were not observed in several of these plots. Another cluster was located in the northeast section of the unit (plots 21, 22, 26 & 27) but in this case the lower fire severity effects were accompanied by low fuel consumptions. In the rest of the unit, fire severity effects did not appear to have a direct relationship with fuel consumption. It is important to consider that some of these visual associations might also be influenced by other factors such as tree height and canopy closure, which can induce some error in the interpretation.

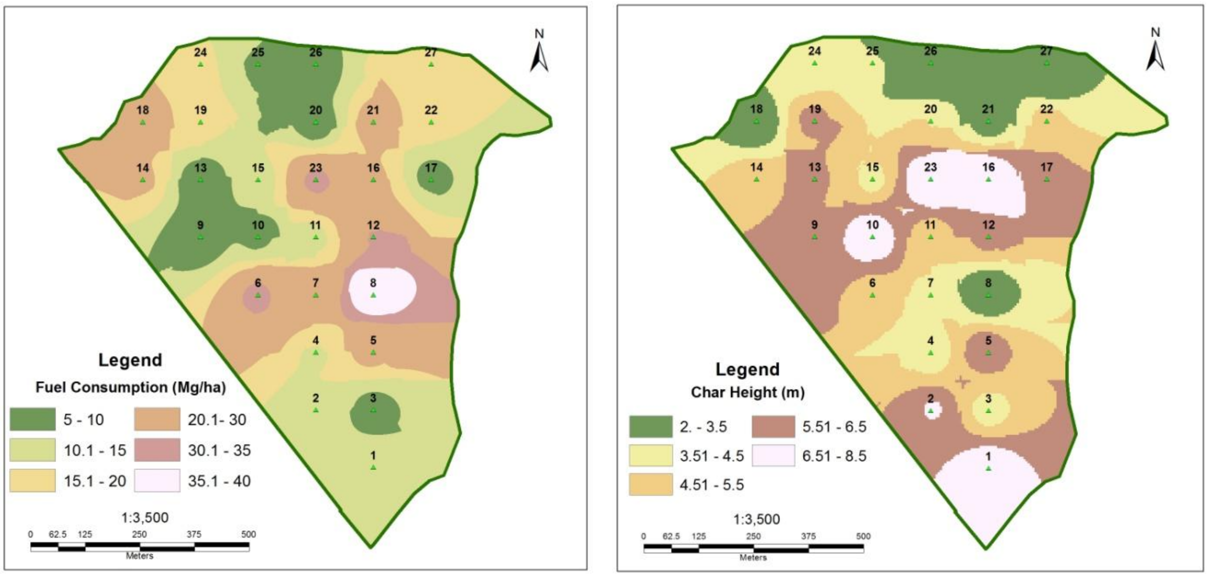

Figure 24: Maps of fuel consumption (Mg/ha) (left) and char height (m) (right) distribution across the unit.

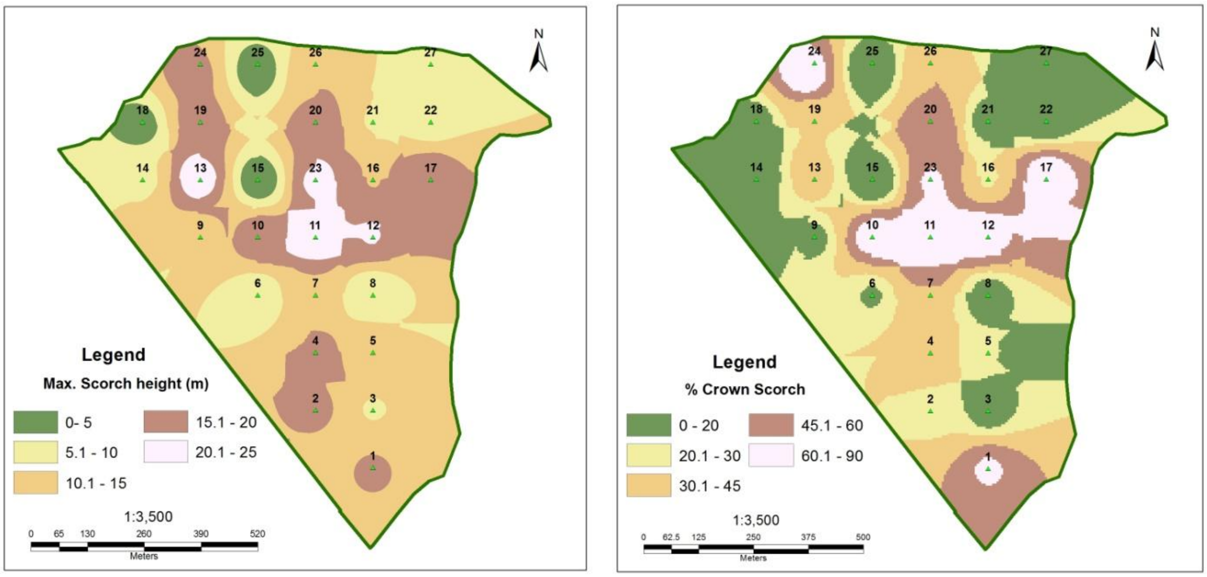

Figure 25: Maps of maximum scorch height (m) (left) and percentage of crown scorched (right) across the unit.

In a nonparametric Spearman's ρ test, all severity variables were found to be positively correlated to some degree, especially percentages of crown scorched and maximum scorch height which had a correlation coefficient of 0.83 (Prob>| ρ | <.00001,

Table 19). However, linear regression analysis showed a weak coefficient of determination between variables (R^2=0.4-0.5, depending on the model, Figure 26).

Table 19: Spearman correlation coefficients and probabilities between fire severity variables in the overstory. Main diagonal elements (1) represent the correlation of a variable with itself. Below the main diagonal there are the correlation coefficients between variables and above the main diagonal is the probability associated with the test null hypothesis of correlation between variables (Prob>|ρ|< 0.05). (H_o= No association between variables)

	Char height (m)	% Scorch crown	Max. Scorch height (m)
Char height (m)	1	0.00022	2.40E-09
% Scorch crown	0.25	1	0.00001
Max. Scorch height (m)	0.39	0.83	1

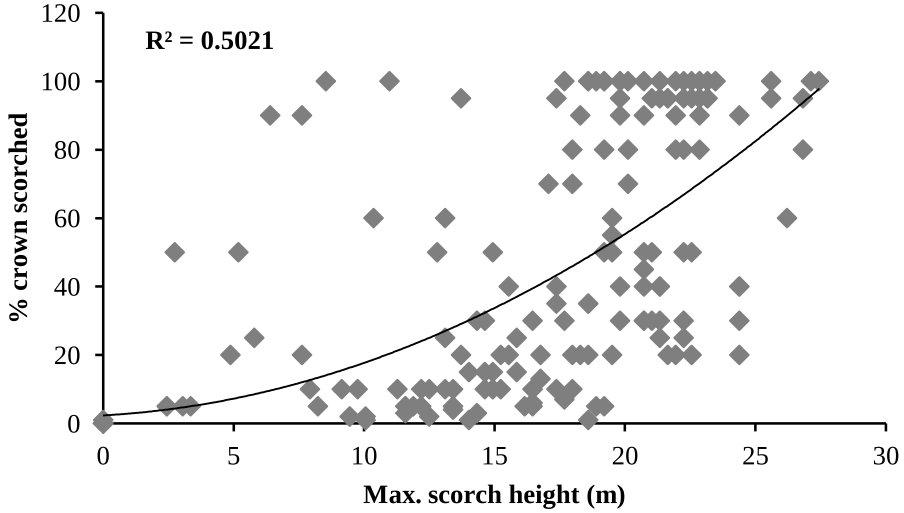

Figure 26: Scatter plot of relationship between tree bole scorch height (m) and % of crown scorched (n= 214).

Fireline intensity and fire severity in the overstory

For the 11 plots where fire intensity values from observations were available, simple linear regression analyses were conducted to test associations between fireline intensity, scorch height and % scorched crown (Figure 27). No significant relationships were found between variables (p-value=0.10, p-value=0.24), probably due to the large variability in fire behavior and small sample size. Associations between maximum fire temperature reached at the center of each plot and fire severity effects in the overstory were also tested for all plots (n=27) but neither were found to be significant (scorch height p-value=0.06, % crown scorched p-value=0.12).

