Fuel lifecycle and long term fire behavior responses to fuel treatments in southeastern US pine ecosystems

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Abstract

We completed an investigation of the long term legacies of fuels treatments in longleaf pine sandhills at Eglin Air Force Base in the panhandle of Florida. From 1994-1999, The Nature Conservancy conducted a large-scale, long-term study at Eglin Air Force Base to compare the effectiveness of midstory reduction treatments, including herbicide, growing season fire, and mechanical clearing on the restoration of longleaf sandhill pine forests. The study plots have been monitored continuously since the completion of the original study and information still exists for all experimental sites, which have been burned as part of the prescribed fire program at Eglin AFB since the study concluded. We examined the legacy of these treatments on fire behavior 15+ years later in these plots. We measured multiple aspects of fuels and fire behavior in a subset of the original plots using a combination spatially explicit fuel sampling, high resolution visual and thermal imagery, wide and narrow field of view radiometers, thermocouples and thermopiles to collect data on fuel type, fuel loading, radiant and convective heat fluxes. We collected data in nine large operational prescribed fires that included the treatment plots in 2011. Preliminary data analyses showed that the impact of the treatments was not detectable in our measurements. The occurrence of frequent low intensity fires in the treatments appeared to have driven a convergence of fuel characteristics in plots with and without management interventions in as little as 16 years. Within stand variation in overstory derived fuels appeared to be more important in explaining fire behavior than the original treatments. We also completed an investigation of heat transfer in midstory oak stems. While these results are still being analyzed we found that in species with rough bark, heat transfer is much more complex and necessitates the consideration of three-dimensional information on bark topography and surface heating to develop accurate tissue damage models. The data we have collected will allow us to make those improvements. We also have developed a promising means (photogrammetry coupled with IR imagery) to rapidly capture the fine scale surface topography and heating of stems useful for improving such models.

Introduction

Project Objectives

Utilizing the re-sampling opportunity from the large scale experiment at Eglin AFB, we addressed task A under FA-RFA09-0001. To meet this request, we:

1. Documented the long-term differences in fire behavior within these treatments as a measure of long-term effectiveness.
2. Collected empirical stem heating data using *in situ* fire behavior measurements in longleaf pine sandhills to improve heat transfer models for woody stems.
3. We are in the process of analyzing and disseminated results for greatest impact on fuels management decision-making.

We have successfully concluded the measurements and have nearly completed analysis of the data. We have made three presentations and in the process of developing manuscripts and technical reports (See Deliverables).

Background

Southern pine forests, historically as well as today, are sustained by fire (Wade and Johanson 1986). Among the southern pine types, longleaf pine forests are the most fire dependent—in fact are among the most dependent globally. Historical fire frequency varied from annual to ten years, but the distribution appears to be skewed toward the most frequent (1-3) fire return intervals (Huffman 2006). This hyper frequent fire is needed to maintain the highest species richness of flowering plants (Glitzenstein et al 2003), to maintain rare species of plants (Kirkman et al. 2004), and fauna including the endangered Red-cockaded Woodpecker (Engstrom et al. 1984). Longleaf pine forests are well-represented on state and Federal lands across the Southeast and provide the primary habitat for the federally endangered Red-cockaded Woodpecker (RCW). Restoring fire regimes and forest structure of this ecosystem represents the most significant ecological challenge to public lands throughout the Southeast.

The southeastern US not only contains the most fire dependent ecosystems, but also has the greatest application of prescribed burning on public and private land nationally. However, before the widespread recognition of the importance of prescribed fire, the region had a significant period of inadequate fire frequency due to the policy of fire suppression in which many sites accumulated fuels and experienced alterations in forest structure. Inadequate fire frequency in habitats of this region result in rapid invasion by fire sensitive trees and shrubs that feedback to changes in fuels, fire behavior, and fire effects (Provencher 1999).

To counter this midstory encroachment and restore forest structure, a number of fuel reduction treatments have been applied to southern pine forests, including growing season fire, herbicide, and mechanical clearing. While each of these methods have been tested for short term response (Provencher 2001; Outcalt and Wade 2004), there have been no studies documenting the longevity of treatment effectiveness. Complete fuel recovery has been documented to take as little as six months in some sites. Whether or not undesired fire effects are mitigated in southern pinelands is closely tied to post treatment application of prescribed fire, which may in turn differ by fuel treatment type (White et al. 1991; Waldrop et al. 1992; Robertson and Ostertag 2006). Frequent prescribed fire is often used as a maintenance tool to manage treated fuelbeds, but evaluation of long-term response to fuel treatments is limited particularly as it relates to the ability to reestablish natural fire regimes post-treatment.

The impact of midstory encroachment on fuels and fire behavior have been poorly studied, although new technology has allowed some breakthroughs (Loudermilk et al. 2009, Hiers et al. 2009). Feedbacks from midstory encroachment are likely to reduce the window of prescribed fire conditions in which fire ignites and carries throughout a burn unit. Although, the effects of midstory on fire behavior are complex, producing decreased fire intensity and patchiness under normal prescribed fire parameters (high RH, low wind speeds) while increasing the risk of catastrophic fire conditions under dry windy conditions, especially during droughts. Moreover, the direct and indirect impacts on fire effects and biotic response to fire have not been thoroughly tested and still yield surprising contradictions to conventional wisdom (Hiers et al 2007). Better understanding of long-term fuel reduction treatment effectiveness would require careful measurement of fuels dynamics over a fire cycle, greater rigor in linking fuel characteristics to fire behavior, and a more fundamental understanding of variation in fire and fire effects.