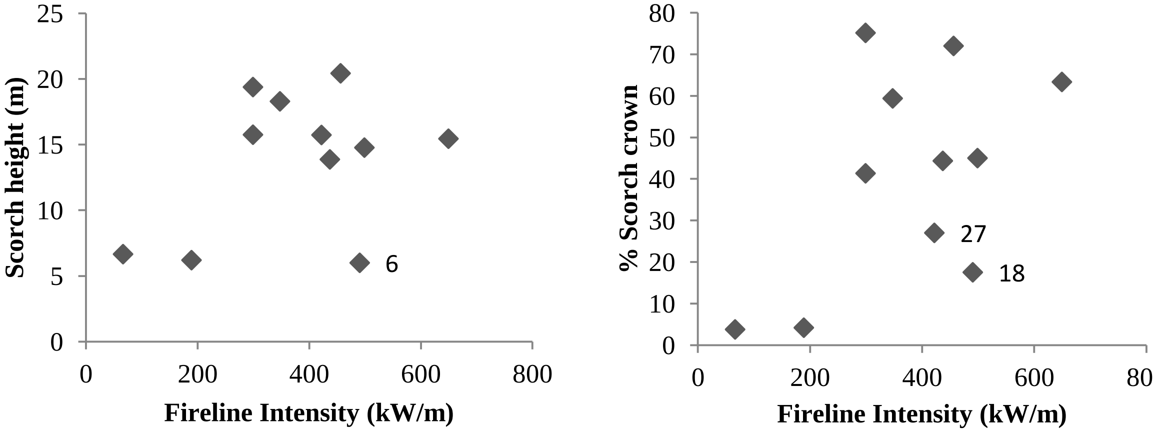

Figure 27: Relationships between bole scorch height (m) and % of scorched crown with fireline intensity (kW/m) estimated from fire behavior observations (FL) at 11 plots distributed across the burn unit.

Fire severity in the overstory and tree mortality

No tree mortality occurred but a few scattered trees outside of the inventoried plots were observed to have dead within 9 months after burning the experimental unit. Several studies have shown that there is a direct relationship between fire severity in the overstory, crown fire initiation (Alexander and Cruz 2012) and tree mortality (Fowler and Sieg 2004; Kobziar et al. 2006; Lutes 2014; Reinhardt et al. 2001) in conifer species. However, longleaf pine is adapted to fire and crown scorch is not a major cause of mortality in mature trees

(Hood 2007; Outcalt and Foltz 2004; Wang et al. 2007). Preliminary results of this study support this since several trees displayed 100% crown scorch after burning but they dropped and grew new needles fast (within 5 months) apparently recovering their photosynthetic capabilities.

On the other hand, recent research is pointing to fire effects in the ground derived from smoldering fires (residence time and moisture content) and environmental conditions such as relative humidity as better predictors for modeling longleaf mortality (Wang et al. 2007). Due to the normal lack of immediate mortality in the overstory in these ecosystems and because of the limited scope of this project, it was not possible to test any of these relationships but future research remains open in case of delayed mortality in the unit.

Fire severity in regeneration: seedlings mortality

*Note: when extrapolated to the landscape scale, a disproportionate number of seedlings was computed; this should be taken into account when interpreting the data.

Longleaf seedlings mortality and fuel consumption at the unit level

At a unit level, the prescribed burn had a mean mortality effect in the regeneration of 3,125 seedlings/ha (1,265 seedlings/ac); average maximum temperature reached at the center of the plots during the burn was 340 °C (644°F) and mean total fuel consumed was 18.2 Mg/ha (8.1 ton/ac), (Table 20).

Table 20: Summary statistics of longleaf seedlings mortality, max. temperature and fuel consumption at the unit level (n=27).

Variable	Mean	S.D.	S.E.	Min.	Max.
Total Mortality (#/ha)	3125	2529	487	247	9143
Max. Temperature Plot (°C)	340	74	14	149	454
Total Fuel Consumed (Mg/ ha)	18.19	9.08	1.75	5.21	40.38

Natural longleaf regeneration is usually found in larger openings, away from adult trees, where more resources (light and nutrients) are available (McGuire et al. 2001; Palik et al. 1997). Due to this patchy distribution and the random location of the plots and openings in the unit, the number of seedlings counted before the burn greatly differed from one plot to another as so did the number of dead seedlings and new regeneration after the burn (Figure 28). This consideration is important when analyzing seedling mortality patterns across the unit and the reason why statistical analysis were conducted based on a ratio of dead seedlings to seedling before the burn.

In general, a higher number of seedlings was found before burning in the southern area of the unit, where natural regeneration was more active due to tree spacing. Plots 1, 2, 3, 4, 5, 6 & 7 were clustered together and located in an area with more openings, so after the fire removed the wiregrass and litter covering the ground, conditions were better for germination than in the north portion. Plots 20, 26 & 27 also had a high number of pre burn seedlings, even though they are located in the northeast of the unit which has a higher tree density but few hardwoods in the understory. The northwest portion of the unit had a higher longleaf tree density and larger presence of hardwoods in the understory and therefore, regeneration was not very active before burning (13, 14, 18, 24 & 25). New regeneration was found at 13 plots, mainly located in the south were tree density was lower.

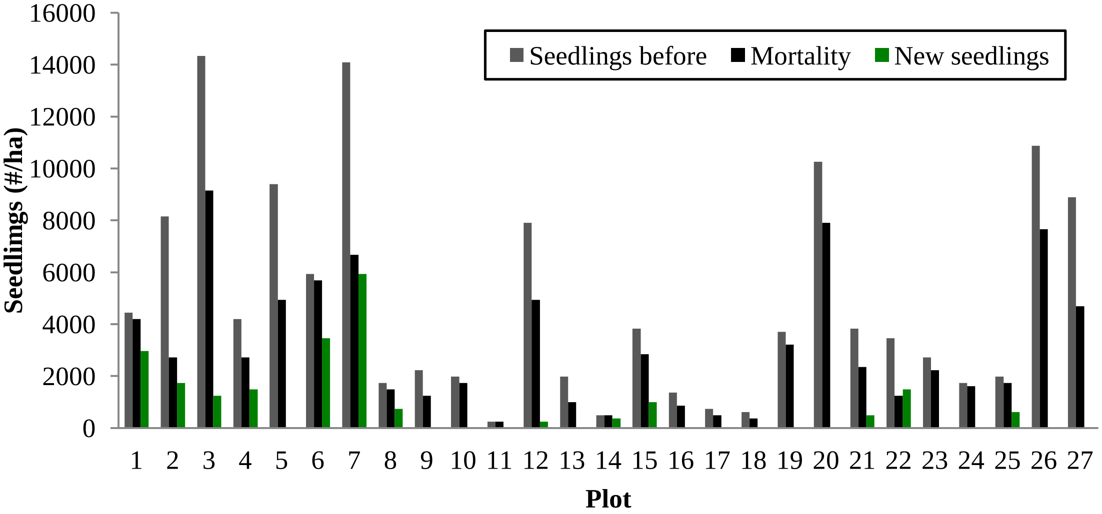

Figure 28: Longleaf seedlings distribution by plot, including number of seedlings before burning, dead seedlings (mortality) and new regeneration after burning

Since data were collected as a count and each individual tree was not identified, it was not possible to separate number of dead seedlings from new regeneration in cases where more seedlings were present after burning than before (height class 0 (between 0 and 0.3 m)). Therefore, this set of data was left out when analyzing mortality to avoid errors due to data contamination.

Simple linear regression analysis between mortality and fuel consumption did not showed a significant relationship. In fact, mortality was high or low independently of fuel consumption. Analyses were performed for total mortality (#/ha) and percentage mortality (dead seedlings/seedlings before), with similar results in both cases (Figure 29). In addition, a nonparametric Spearman correlation test was conducted and no significance was found between these variables.

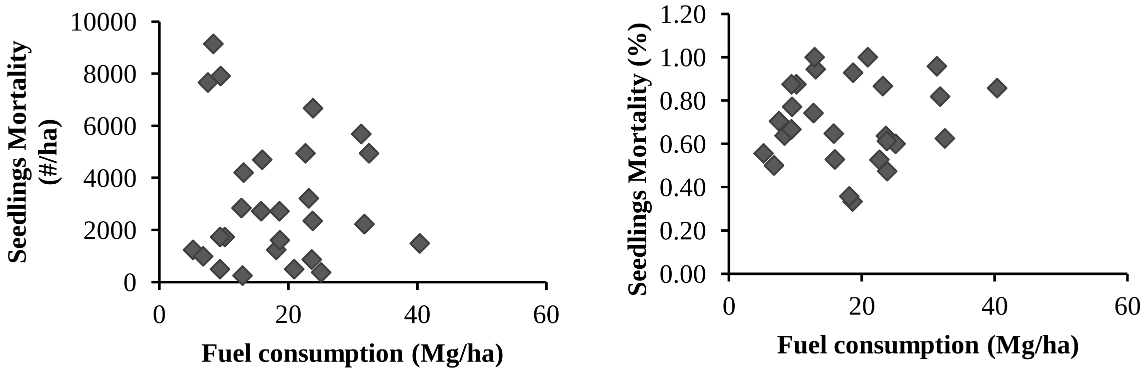

Figure 29: Longleaf seedlings total mortality and percentage mortality (independently of seedling height class) by plot vs. mean fuel consumption (Mg/ha) at each plot (n=27).