Methods

Study Sites: Eglin Air Force Base

This study was conducted at Eglin Air Force Base (EAFB), Niceville, FL during 2010-2013 (Figure 1). EAFB, the former Choctawhatchee National Forest, located in the Florida panhandle, USA, and serves as an important reservoir of the longleaf pine ecosystem, containing nearly 180,000 ha of longleaf pine and over half of the remaining old growth (Varner et al. 2000; Holliday 2001). Lack of fire in some areas has led to the increase in density and crown cover of deciduous oaks as well as the expansion of *Pinus clausa* Vasey into the ecosystem and an increase of evergreen oaks such as *Q. virginiana* Miller (McCay 2000). EAFB conducts extensive longleaf restoration and management activities. All study sites were within the Southern Pine Hills District of the Coastal Plain Physiographic Province with deep, well-drained sandy soils (Brown et al. 1990). Soils of the study sites were all typic Quartzipsamments of the Lakeland series with mean depth to water table > 200 cm (Overing et al. 1995). The climate of the area is subtropical, with warm, humid summers and mild winters. Mean annual temperatures in the area are 19.7°C, with a mean annual precipitation of 1580 mm, most of which falls from June to September (Overing et al. 1995). Elevations of the study sites were 52 to 85 m above sea level, and all sites had the minimal topography typical of sand hills (Myers 1990). Vegetation was dominated by a longleaf pine overstory with a midstory of various deciduous oaks, e.g., *Quercus laevis* Walter, *Q. margaretta* Ashe, *Q. incana* Bartram, *Q. germinata* Small. The understory herbs and forbs are extremely diverse (Kirkman et a. 2013).

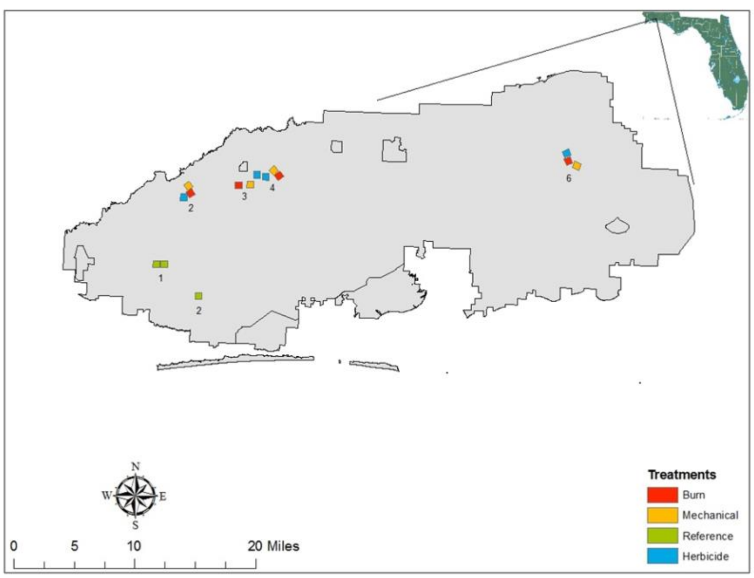


Figure 1. Study site with treatment blocks locations (numbered 1-6). EAFB is indicated by gray.

Sampling Design

The experiment was originally established for a long-term mid-story reduction study led by the

Nature Conservancy from 1994 to 1999 (Provencher et al. 2000). The study was arranged in six blocks with three experimental hardwood reduction treatments following a randomized complete block design. Treatments were applied in 1995 and consisted of girdling and felling of oaks and leaving slash, a broadcast application granular 75% hexazinone at 2.24 kg/ha and a burn only treatment. Of the six replicates in the original study, four replicates remained intact and available for sampling in this project. All plots have been burned both by prescribed fire (with some wildfires) multiple times since the completion of the study in 1999. In general, most sites had a two year accumulation of fuels when our experimental burns were applied in 2011 (Table 1). The fire return interval on the site averaged 3 years since the completion of the original study in 1999. We included three additional plots as reference sites to provide a benchmark for the desired future condition. We re-sample twelve of the eighteen 81-ha study plots from the original Nature Conservancy study as well as the three reference plots.

Each 81-ha oak removal treatment had four existing 40m x 40m long term monitoring plots that were established in the original study. Within each 81 ha treatment, one of the four monitoring plots was selected for establishment of a 4m x 4m highly instrumented plot (HIP) where detailed fire behavior observations would be made. Selection of the inventory plots for placement of the HIP was done with respect to its structural and spatial characteristics so as to capture the treatment wide legacy that remained from the original treatments. Further stratification was employed to avoid roads, creeks and fire breaks where unit wide fire behavior would not be represented due to the impacts of historical fire shadows or the impacts of operational techniques such as black lining (backing fire).

Table 1. Burn history from plots after completion of TNC study in 1999, a red x indicates a wildfire.

Plot	Year											
	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011
1a Ref	x		x		x		x			x		x
1b Ref	x	x					x			x		x
2 Herb		x		x				x	x	x		x
2 Mech					x				x	x		x
2 Burn		x		x				x		x		x
2 Ref	x	x		x	x	x	x	x	x		x	x
3 Herb				x	x			x		x		x
3 Mech							x		x	x		x
3 Burn		x				x			x			
4 Herb	x			x			x		x	x		x
4 Mech				x				x		x		x
4 Burn	x	x		x			x		x	x		x
6 Herb	x				x				x	x		x
6 Mech	x			x	x				x	x		x
6 Burn	x				x				x	x		x

Fuel Characterization

Once the long-term 40 x 40 m^2 inventory plots were selected, a HIP was established within each. Each HIP consisted of 4m x 4m area that was large enough to capture fuel heterogeneity at the 0.5 m scale while allowing for intensive point intercept sampling without disturbing the fuel structure. This was accomplished by suspending an extension ladder above the plot where points could be measured from above without disturbing the vegetation. Point intercept sampling was utilized within the HIP at the 0.5m scale for a total of 64 sample points per HIP. Each sample point represented the fuel characteristics within a 0.5 m^2 area or pixel. Therefore, each HIP had a 64 pixel "picture" to capture the fuel heterogeneity within the 4m x 4m area. Fuel characteristics measured at each point included height (height from mineral soil in cm) and type of fuel present. Selection of fuel type categories was influenced by categories established by Heirs et al. (2009). The 18 categories and their descriptions selected for this study are in Table 2.