Longleaf seedlings/saplings mortality by height class and Temperature

Overall average maximum temperature was reached at the ground level (340 °C, 644°F) and decreased as the height increased. In the 23 plots where mortality was observed in seedlings 0.3 m high or taller, mean maximum temperature was 227 °C (441°F). No temperatures above 93 °C were recorded higher than 1.5 meters (Table 21). The lowest seedling mortality percent was observed at height class 0 but these values were left out of the statistical analysis to avoid uncertainty in the results. Seedlings mortality percent in the remaining dataset displayed a tendency to increase with height (from 0.3 to 1.5 m); with a higher rate of increase between 0.3 and 1.2 m. No information was available for mortality in taller seedlings (1.8 m), since none were counted in the pre burn inventory.

Table 21: Seedlings mortality and mean maximum temperature reached a during the burn by height class(m).

Height (m)	Variable	n	Mean	S.D.	Min.	Max.
0.3	Temperautre (°C)	23	227.43	93.84	121	371
	Seedlings Before (#/ha)		1982.17	1738.39	247	6425
	Mortality (#/ha)		1520.26	1331.99	0	4571
	Mortality percent (%)		0.81	0.27	0	1
0.6	Temperautre (°C)	17	163.18	68.65	90	316
	Seedlings Before (#/ha)		1613.35	1802.47	124	6178
	Mortality (#/ha)		1417.18	1583.55	124	5189
	Mortality percent (%)		0.89	0.18	0.33	1
0.9	Temperautre (°C)	5	114.2	24.87	90	149
	Seedlings Before (#/ha)		345.8	135.29	247	494
	Mortality (#/ha)		321.2	110.52	247	494
	Mortality percent (%)		0.95	0.11	0.75	1
1.2	Temperautre (°C)	3	109.67	34.06	90	149
	Seedlings Before (#/ha)		288.33	71.59	247	371
	Mortality (#/ha)		288.33	71.59	247	371
	Mortality percent (%)		1	0	1	1
1.5	Temperautre (°C)	1	93	0	93	93
	Seedlings Before (#/ha)		247	0	247	247
	Mortality (#/ha)		247	0	247	247
	Mortality percent (%)		1	0	1	1

Preliminary exploration was performed to understand the relationships between seedling mortality and temperature at different heights (Figure 30). Figure 30 should be interpreted with caution considering that it is only displaying the average mortality percentage and maximum temperature at each height, not the statistical relationships between mortality (dependent variable), temperature and height (independent variables). Despite this, mortality percentage does not increase when temperature decreases, but it does increase when height increases, and the interaction effect between height and temperature cannot be interpreted in the graph.

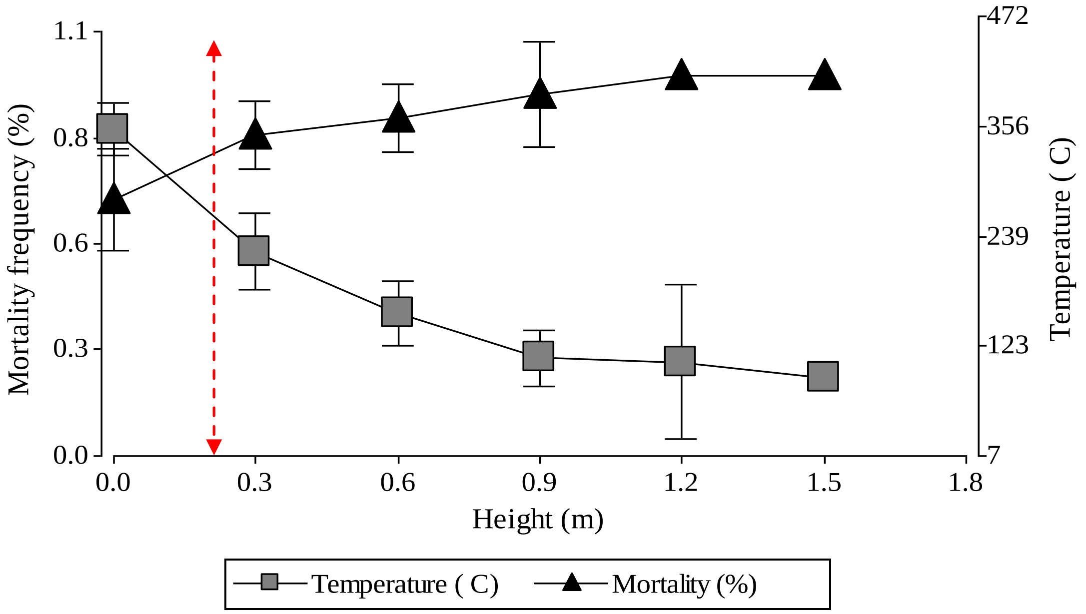

Figure 30: Seedling mortality (%) and maximum temperature (°C) by height (m) (with 95% CI bars). Mortality data left of the red line include new seedling response following fire and were left out of statistical analysis.

Based on the data available (n=49), several mortality models were analyzed. Equation 13 is the one that best represented the data. It is a negative binomial regression model with the form:

$$\text{Mortality} = 0.7123 + 1.0325\text{H} - 0.0003\text{T} + 0.00374\ (\text{HT}) \qquad (13)$$

Where **mortality** equals **Log** $\left(\frac{\pi}{1-\pi}\right)$ which is the log of the odds ratio (where π is the probability of mortality and **1-π** is the probability of no mortality); **H** is seedling height (m), **T** is temperature (°C) and **HT** is the interaction between both independent variables. Both variables and their interaction were found highly significant (p-value<0.0001, Table 22; Figure 31).

Table 22: SAS output from GLIMMIX procedure. Model information and parameter estimates for negative binomial regression model to predict percentage of seedlings mortality based on temperature and height (n=49).

Model Information	
Response Variable (Events)	Mortality
Response Variable (Trials)	Seedlings before
Response Distribution	Binomial
Link Function	Logit
Estimation Technique	Maximum Likelihood
Degrees of Freedom Method	Residual

Parameter Estimates				
Effect	**Estimate**	**SE**	**t Value**	**Pr > |t|**
Intercept	0.7123	0.07373	9.66	<.0001
Height (m)	1.0325	0.1784	5.79	<.0001
Temp (°C)	-0.00304	0.000414	-7.33	<.0001
Height*Temp	0.01229	0.001152	10.67	<.0001

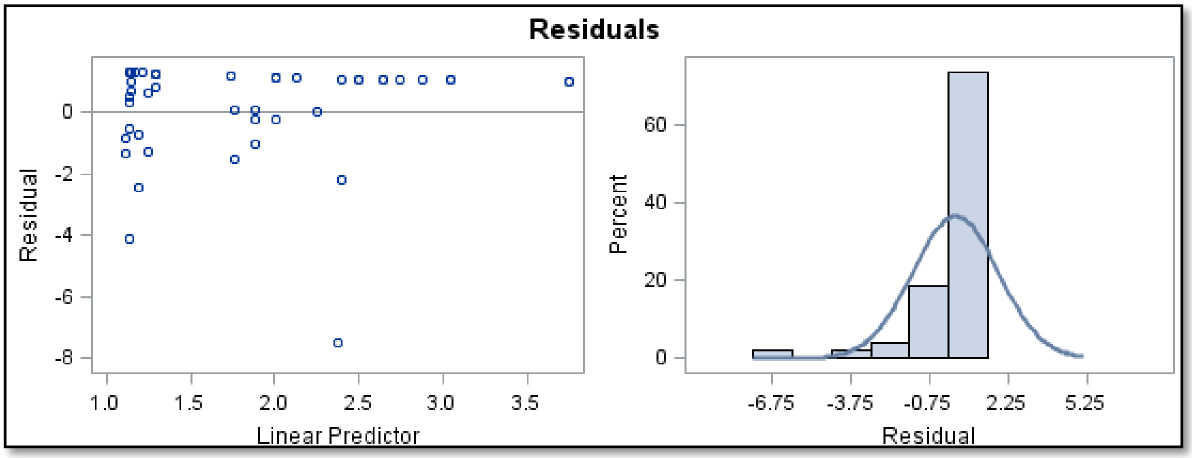

Figure 31: Residual plot of negative binomial regression model to predict percentage of longleaf seedlings mortality based on temperature and height (n=49).