To get estimates of fuel loadings among the treatments and around the HIPS, destructive sampling methods were employed. Clip plots were utilized at the 0.5m x 0.5m scale to coincide with the resolution of data collected in the HIPS. Ten (0.25m^2) clip plots were placed just outside the larger 40m x 40m inventory plots in each 81 ha treatment. Vegetation within these clip plots was characterized using the point intercept method as described above allowing for identification with respect to their respective fuel categories. Once the point intercept data was collected within the clip plot the vegetation (fuel) was collected, oven dried at 70 °C for 48 hours and weighed for estimation of bulk density.

Table 2. Fuel categories used to classify fuel cells in HIP.

Fuel Type	Description
10 Hour	woody fuels < 0.25 inches in diameter
100 Hour	woody fuels 1 to 3 inches in diameter
Perched Pine Litter	pine litter suspended above the soil surface and not included in the litter depth, includes needles, bark, etc.
Pine Litter (flat)	pine needle or bark litter, included in litter depth measurements
Perched Decidious Oak Litter	deciduous oak litter suspended above the soil surface and not included in the litter depth, includes needles, bark, etc.
Decidious Oak Litter (flat)	leaf litter of deciduous shrubs or trees, included in litter depth measurements
Ever Oak Litter	leaf litter of evergreen hardwood shrubs or trees (primarily live oak), included in litter depth measurements
Wiregrass	live or dead wiregrass
Other Graminoids	live or dead sedges and grasses other than wiregrass
Shrubs	stems, foliage, etc. of live woody plants (oaks, poison ivy, blueberries, blackberries, persimmon, sassafras, etc.)
Turkey Oak Shrub	turkey oak shrubs, seperate category due to its abundance and characteristic as primary fuel sorce in some treatments
Forbs (and Forb Litter)	live or dead herbaceous flowering plants or their litter, ferns were also included in this category, even though they aren't forbs
Bare Ground	bare mineral soil
Pine cones	pine cones, usually included in litter depth measurements
Pine Bark	pine bark, flat on ground preventing a mineral soil measurement
Smilax	smilax (green briar) seperated from Shrubs due to its abundance
Palmetto	saw palmetto, separate category due to its structure and characteristics as a fuel source
Pine Regeneration	long leaf pine seedlings, grass stage

Fire Behavior - Infrared Thermography

Spatially explicit fire intensity measurements were recorded using infrared (IR) thermography. This method has proven effective in linking fuel characteristics with fire behavior in longleaf pine forests (Heirs et al. 2009, Loudermilk et al. 2012). Two thermal imaging systems from FLIR Inc. (FLIR SC660 and FLIR S60) were utilized. Both imaging systems were deployed at nadir from an aluminum tripod system designed for this study (Figure 2). The tripod system allowed the FLIR cameras to be suspended 7.2m above the HIP. The tripod system was designed at this height to allow the entire 4m x 4m HIP to be captured within the 45 degree wide angle lens on each IR camera. The SC660 has a spectral resolution of 640 x 480 pixels compared to the coarser resolution of the S60 at 320 x 240 pixels. Both cameras have a sensitivity of 0.06°C with an accuracy of ± 2% and captured images a 1 Hz for the duration of the fire. The recorded temperature range for the S60 was -40°C to 1500°C while the SC660 records from 300°C to 2000°C. The difference in temperature range was mitigated by only using images >300°C in the analysis for both imaging platforms. Images were georeferenced to plot corners using thermal targets. Thermal targets were 12cm x 12cm pieces of foil which show

Figure 2. FLIR tripod system suspended above the HIP and deployed in advance of the fire front.

up as cold areas in the image due to a low emissivity value. Nadir high resolution digital images were also taken from the tripod system pre-burn as well as high definition video for the duration of the fire event.

In-situ Fire Behavior

In-situ fire behavior measurements were also recorded using self-contained fire behavior sensor platforms with recently proven methods and equipment developed under a previous JFSP study (Hardy and Riggan JFSP 03-S-01). The platform, the Fire Behavior Flux Package (FBP), consists of radiometers that measure total and radiant energy fluxes, small-gauge thermocouples (nominally 0.13mm diameter wire) that sense flame and air temperature, and pitot-static type velocity probes that sense the magnitude and direction of airflow before, during, and after the fire passes. Digital visual imagery was an integral component of the package and allowed an objective analysis of the flame height, flame length, flame depth, flame angle, and rate of fire spread. All equipment was enclosed in fire resistant housing. These packages were not only utilized to support infrared measurements from the tripod system but also to expand fire behavior measurements outside of the HIP and better capture heterogeneity of fire behavior around the larger 40m x 40m inventory plot.

Hardwood Stem Heating Experiment

For our stem heating experiment, three different experimental sites were installed at Eglin AFB in a mature longleaf sandhill forest representative of the reference plots described above. The sites contained scattered clumps of small diameter *Quercus laevis* stems (~3-5 cm diameter at 1 meter height). These sites and diameters were chosen because of manager interest in removing the aboveground portions of oaks. Each site was burned twice in July, 2013. The moist weather conditions led to the addition of supplementary dry fuels consisting of pine needles and/or straw in a 3 m radius around the instrumented stems. The background fuels at the site consisted of an 18 month rough, with approximately 2 tons acre^{-1} of fine fuels. Both straw and pine needles were added for the first two fires in two of the sites. The third site was burned twice with only the addition of pine straw.