In general, these regression models are difficult to interpret since estimates of the coefficients are given as the log form of the response variable; and computer programs are needed to transform them in mortality prediction values applicable from a management point of view. To understand the predicted effects and to facilitate using the model to make predictions, an inverse link function was run in SAS to interpret some odds ratio estimates. Interpretation of the effects was conducted on a multiplicative scale (as odds ratios or incidence rate) and percentage of mortality was estimated for selected temperatures (Table 23 & Table 24).

Since the interaction between height and temperature is significant in the model (p-value < 0.0001) interpretation of mortality has to be conducted considering both variables. Considering 300 °C as a temperature base line and keeping height constant, when temperature increases by 10 °C, the effect of the temperature increases by a factor of 1.081; that is, the percentage of mortality is increased by (1.081−1)×100% = 8.1%. In the same conditions, a decrease of 10 °C in temperature would result in 7.5% reduction in mortality (Table 23).

Table 23: Odds ratio estimates for variations in temperature (at a constant height) and corresponding percent variation in mortality, (Height = 0.8826 corresponds with mean seedling height for the data set).

Odds Ratio Estimates							Percentage of Mortality
Temp (°C)	Height (m)	Temp (°C)	Estimate	DF	95% CL		
290	0.8826	300	0.925	45	0.913	0.937	-7.5
310	0.8826	300	1.081	45	1.067	1.095	8.1
320	0.8826	300	1.169	45	1.139	1.199	16.9
330	0.8826	300	1.264	45	1.216	1.314	26.4

Mortality predictions based on height changes have a more complex interpretation due to the nature of the odds ratio estimates obtained from the model. Considering 0.3 m as a height base line and keeping temperature constant, when height increases by 0.3 m, the percentage of mortality increases by multiple of 2.47; and if the height increases from 0.3 to 0.9 m, the percentage of mortality increases by 6.1 times mortality predicted for seedlings at 0.3 m (Table 24).

Table 24: Odds ratio estimates for variations in height (at a constant temperature) and corresponding amount of variation in mortality, (Temperature = 161.28 corresponds with mean temperature for the data set).

Odds Ratio Estimates						
Height (m)	**Temp (°C)**	**Height (m)**	**Estimate**	**DF**	**95% CL**	
1.5	161.28	0.3	37.232	45	31.354	44.212
1.2	161.28	0.3	15.073	45	13.25	17.146
0.9	161.28	0.3	6.102	45	5.599	6.649
0.6	161.28	0.3	2.47	45	2.366	2.579

DISCUSSION AND CONCLUSIONS

This study indicates that before burning, the total fuel load in Unit 27 at the Calloway Forest varied from 21.31 to 24.11 Mg/ha (9.51-10.76 ton/acre) depending on the estimation method. The highest loadings came from litter and duff components (54-49 % and 39-39%, respectively), as expected in this type of Southern ecosystem (Sackett 1975). Load estimates were consistent with values found in similar ecosystems (Evans 2012; Lashley 2014; Robertson, personal communication 2014), but differed from a recent study conducted in the same area (Strand et al. 2013). A more in depth analysis of the differences between these studies revealed that inventory design, fuel definitions and collection methods were different and, therefore the outputs not comparable. Detailed information about fuel load estimations and management recommendations regarding them can be found in Chapter 1 of this document.

Fuel load distribution was heterogeneous across the unit. Although previous research has pointed to tree density influencing litter distributions (Bale 2009), with the information available in this study, significant relationships between basal area and forest floor fuels were not observed. Previous studies in coniferous forests have also found that litter and duff tend to accumulate at the base of the trees (Hille and Den Ouden 2005). No information about these “mounds” was collected during the field inventory and further analyses about weather canopy cover related to these fuel accumulations were not possible. However, especially when working with long-unburned stands, I recommend placing particular stress upon this fuel distribution pattern since duff smoldering at the base of trees is highly related with tree mortality (Hood 2010; Kreye et al. 2014; Varner 2005).

Total fuel load consumption estimates were different depending on estimation method, ranging between 12.1 Mg/ha (5.4 ton/ac) for biomass collection and 17.3 Mg/ha (7.73 ton/acre) for planar intersect (PI). PI total fuel estimation was 5 Mg/ha (2.3 ton/ac) higher with similar higher estimates for litter and duff consumption predictions. Due to the characteristics of each method (Catchpole and Wheeler 1992; Sikkink and Keane 2008), variances observed in the data and the possible error sources, estimates obtained with the biomass collection were considered more precise for litter and duff consumption values. Wiregrass aboveground parts were completely consumed during the burn so consumption was considered 100%. CWM loadings increased between the pre burn inventory and the day of the burn due to weather conditions, so, estimates of consumption for this component were difficult to assess. These woody fuels were not main carriers of the fire and therefore did not play an important roll affecting fire behavior and associated fire effects. However, it is interesting to highlight that 17 out of the 27 plot had higher CWM loads after burning than before (negative consumption values), due to an increase in the number of branches on the ground between the first inventory and the burn.

When modeling litter and duff consumption with software such as FOFEM or Consume, it is usual to assume total combustion in litter and duff. However, this effect only occurs in the most intense fires. Fuel consumption in longleaf ecosystems that have been managed with low intensity-frequent fires is patchy and highly variable because of the heterogeneity of the litter and wiregrass distributions. Previous research, has shown that about 2.2 Mg/ha (1 ton/acre) of litter remains after fire passes through (Bale 2009). This agrees with results observed in this study with 0.73 to 3.31 Mg/ha (0.3-1.5 ton/acre) of litter left unburned. Duff consumption can be even patchier, ranging from completely burned areas to unburned or scarcely burned areas (Miyanishi and Johnson 2002; Miyanishi 2001). Consumption is closely related with moisture content (Miyanishi 2001; Varner et al. 2007) and partially dependent on mineral content in the duff (Garlough and Keyes 2011). Since the burn was conducted in the dormant season (higher moisture content) and in an area where sand is quite mixed with duff, low smoldering consumption rates were expected. This assumption was consistent with the results observed and about half of the available duff was left unburned (3 to 5 Mg/ha, 1.5-2.5 ton/acre).

Recent studies have suggested pre burn forest floor depth is a good indicator of forest floor removal after burning, independent of fuel moisture (Goodrick et al. 2010; Wang et al. 2007). Based on this assumption, I tested the equation proposed by Wang et al. (2007) for longleaf ecosystems. Measured and estimated values differed by 9.4 mm (0.4") with 15 % more consumption observed than predicted. Since duff depth field measurements were subject to several sources of inaccuracy, this difference in forest floor removal might be due to errors associated with measurements rather than errors associated with the predictors. The forest floor depth removal equation obtained from pre burn data available from the study had a very high coefficient of determination ($R^2 = 0.959$). This confirmed that a strong association exists between forest floor depth removal and pre burn forest floor depth. However, the equation developed was based only on field measurements and data from one experimental burn and farther calibration is needed. Since fuel consumption is conditional on the effects of fuel moisture, weather and fire behavior (Anderson et al. 2003; Goodrick et al. 2010) and these variables were not included in the analysis, I recommend interpreting this information with caution and understanding its limitations.

Weather conditions during the burn were within the desired weather prescription and there were no unexpected changes. Hotter conditions, with higher temperatures and lower relative humidity, were observed from 2:00 to 4:00 pm. This affected fire behavior and an increase in flame length and fire intensity was observed. Fireline intensity estimations based on fire behavior observations (FL) (Byram 1959) ranged from 298 kW/m (FL = 1.02 m) in the east side to 588 kW/m (FL = 1.42 m) in the northwest. They were similar to previous data reported for low intensity burns in longleaf ecosystems (Alexander and Cruz 2012) and former burns conducted at the Calloway Forest (Strand et al. 2013).

Relationships between fire intensity and fire severity in the overstory have been widely studied; and relationships between fireline intensity and scorch height have been used to model crown fire initiation and fire effects (Alexander 1982; Alexander and Cruz 2012; Byram 1959; Van Wagner 1973). However, with the information available, no apparent relationship between these variables was found in the study area, probably due to the small sample size (n=11). On the other hand, percent of crown scorched has been shown to be successful for modeling post-fire tree mortality in several species (Borchert et al. 2002; Fowler and Sieg 2004; Kobziar et al. 2006; Ryan and Reinhardt 1988) and it is used as a predictive variable in modeling software such as FOFEM (Lutes 2014). However, due to the high tolerance of longleaf pine to fire (Hood 2010; Outcalt and Foltz 2004), it seems that crown scorched is not a good indicator of longleaf mortality (Wang et al. 2007) since complete crown scorch may not result in longleaf tree mortality, especially when prescribed fires are conducted during the dormant season (Sparks et al. 2002). In this study, 22% of the inventoried trees had above 85% crown scorched. Nevertheless, no mortality was observed in the unit 9 months after burning. These results support that % crown scorched is a poor indicator of immediate tree mortality in .longleaf pine.

Delayed mortality might occur several years after burning. I suggest continuing to monitor tree condition and proceed with further investigation in case of mortality. Variables such as environmental conditions (Goodrick et al. 2010), duff moisture (Ferguson et al. 2002; Varner et al. 2007), burn season (Sparks et al. 2002) and external factors (insects) (Evans 2012; Sullivan et al. 2003) should be considered since they seem to be more closely tied to mortality than fire severity effects in the canopy.

After analyzing seedling mortality and its relationship with fuel consumption, no significant relationships were found with the information available. This result differs from previous research (Forest Service Research Notes 1974) and those reported by Gagnon et al. (2010) who found significant relationships between high litter loadings and seedling mortality in longleaf stands.

Gagnon et al. (2010) also found that seedlings < 0.2 m (0.65 ft) were more likely to die after burning than seedlings bigger than 0.2 m with root collar diameter (RCD) < 15 cm (5.9 inches); however, the causes of mortality were not clearly related to fuel loadings. In this study, since seedling data for individuals < 0.3 m was unreliable and was left out of the analysis, it was not possible to corroborate this observation. Results from data analysis indicated that seedling mortality increased with height between 0.3 m and 1.5 m. (1-4 ft). This is consistent with the characteristics of the species whose rocket stage (after grass stage to approximately 1.5 m (5 ft)) has been described as the most vulnerable period for seedlings (The Longleaf Alliance 2015). On the other hand, recent research (Forest Service Research Notes 1974; Knapp et al., personal communication 2014) has pointed to RCD as a better indicator of mortality than height class. Lack of information on RCD should be considered when interpreting the results of this study should be included for future research.

Finally, the mortality model developed in this study was based on field data from one burn and therefore it has limited applicability. Due to statistical limitations of the data, the result is a complex model and that can be difficult to interpret; therefore, it should be evaluated on other prescribed fires in longleaf pine forests. Although the mortality model has several limitations, it is a good starting point to help understand dynamics between prescribed fire effects and regenerations and it does contribute to the limited knowledge between fire and longleaf seedling response.

GENERAL BURN OBJECTIVES ACCOMPLISHMENT REVIEW

The four general objectives for the prescribed burn plan for Unit 27 were:

1. Provide for safety of fire crew and public: Safety was assured for all people actively participating in the burn as well as for others in the area.
2. Top kill 50% of the hardwood mid-story (DBH< 3"): This information was not analyzed in the study.
3. Reduce fuel load by 50% or 25. 4 mm (1") in the 50.8 mm (2") fine fuel layer (litter).

   Total fuel load was reduced by 57% according to the biomass collection method and by 72% according to the planar intersect method. Total pre burn litter depth was slightly higher than that specify in the burn plan, with an actual depth of 54.7 mm (2.2"). Corresponding post burn depth was 3.3 mm (0.1"). Therefore, observed litter removal after burning was 51.4 mm (2.1") which is more than double that initially planned. In addition, there was also a duff depth removal of 9.8 mm (0.4").
4. Maintain flame lengths below 1.2-1.5 m (4-5 ft) to minimize crown scorch and tree stress on longleaf pines

   In general, observed mean flame lengths were below 1.5 m (5 ft) but above 1.2 m (4ft), especially in the northwest part of the unit; after 1:30 pm mean flame lengths were above 1.2 independent of their location. Crown scorch was observed in 161 trees out of 214 sampled (75% crown scorch), with 24 trees completely scorched (100%) and 46 having more than 85% of the crown affected.

MANAGEMENT RECOMMENDATIONS

- Fuel loadings and forest floor depth were higher than expected based on data included in the burn plan. Since fuel loading directly affects fire behavior, it is recommended to incorporate a fuel monitoring program as part of the Calloway Forest management plan. Furthermore, specific information and management objectives for each burn unit should be incorporated to help monitor, plan and meet the goals of individual burns.
- Larger litter and duff accumulations were observed at the base of the trees during field work, but were not documented. Land managers should consider this accumulation pattern, especially when introducing fire in long-unburned stands, because recent research is pointing to smoldering in the accumulated organic matter at the base of the tree as the most probable cause of mature longleaf pines mortality.
- Burn managers should consider different firing techniques if lower duff depth removal (smoldering) is desired (such us heading fires). In addition, incorporating both dormant and growing-season burns, with variability in fire return intervals and fire intensity, would create a mosaic of fire effects in the ground and help to maximize understory plant species and structural diversity.
- On site weather estimations reported higher RH% (5-12%) and lower wind speed estimates (3-4 km/h) than those provided by the RAWS. I suggest fire managers consider these variations, especially in hotter times of the day, when fire behavior can be more explosive. Also, I recommend calibrating electronic devices such as Kestrels every season, as well as conducting training and refresher courses for fire crew members.

- Percentage of crown scorched in longleaf trees should not be a big concern for longleaf land managers if terminal buds are not affected. It is recommended that burning activities be limited in the transition period between dormant and growing season (late March-April). In that period terminal buds are more susceptible to fire damage and insect attacks (especially southern pine beetles) more probable due to population dynamics.
- Finally, when natural regeneration survival is a concern, I recommend taking into account that seedlings mortality can be higher in seedlings that are between 0.3 and 1.5 m tall. In addition, recent research points to root collar diameter (RCD) as a good indicator of survival and recommend actions are to not burn a plantation until RCD is greater than 1.3 cm (0.5 inches), (Knapp et al., unpublished material 2014). Also, I recommend burning young plantations in the dormant season or, if burning in the growing season, waiting until after the “candle” has become covered with green needles (May or June).

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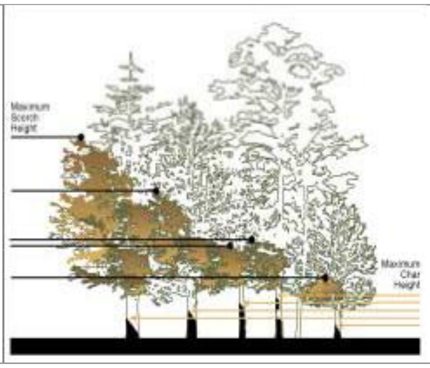
APPENDICES

Appendix A: Monitoring protocols for Study area

Pre-burn monitoring protocols for Unit 27 (Calloway Forest)