Each live stem had a notch sawed into it at 25-45 cm above the ground, facing the oncoming fire front. The notch was deep enough to see the cambium and the upper part of the notch was high enough to allow a 25mm long, 0.6mm diameter needle to be inserted to create a pilot hole for each thermocouple probe insertion. The thermocouple probes (type T) were positioned in the tips of 30 and 33 gauge hypodermic needles that were inserted into each stem. The bark of turkey oak is rugose with a somewhat regular ridges and groove structure. Because of this, in each stem, one probe was placed directly behind a groove and another behind a ridge. In site three, two of the trees had slightly different probe positioning. A single stem had probes inserted in line instead of adjacent to each other, one being at the boundary of the bark and cambium, the other midway into the bark-cork cambium interface.

The thermocouple leads were threaded through aluminum conduit to a Campbell Scientific Inc. (Logan, Utah) 23X datalogger. Temperatures were logged at 1 second intervals. The exposed leads directly above the notch were wrapped in strips of aluminized fiberglass fire shelter material. In the third site, ceramic padded insulation was added around the notch for additional protection after three thermocouples failed during an initial burn. A FLIR camera, FBP and four video cameras were installed around each site to measure fire intensity (Figure 3).

Figure 3. The experimental setup for the stem heating experiment showing FBP, FLIR, visual imagery and datalogger set up.

Photogrammetry

We used a photogrammetry technique to characterize individual stem topography. The technique produces a dense surface model (DSM), similar to LIDAR, where two or more overlapping digital photographs are spatially referenced to create a three-dimensional surface. Targets (colored push pins) were placed outside the stem area of interest for one side of the stem for photogrammetry processing. Distance between targets was recorded. A black background (foam board) was used to obstruct outside vegetation within each photograph. Paired low angle photographs were taken of the designated side of each stem using a Canon EOS Rebel XTi, with a Canon Ultrasonic 20 mm fixed lens, and manual focus. Photogrammetry software, PhotoModeler Scanner (2013, Eos Systems, Inc., Vancouver, British Columbia), was used for processing the digital imagery. Paired images were run through the 'Smart Match' option within the software which automates the photogrammetry process. Targets and distances between targets were used to appropriately scale and orient the paired photographs, using software error statistics for quality control. Once the imagery was referenced, a DSM (e.g., Figure 4) was created at a sampling interval of 5 mm for each stem. Topographic measurements can be estimated along each stem and where each thermocouple was inserted.

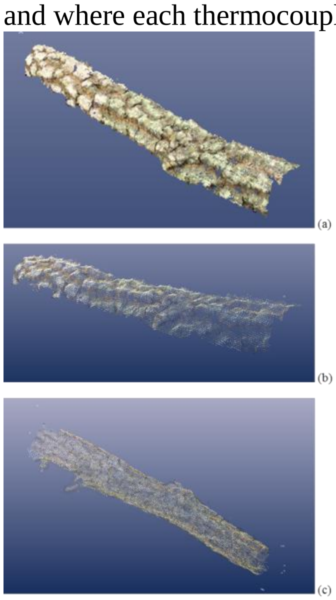


Figure 4. Stem topography, developed from photogrammetry of one stem approximately 25 cm long. Dense surface model (a), close-up of DSM illustrating topography and 3D point-cloud, (c) DSM of entire stem (4 sets of paired images).

Results

Experimental Burns

We successfully completed six large operational burns (350-2000 acres) that included the experimental plots in two field campaigns in early 2011 (Table 3). All but a single experimental burn treatment plot were burned. We successfully captured high resolution thermal imagery in 13 of the 14 HIP plots that burned, with instrument failure in a single herbicide treatment plot. FBP data was successfully collected in all burns in at least three platforms per block.

Table 3. Burn dates of experimental plots.

Herbicide		Mechanical		Burn		Reference	
Block	Burn Date	Block	Burn Date	Block	Burn Date	Block	Burn Date
2	2/19/2011	2	4/16/2011	2	4/17/2011	1	2/06/2011
3	2/11/2011	3	2/11/2011	3	No Burn	1	2/06/2011
4	2/14/2011	4	2/13/2011	4	2/13/2011	2	2/20/2011
6	2/08/2011	6	2/08/2011	6	2/08/2011		

Fuel Characterization

Structural legacies from the long term fuel reduction treatments seem visually apparent among the plots with regard to distribution and size class in oak stems between the treatments (see Figure 5). However, neither our fuels nor fire behavior data detected a treatment effect. The point intercept data collected at the 0.5m scale in the HIP's did not show significant differences among the treatments 16 years post treatment. Point intercept data was tallied at each sample point by fuel category and converted to a percent cover value and used in a non-metric multidimensional scaling ordination. The ordination is useful for exploring for potential differences in the multivariate fuel data. Treatments did not show significant groupings (Figure 6). A two dimensional solution was optimal with a final stress of 11.89 (p=0.02). Axis 1 values were driven mainly by various oak litters, whereas axis 2 values were driven mostly by wiregrass, perched pine litter, palms and open ground. The results showed that there was structure in the fuel data (the ordination explained 89% of the variation in the fuel data) but this structure was unrelated to the fuel treatments. This is likely largely due to the presence of highly heterogeneous fuels at the sub-meter scale swamping variation among treatments.