<table>
<tr><th>Data Type</th><th>Attributes and Details</th><th>Equipment</th></tr>
<tr><td>**Plot location**</td><td>UTM coordinates of plot center</td><td>GPS, rebar, hammer, flagging,</td></tr>
<tr><td>**Aspect**</td><td>Azimuth</td><td>Compass</td></tr>
<tr><td>**Elevation**</td><td>From DEM/GIS</td><td></td></tr>
<tr><td>**Slope**</td><td>Nearest percent</td><td>Clinometer</td></tr>
<tr><td>**Slope position**</td><td>upper, mid, lower</td><td></td></tr>
<tr><td>**Slope shape**</td><td>flat, concave, convex</td><td></td></tr>
<tr><td>**Photos**</td><td>1 repeatable photo point will be established per plot (located at center, 5 pics (N,E,S,W, canopy)</td><td>Digital camera, plot ID placards, pole</td></tr>
<tr><td rowspan="2">**Fuels Measurements**</td><td>**Planar Intercept Method (Brown’s)**
Three 50-ft transects, located at the center of the plot and 120° apart.
Litter and duff depths: 4 measurements
CWM: count 1-hr: 6 feet 10-hr: 6 feet 100-hr: 12 feet 1000-hr: 50 feet. 1000-hr fuels (woody ≥ 3” diameter at intersection) by diameter</td><td>50 ft tape, ruler, sampling dowels (1/4 in. and 1 in.), survey pins, trowel</td></tr>
<tr><td>**Biomass sample**
One per plot. Collect all dead and live fuels locate in a 2.6 x 2.6 square ft, 25 feet from center of the plot at a random bearing.</td><td>trowel, gloves, plastic bags, tags, square frame</td></tr>
<tr><td>**Understory**
(data will be collected for non-tree species in 1 of the 50-ft Line Intercept transects, as fuels)
Measure distance/estimate percentage of cover</td><td>ID deciduous/evergreen shrubs
Measure distance in the transect and estimate %Cover related to total length (50-ft) for the following life forms:
bare ground, grass/grass-like, ferns, other herbs/forbs, vines, deciduous and evergreen shrubs</td><td>Tape/ruler
shrubs field guide</td></tr>
<tr><td rowspan="4">**Trees**
(data collected for all trees ≥ 2 inches DBH within a 1/10th acre fixed radius plot) **(radio= 37 feet)**</td><td>Species</td><td>ID field guides</td></tr>
<tr><td>DBH, Height</td><td>Clinometers</td></tr>
<tr><td>Mortality class: 0,1,2,3,4</td><td></td></tr>
<tr><td>Crown class: D, C, I, O</td><td></td></tr>
<tr><td rowspan="3">**Regeneration**
(seedlings will be separated by sp and count by height class (if < 2 inches DBH) within a 1/50th or 1/100th acre fixed radius plot)
(radio= 16’6 feet)</td><td>Stem count by species</td><td></td></tr>
<tr><td>Stem height:<table>
<tr><td>**1**</td><td>≤ 6 in or 0.5 ft</td><td>**5**</td><td>3.1 ft – 6 ft</td></tr>
<tr><td>**2**</td><td>6.1 in - 1 ft</td><td>**6**</td><td>6.1 ft – 9 ft</td></tr>
<tr><td>**3**</td><td>1.1 ft – 2 ft</td><td>**7**</td><td>9.1 ft – 12 ft</td></tr>
<tr><td>**4**</td><td>2.1 ft – 3 ft</td><td>**8**</td><td>12.1 ft – 15 ft</td></tr>
</table></td><td>Yardstick, ruler</td></tr>
<tr><td>Stem origin: Sprout/sucker & Single stem</td><td></td></tr>
</table>

Post burn monitoring protocols for Unit 27 (Calloway Forest)

<table>
<tr><th>Data Type</th><th>Attributes and Details</th><th>Equipment</th></tr>
<tr><td>Photos</td><td>1 repeatable photo point will be established per plot (located at center, 5 pics (N,E,S,W, canopy)</td><td>Digital camera, plot ID placards, pole</td></tr>
<tr><td>Fire Severity across the macroplot</td><td colspan="2"><table>
<tr><th>Fire Severity</th><th>Substrate</th><th>Forest</th><th>Shrub</th><th>Grassland</th></tr>
<tr><td>Unburned (5)</td><td></td><td></td><td></td><td></td></tr>
<tr><td>Scorched (4)</td><td></td><td></td><td></td><td></td></tr>
<tr><td>Lightly Burned (3)</td><td></td><td></td><td></td><td></td></tr>
<tr><td>Moderately Burned (2)</td><td></td><td></td><td></td><td></td></tr>
<tr><td>Heavily burned (1)</td><td></td><td></td><td></td><td></td></tr>
<tr><td>Not Applicable (0)</td><td></td><td></td><td></td><td></td></tr>
</table></td></tr>
<tr><td rowspan="2">Fuels Measurements</td><td>Planar Intercept Method (Brown's)
Three 50-ft transects, located at the center of the plot and 120° apart.
Litter and duff depths: 4 measurements
CWM: count 1-hr: 6 feet 10-hr: 6 feet 100-hr: 12 feet 1000-hr: 50 feet. 1000-hr fuels (woody ≥ 3” diameter at intersection) by diameter</td><td>50 ft tape, ruler, sampling dowels (1/4 in. and 1 in.), survey pins, trowel</td></tr>
<tr><td>Biomass sample
One per plot. Collect all dead and live fuels locate in a 2.6 x 2.6 square ft, 25 feet from center of the plot at a random bearing.</td><td>trowel, gloves, plastic bags, tags, square frame</td></tr>
<tr><td>Understory (data collected in all 50-ft Line Intercept transects)</td><td>ID deciduous/evergreen shrubs
Measure distance in the transect and estimate %Cover related to total length (50-ft) for the following life forms:</td><td>Tape/ruler
shrubs field guide</td></tr>
<tr><td>Trees
(data collected for all trees ≥ 2 inches DBH within a 1/10th acre fixed radius plot)
(radio= 37 feet)</td><td>
</td><td>-Species
-DBH
-Max. Scorch height
-% Scorch crown
-Char height</td></tr>
<tr><td rowspan="2">Regeneration
(seedlings will be separated by sp and count by height class (if < 2 inches DBH) within a 1/50th or 1/100th acre fixed radius plot)
(radio= 16’6 feet)</td><td>Stem height:<table>
<tr><td>1</td><td>≤ 6 in or 0.5 ft</td><td>5</td><td>3.1 ft – 6 ft</td></tr>
<tr><td>2</td><td>6.1 in - 1 ft</td><td>6</td><td>6.1 ft – 9 ft</td></tr>
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</table></td><td>Yardstick, ruler</td></tr>
<tr><td>Stem origin: Sprout or Single stem</td><td></td></tr>
</table>

Appendix B: Pre burn fuel loads in Unit 27, at Calloway Forest Preserve.

Table B 1: Pre burn fuel loads collected with the Biomass sample method at burn unit 27, at Calloway Forest Preserve. Fuels by fuel type, n=27.

	Litter		**Duff**		**Wiregrass**		**Total CWM**		**Other live**		**Total Biomass**	
Plot Id	**Mg/ha**	**(ton/ac)**	**Mg/ha**	**(ton/ac)**	**Mg/ha**	**(ton/ac)**	**Mg/ha**	**(ton/ac)**	**Mg/ha**	**(ton/ac)**	**Mg/ha**	**(ton/ac)**
1	14.99	6.68	1.48	0.66	0.00	0.00	0.39	0.18	3.33	1.49	20.19	9.01
2	4.65	2.08	6.52	2.91	5.30	2.36	0.00	0.00	0.65	0.29	17.12	7.64
3	8.11	3.62	20.05	8.94	1.14	0.51	0.67	0.30	0.00	0.00	29.96	13.37
4	4.33	1.93	2.81	1.25	1.46	0.65	0.00	0.00	0.03	0.01	8.64	3.85
5	12.80	5.71	12.08	5.39	0.00	0.00	0.56	0.25	0.18	0.08	25.62	11.43
6	10.47	4.67	2.98	1.33	0.00	0.00	0.17	0.07	0.09	0.04	13.71	6.11
7	13.68	6.10	4.60	2.05	0.00	0.00	6.37	2.84	2.55	1.14	27.21	12.14
8	12.64	5.64	4.36	1.95	0.00	0.00	1.18	0.53	0.00	0.00	18.19	8.11
9	8.95	3.99	2.04	0.91	0.00	0.00	2.07	0.92	0.31	0.14	13.37	5.97
10	11.33	5.05	12.74	5.68	1.90	0.85	0.89	0.40	0.94	0.42	27.80	12.40
11	13.96	6.23	21.95	9.79	0.00	0.00	0.76	0.34	0.00	0.00	36.67	16.36
12	9.71	4.33	22.44	10.01	2.75	1.23	0.18	0.08	0.00	0.00	35.09	15.65
13	17.51	7.81	7.30	3.26	0.00	0.00	0.42	0.19	0.00	0.00	25.24	11.26
14	16.26	7.26	8.96	4.00	0.00	0.00	0.24	0.11	0.91	0.41	26.37	11.76
15	9.35	4.17	3.17	1.41	0.00	0.00	0.32	0.14	0.00	0.00	12.84	5.73
16	15.47	6.90	7.92	3.53	2.96	1.32	0.00	0.00	0.00	0.00	26.34	11.75
17	14.77	6.59	4.78	2.13	1.19	0.53	0.00	0.00	0.00	0.00	20.74	9.25
18	11.45	5.11	4.35	1.94	0.00	0.00	0.00	0.00	1.34	0.60	17.15	7.65
19	8.64	3.85	1.81	0.81	5.40	2.41	0.00	0.00	0.00	0.00	15.86	7.07
20	11.96	5.34	4.71	2.10	2.91	1.30	0.00	0.00	0.00	0.00	19.59	8.74
21	4.38	1.95	3.16	1.41	0.67	0.30	5.45	2.43	0.00	0.00	13.65	6.09
22	12.66	5.65	4.39	1.96	0.56	0.25	0.32	0.14	0.00	0.00	17.94	8.00
23	13.89	6.20	16.03	7.15	0.00	0.00	0.52	0.23	0.00	0.00	30.44	13.58
24	13.26	5.92	1.55	0.69	2.00	0.89	0.34	0.15	0.00	0.00	17.15	7.65
25	12.25	5.46	8.25	3.68	0.00	0.00	0.74	0.33	0.00	0.00	21.24	9.47
26	13.69	6.11	8.16	3.64	0.00	0.00	1.24	0.55	0.00	0.00	23.08	10.30
27	10.24	4.57	3.90	1.74	0.00	0.00	0.00	0.00	0.00	0.00	14.14	6.31
Avg.	11.53	5.15	7.50	3.35	1.05	0.47	0.85	0.38	0.38	0.17	21.31	9.51