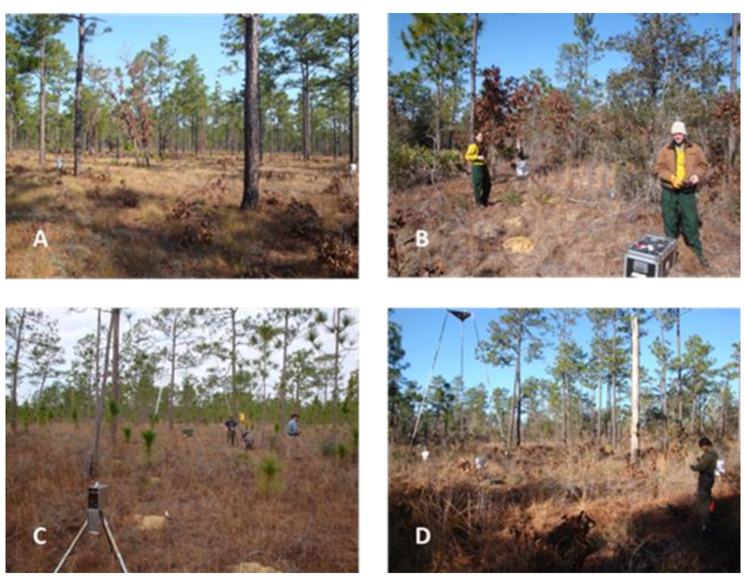


Figure 5. Representative images of structural legacies 16 years post treatment: A-Reference; B-Mechanical; C-Herbicide; D-Burn.

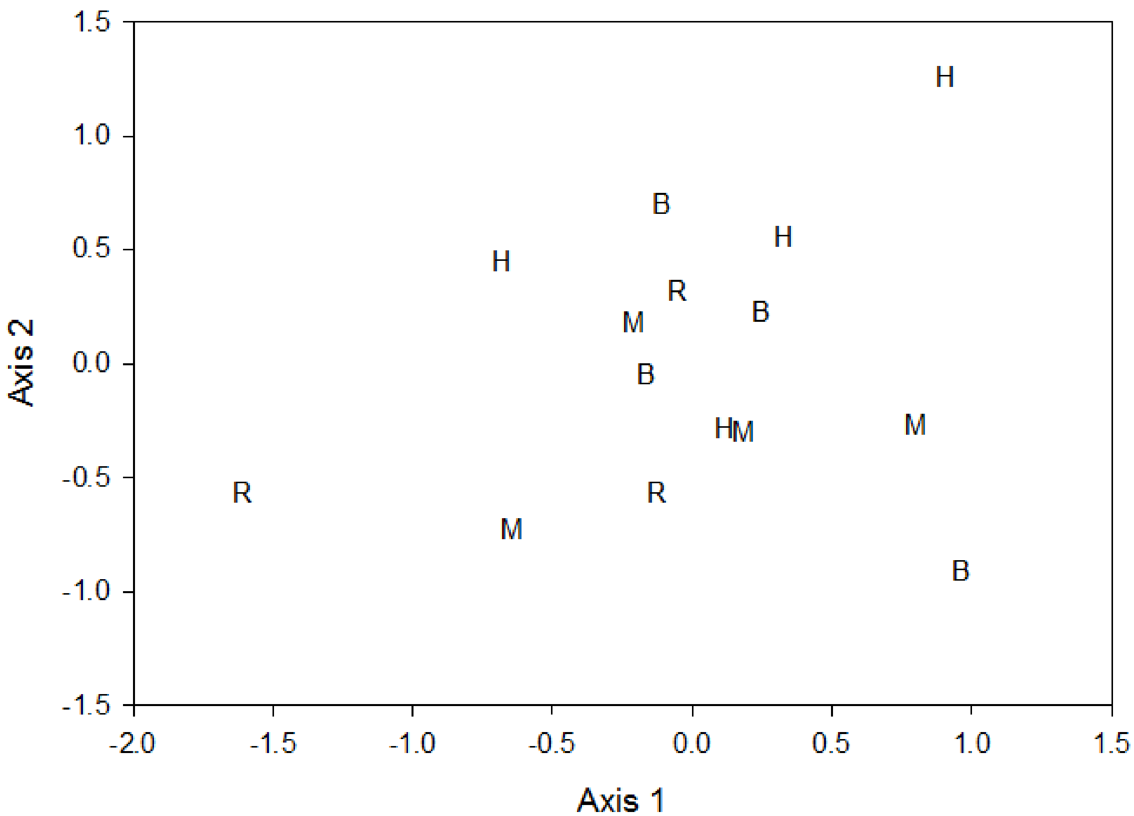


Figure 6. NMS ordination of fuel point sampling data. The letters indicate the first letter of the treatment type.

Fuel Loading

The clip plot data showed the same pattern as the point intercept data with no significant differences in fuel loads between the treatments. Fuel loads ranged from roughly 3,000 kg/ha to 9,500 kg/ha. Figure 7 illustrates the average fuel loads by block and treatment. Although variation existed between the treatments, it was not great enough to warrant substantial expectations with respect to expected or observed fire behavior. This is likely because of synergy in the elapsed time since each of the treatments had experienced fire.