Table B 2: Pre burn fuel loads collected with the Planar Intersect method at burn unit 27, at Calloway Forest Preserve. Fuels by fuel type, n=27.

	Mean Litter depth		**Mean Duff depth**		**Litter**		**Duff**		**Wiregrass**		**CWM**		**Total loading**	
Plot Id	**mm**	**(in)**	**mm**	**(in)**	**Mg/ha**	**(ton/ac)**	**Mg/ha**	**(ton/ac)**	**Mg/ha**	**(ton/ac)**	**Mg/ha**	**(ton/ac)**	**Mg/ha**	**(ton/ac)**
1	45.72	1.8	10.16	0.4	9.98	4.45	6.75	3.01	0.27	0.12	2.10	0.94	19.10	8.52
2	48.26	1.9	5.08	0.2	10.53	4.70	3.38	1.51	0.30	0.13	0.62	0.27	14.82	6.61
3	27.94	1.1	2.54	0.1	6.10	2.72	1.69	0.75	0.29	0.13	0.00	0.00	8.07	3.60
4	63.50	2.5	5.08	0.2	13.86	6.18	3.38	1.51	0.25	0.11	0.26	0.11	17.74	7.91
5	35.56	1.4	30.48	1.2	7.76	3.46	20.26	9.04	0.01	0.00	8.21	3.66	36.23	16.16
6	96.52	3.8	25.40	1.0	21.06	9.39	16.88	7.53	0.30	0.13	14.32	6.39	52.56	23.45
7	104.14	4.1	5.08	0.2	22.72	10.14	3.38	1.51	0.30	0.14	1.34	0.60	27.74	12.37
8	76.20	3.0	38.10	1.5	16.63	7.42	25.32	11.30	0.60	0.27	0.08	0.04	42.64	19.02
9	17.78	0.7	7.62	0.3	3.88	1.73	5.06	2.26	0.18	0.08	0.77	0.34	9.89	4.41
10	30.48	1.2	15.24	0.6	6.65	2.97	10.13	4.52	0.10	0.05	0.00	0.00	16.88	7.53
11	35.56	1.4	12.70	0.5	7.76	3.46	8.44	3.77	0.14	0.06	4.34	1.94	20.68	9.23
12	30.48	1.2	35.56	1.4	6.65	2.97	23.64	10.54	0.40	0.18	0.00	0.00	30.68	13.69
13	30.48	1.2	7.62	0.3	6.65	2.97	5.06	2.26	0.04	0.02	0.53	0.24	12.29	5.48
14	88.90	3.5	17.78	0.7	19.40	8.65	11.82	5.27	0.01	0.00	0.00	0.00	31.22	13.93
15	43.18	1.7	7.62	0.3	9.42	4.20	5.06	2.26	0.03	0.01	3.59	1.60	18.10	8.07
16	35.56	1.4	25.40	1.0	7.76	3.46	16.88	7.53	0.31	0.14	1.59	0.71	26.55	11.84
17	35.56	1.4	10.16	0.4	7.76	3.46	6.75	3.01	0.08	0.04	7.00	3.12	21.59	9.63
18	116.84	4.6	12.70	0.5	25.49	11.37	8.44	3.77	0.08	0.04	0.58	0.26	34.59	15.43
19	68.58	2.7	12.70	0.5	14.96	6.68	8.44	3.77	0.35	0.16	3.70	1.65	27.46	12.25
20	35.56	1.4	5.08	0.2	7.76	3.46	3.38	1.51	0.28	0.12	1.85	0.83	13.27	5.92
21	86.36	3.4	7.62	0.3	18.84	8.41	5.06	2.26	0.40	0.18	1.92	0.85	26.23	11.70
22	53.34	2.1	20.32	0.8	11.64	5.19	13.51	6.02	0.08	0.04	4.75	2.12	29.97	13.37
23	83.82	3.3	27.94	1.1	18.29	8.16	18.57	8.28	0.21	0.10	0.51	0.23	37.59	16.77
24	60.96	2.4	12.70	0.5	13.30	5.93	8.44	3.77	0.33	0.15	0.28	0.12	22.34	9.97
25	48.26	1.9	10.16	0.4	10.53	4.70	6.75	3.01	0.12	0.05	1.28	0.57	18.68	8.33
26	33.02	1.3	7.62	0.3	7.20	3.21	5.06	2.26	0.14	0.06	2.38	1.06	14.79	6.60
27	43.18	1.7	7.62	0.3	9.42	4.20	5.06	2.26	0.04	0.02	4.83	2.16	19.36	8.64
Avg.	**54.66**	**2.2**	**14.30**	**0.6**	**11.9**	**5.3**	**9.5**	**4.2**	**0.2**	**0.1**	**2.5**	**1.1**	**24.1**	**10.8**

Appendix C: Post burn fuel loads in Unit 27, at Calloway Forest Preserve (April 2014)

Table C 1: Post burn fuel loads collected with the Biomass sample method at burn unit 27, at Calloway Forest Preserve. Fuels by fuel type, n=27.

	Litter		Duff		Wiregrass		Total CWM		Other live		Total Biomass	
Plot Id	**Mg/ha**	**(ton/ac)**	**Mg/ha**	**(ton/ac)**	**Mg/ha**	**(ton/ac)**	**Mg/ha**	**(ton/ac)**	**Mg/ha**	**(ton/ac)**	**Mg/ha**	**(ton/ac)**
1	1.29	0.58	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.29	0.58
2	2.71	1.21	0.00	0.00	0.00	0.00	0.37	0.17	0.00	0.00	3.08	1.37
3	2.54	1.13	3.71	1.65	0.00	0.00	0.00	0.00	0.00	0.00	6.25	2.79
4	4.02	1.79	3.42	1.52	0.00	0.00	1.01	0.45	0.00	0.00	8.44	3.77
5	3.41	1.52	11.36	5.07	0.00	0.00	0.20	0.09	0.00	0.00	14.97	6.68
6	1.23	0.55	1.13	0.51	0.00	0.00	0.00	0.00	0.00	0.00	2.36	1.05
7	1.70	0.76	3.25	1.45	0.00	0.00	0.41	0.18	0.00	0.00	5.37	2.40
8	1.96	0.87	2.17	0.97	0.00	0.00	0.00	0.00	0.00	0.00	4.12	1.84
9	2.26	1.01	4.23	1.89	0.00	0.00	0.55	0.24	0.00	0.00	7.03	3.14
10	4.75	2.12	22.72	10.14	0.00	0.00	1.65	0.74	0.00	0.00	29.12	12.99
11	3.03	1.35	10.01	4.46	0.00	0.00	0.62	0.28	0.00	0.00	13.66	6.09
12	1.46	0.65	2.04	0.91	0.00	0.00	0.00	0.00	0.00	0.00	3.50	1.56
13	3.04	1.36	8.43	3.76	0.00	0.00	1.13	0.51	0.00	0.00	12.61	5.62
14	7.17	3.20	9.03	4.03	0.00	0.00	0.55	0.25	0.00	0.00	16.75	7.47
15	3.82	1.70	5.15	2.30	0.00	0.00	0.61	0.27	0.00	0.00	9.58	4.27
16	3.89	1.74	11.34	5.06	0.00	0.00	0.95	0.43	0.00	0.00	16.18	7.22
17	2.39	1.07	2.34	1.04	0.00	0.00	0.40	0.18	0.00	0.00	5.13	2.29
18	3.74	1.67	4.73	2.11	0.00	0.00	0.46	0.21	0.00	0.00	8.93	3.98
19	3.40	1.52	3.18	1.42	0.00	0.00	0.63	0.28	0.00	0.00	7.21	3.22
20	6.37	2.84	5.41	2.41	0.00	0.00	0.87	0.39	0.00	0.00	12.65	5.65
21	3.10	1.38	3.91	1.74	0.00	0.00	0.00	0.00	0.00	0.00	7.01	3.13
22	3.29	1.47	6.46	2.88	0.00	0.00	1.11	0.50	0.00	0.00	10.86	4.84
23	5.33	2.38	3.62	1.62	0.00	0.00	0.00	0.00	0.00	0.00	8.96	4.00
24	2.86	1.28	2.35	1.05	0.00	0.00	0.00	0.00	0.00	0.00	5.21	2.32
25	5.28	2.35	2.96	1.32	0.00	0.00	0.06	0.03	0.00	0.00	8.29	3.70
26	3.26	1.45	5.83	2.60	0.00	0.00	0.40	0.18	0.00	0.00	9.48	4.23
27	2.44	1.09	7.09	3.16	0.00	0.00	0.90	0.40	0.00	0.00	10.43	4.65
Avg.	3.32	1.48	5.40	2.41	0.00	0.00	0.48	0.21	0.00	0.00	9.20	4.11