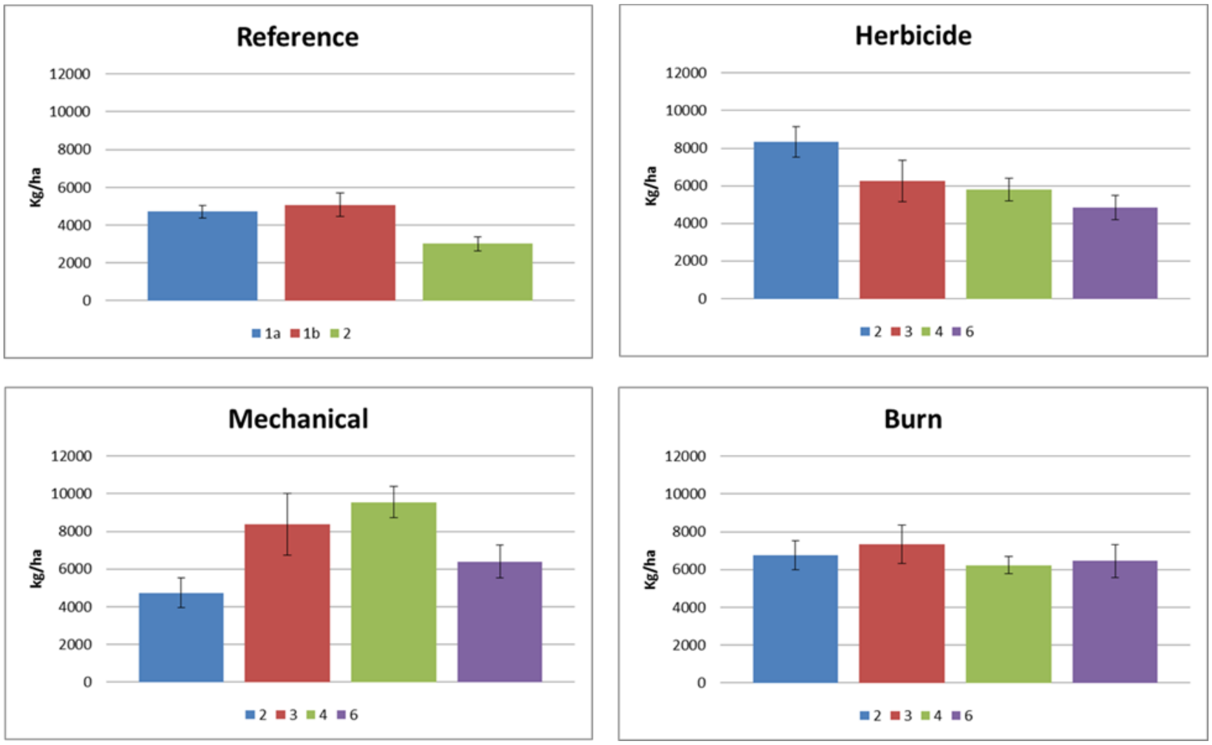


Figure 7. Average fuel load of plots measured pre-burn by treatment.

Fuel Consumption

Fuel loading and consumption data (R. Ottmar, unpublished data) was collected during the 2011 Prescribed Fire Combustion Atmospheric Research Experiment (RxCADRE, Figures 8 and 9). The 2011 RxCADRE burns included block 6 and reference plots 1a and 1b. The fuel loading estimates and the high consumption values highlight the dominance of fine fuels in longleaf sandhills.

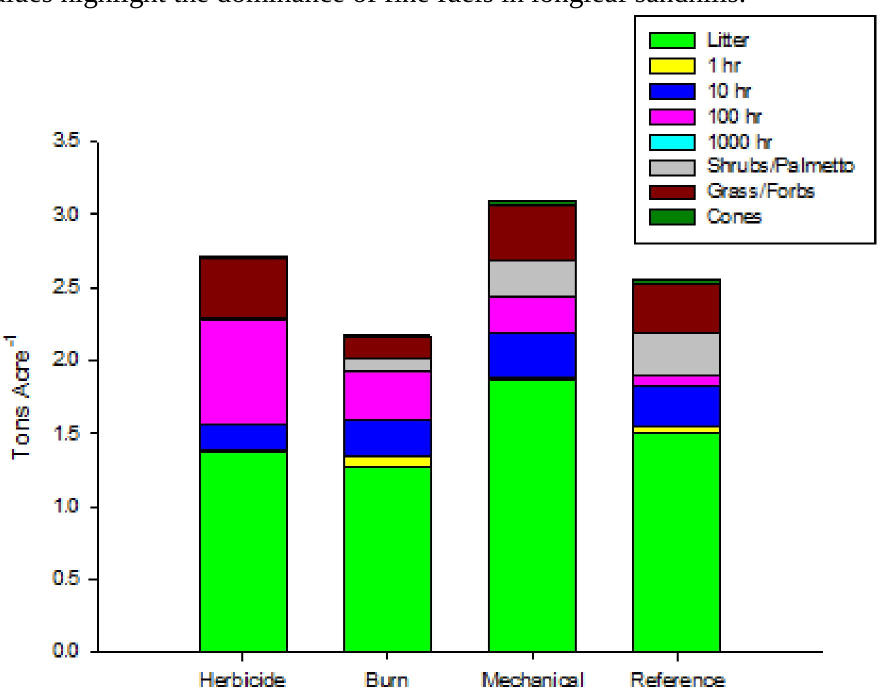


Figure 8. Fuel loading in block 6 and reference plot 1.

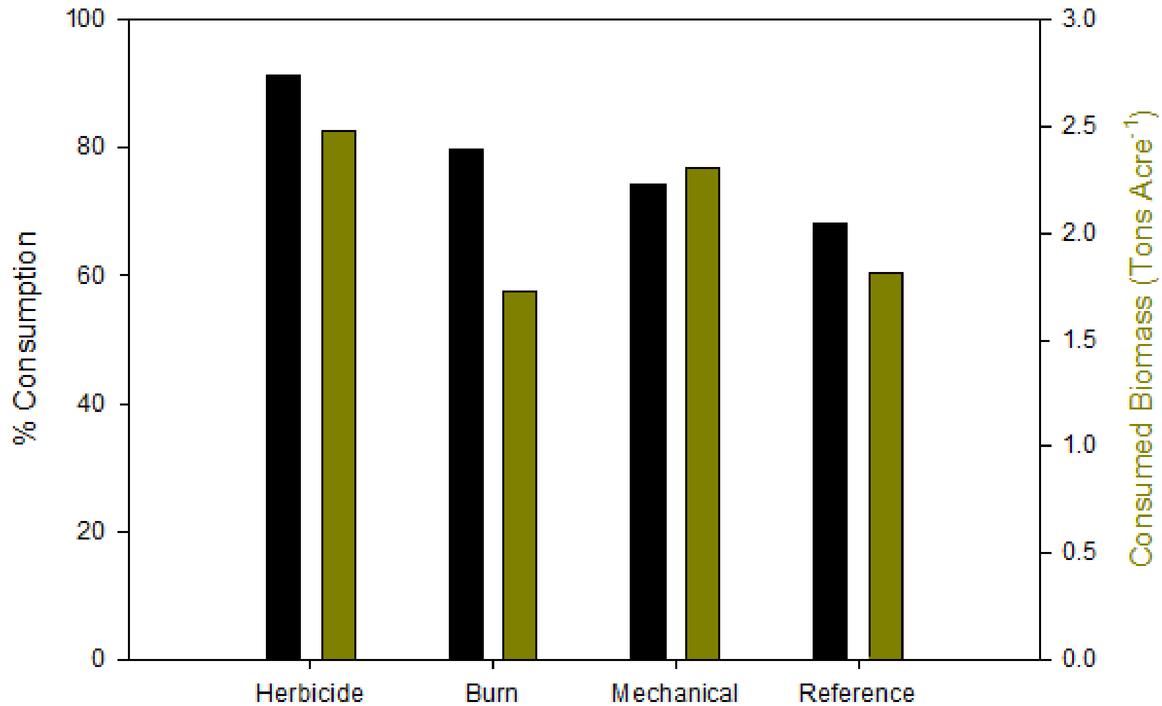


Figure 9. Fuel Consumption in block 6 and reference plot 1. The black bars indicate percent consumption; the green bars indicate the quantity of fuel consumed.

Fire Behavior – Infrared Thermography and FBP

Data from the FLIR thermal imaging system was successfully collected for all HIPs with the exception of one burn treatment (block 3) that did not get burned due to complexity with scheduling and Air Force missions and one herbicide treatment (block 6) where the imaging system malfunctioned. There was also considerable variation in fire radiative power among the HIPs and this variation was independent of treatment (Figure 10). A MANOVA of the fire behavior variables among treatments was not significant (Wilks Λ =0.277 p=0.62). The box plot shown in Figure 11 was representative of all the FLIR dependent variables in the analysis: very little among treatment variation, but considerable within plot variation. These results mirror those of the fuels analyses above and biodiversity patterns? reported in Kirkman et al. (2013). We are also investigating interesting patterns of spatial variation in fire intensity.

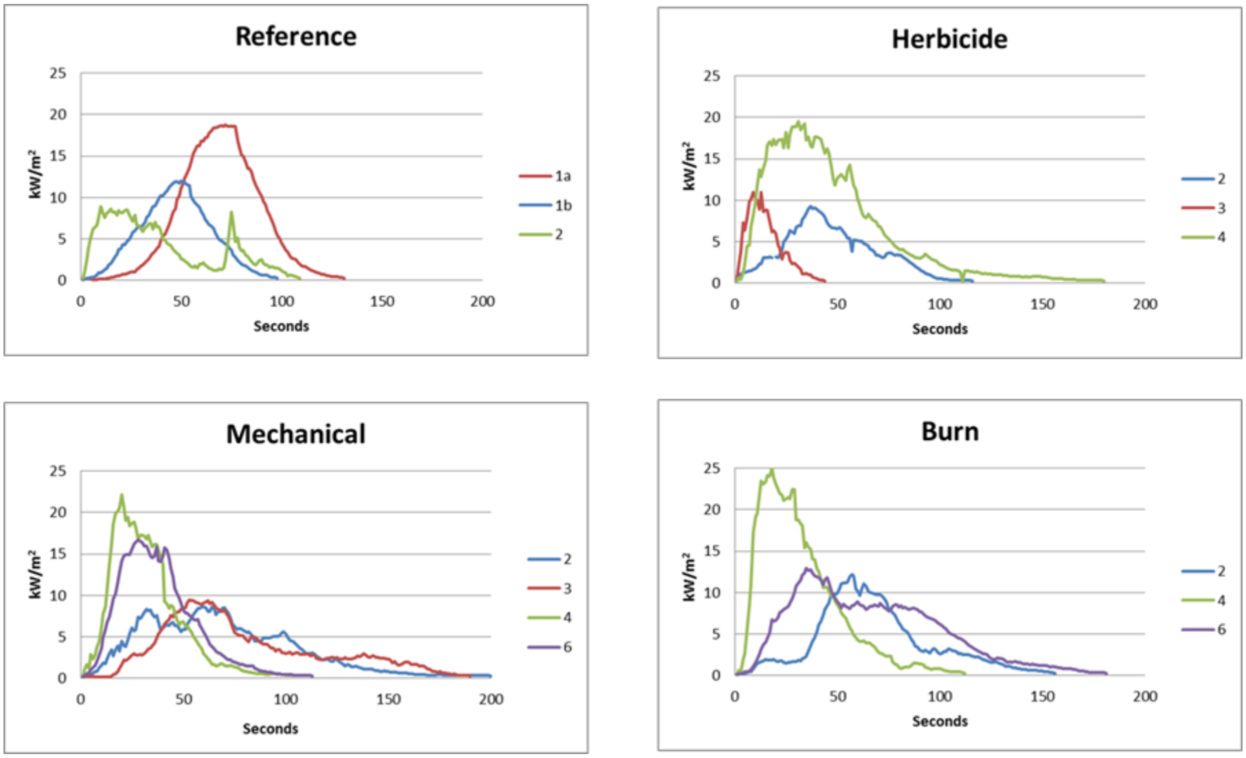


Figure 10. Fire radiant power in each HIP by block and treatment. The different line colors indicate different blocks.