Table C 2: Post burn fuel loads collected with the Planar Intersect method at burn unit 27, at Calloway Forest Preserve. Fuels by fuel type, n=27.

	Mean Litter depth		Mean Duff depth		Litter		Duff		Wiregrass		CWM		Total loading	
Plot Id	**mm**	**(in)**	**mm**	**(in)**	**Mg/ha**	**(ton/ac)**	**Mg/ha**	**(ton/ac)**	**Mg/ha**	**(ton/ac)**	**Mg/ha**	**(ton/ac)**	**Mg/ha**	**(ton/ac)**
1	2.54	0.1	2.54	0.1	0.55	0.25	1.69	0.75	0.09	0.04	3.52	1.57	5.85	2.61
2	1.91	0.1	0.00	0.0	0.42	0.19	0.00	0.00	0.05	0.02	0.79	0.35	1.26	0.56
3	0.64	0.0	0.64	0.0	0.14	0.06	0.42	0.19	0.05	0.02	0.00	0.00	0.61	0.27
4	2.54	0.1	3.18	0.1	0.55	0.25	2.11	0.94	0.05	0.02	0.51	0.23	3.23	1.44
5	3.81	0.2	8.89	0.4	0.83	0.37	5.91	2.64	0.00	0.00	6.83	3.05	13.58	6.06
6	0.64	0.0	10.80	0.4	0.14	0.06	7.17	3.20	0.03	0.01	13.65	6.09	20.99	9.36
7	1.91	0.1	2.12	0.1	0.42	0.19	1.41	0.63	0.04	0.02	1.79	0.80	3.65	1.63
8	1.27	0.1	0.00	0.0	0.28	0.12	0.00	0.00	0.09	0.04	1.38	0.62	1.74	0.78
9	3.18	0.1	3.39	0.1	0.69	0.31	2.25	1.00	0.03	0.01	1.56	0.69	4.53	2.02
10	3.81	0.2	8.89	0.4	0.83	0.37	5.91	2.64	0.01	0.01	1.79	0.80	8.54	3.81
11	2.54	0.1	3.18	0.1	0.55	0.25	2.11	0.94	0.01	0.01	4.98	2.22	7.66	3.42
12	1.27	0.1	0.00	0.0	0.28	0.12	0.00	0.00	0.03	0.02	0.26	0.11	0.57	0.25
13	3.81	0.2	3.81	0.2	0.83	0.37	2.53	1.13	0.01	0.01	2.11	0.94	5.48	2.45
14	6.99	0.3	12.07	0.5	1.52	0.68	8.02	3.58	0.00	0.00	0.77	0.34	10.31	4.60
15	1.91	0.1	1.91	0.1	0.42	0.19	1.27	0.56	0.02	0.01	3.66	1.63	5.36	2.39
16	2.75	0.1	5.08	0.2	0.60	0.27	3.38	1.51	0.02	0.01	1.59	0.71	5.59	2.49
17	3.18	0.1	8.26	0.3	0.69	0.31	5.49	2.45	0.04	0.02	7.12	3.18	13.34	5.95
18	6.35	0.3	4.87	0.2	1.39	0.62	3.24	1.44	0.00	0.00	4.81	2.14	9.43	4.21
19	3.18	0.1	10.16	0.4	0.69	0.31	6.75	3.01	0.06	0.02	1.89	0.84	9.39	4.19
20	3.81	0.2	3.18	0.1	0.83	0.37	2.11	0.94	0.06	0.03	3.47	1.55	6.46	2.88
21	1.91	0.1	1.91	0.1	0.42	0.19	1.27	0.56	0.05	0.02	1.04	0.46	2.77	1.23
22	5.72	0.2	11.22	0.4	1.25	0.56	7.46	3.33	0.01	0.00	3.63	1.62	12.34	5.51
23	4.45	0.2	4.23	0.2	0.97	0.43	2.81	1.26	0.02	0.01	1.79	0.80	5.60	2.50
24	3.81	0.2	6.35	0.3	0.83	0.37	4.22	1.88	0.04	0.02	0.28	0.12	5.37	2.39
25	3.18	0.1	10.80	0.4	0.69	0.31	7.17	3.20	0.03	0.01	1.28	0.57	9.18	4.09
26	6.99	0.3	4.02	0.2	1.52	0.68	2.67	1.19	0.10	0.04	2.93	1.31	7.23	3.22
27	5.72	0.2	1.27	0.1	1.25	0.56	0.84	0.38	0.01	0.00	1.28	0.57	3.38	1.51
Avg.	**3.32**	**0.13**	**4.92**	**0.19**	**0.73**	**0.32**	**3.27**	**1.46**	**0.03**	**0.02**	**2.77**	**1.23**	**6.79**	**3.03**

Appendix D: Fuel consumption

Table D 1: Final fuel consumption (at a plot level) adopted through the study. Original litter, duff, and CWM from the Planar Intersect method. Wiregrass from Biomass collection method.

	Fuel consumption in Mg/ha (ton/acre)				
Plot Id	**Litter**	**Duff**	**Wiregrass**	**CWM**	**Total**
1	9.42	5.06	0.00	-1.42	13.06 (5.82)
2	10.11	3.38	5.30	-0.17	18.61 (8.30)
3	5.96	1.27	1.14	0.00	8.36 (3.73)
4	13.30	1.27	1.46	-0.26	15.77 (7.04)
5	6.93	14.35	0.00	1.37	22.65 (10.15)
6	20.92	9.71	0.00	0.68	31.30 (13.96)
7	22.31	1.97	0.00	-0.45	23.82 (10.63)
8	16.35	25.32	0.00	-1.30	40.38 (18.01)
9	3.19	2.81	0.00	-0.79	5.21 (2.32)
10	5.82	4.22	1.90	-1.79	10.15 (4.53)
11	7.20	6.33	0.00	-0.64	12.89 (5.75)
12	6.37	23.64	2.75	-0.26	32.51 (14.50)
13	5.82	2.53	0.00	-1.57	6.78 (3.02)
14	17.87	3.80	0.00	-0.77	20.90 (9.32)
15	9.01	3.80	0.00	-0.08	12.73 (5.68)
16	7.16	13.51	2.96	0.00	23.62 (10.54)
17	7.07	1.27	1.19	-0.13	9.40 (4.19)
18	24.11	5.21	0.00	-4.23	25.08 (11.19)
19	14.27	1.69	5.40	1.81	23.17 (10.34)
20	6.93	1.27	2.91	-1.62	9.49 (4.24)
21	18.43	3.80	0.67	0.88	23.77 (10.61)
22	10.39	6.05	0.56	1.12	18.12 (8.08)
23	17.32	15.76	0.00	-1.28	31.80 (14.18)
24	12.47	4.22	2.00	0.00	18.69 (8.34)
25	9.84	-0.42	0.00	0.00	9.42 (4.20)
26	5.68	2.39	0.00	-0.55	7.52 (3.36)
27	8.17	4.22	0.00	3.55	15.95 (7.11)