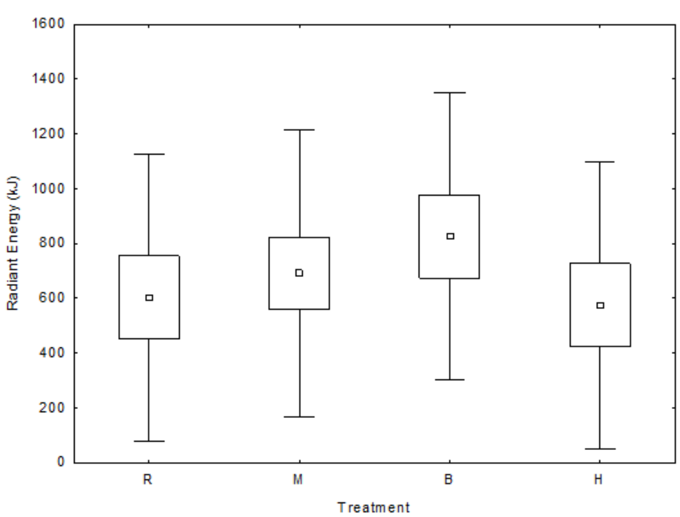


Figure 11. Box plot of FLIR collected radiant energy values among treatments. The points represent the mean, the box is +/- 1 SE and the whiskers are +/- 2 SD.

The FBP's wider area of measurement also failed to detect major differences among treatments though analysis is ongoing. Figure 12 provides representative examples of FBP measurements in the treatments. Much like the FLIR and fuels measurements, variation within treatments swamps any legacies of the original treatment effects.

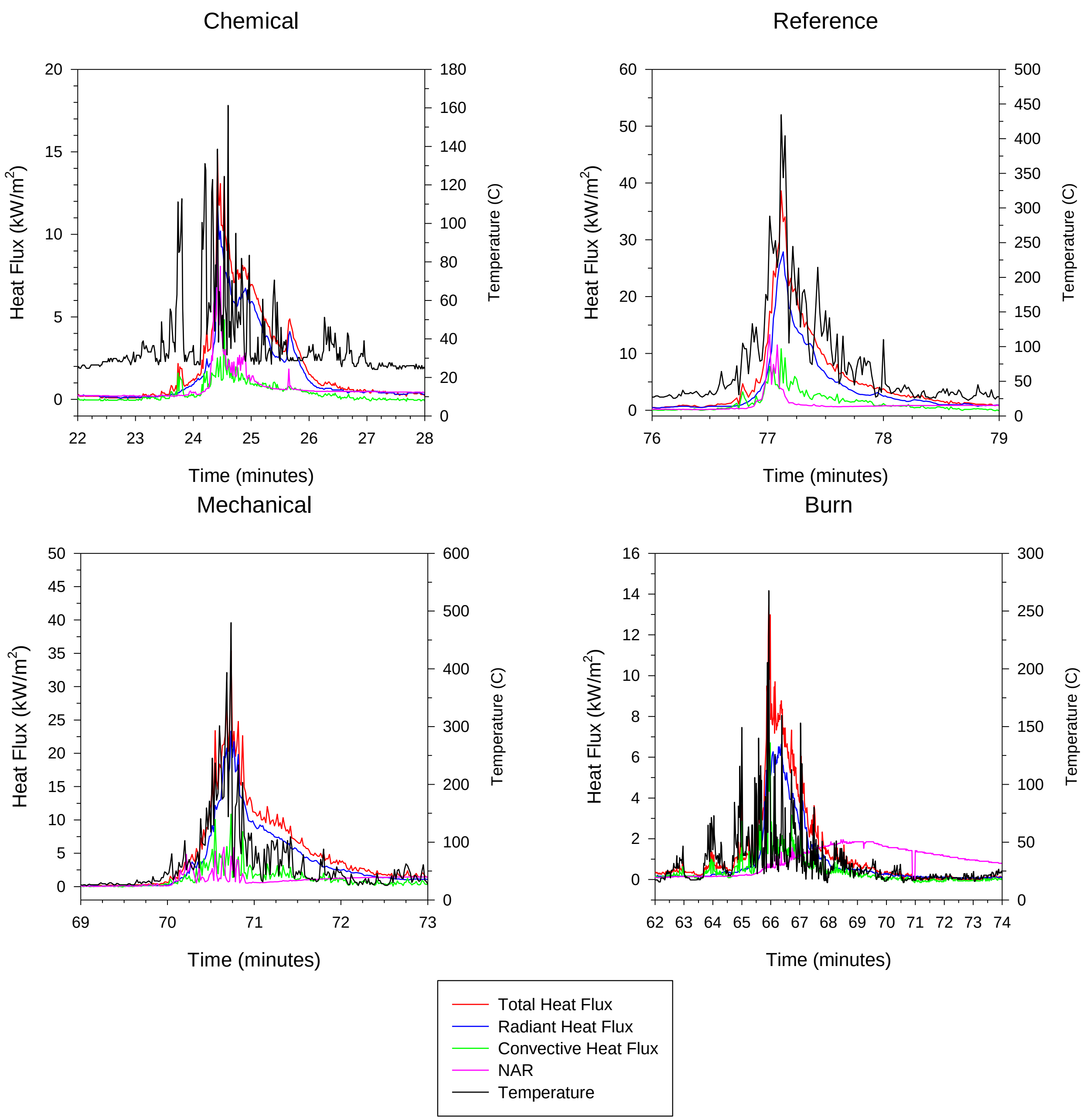


Figure 12. Example output from FBP packages in each fuel treatment type. Note the different scales of the axes. NAR refers to the narrow angle field of view radiometer.

We are presently examining the within plot variation in more detail. The critical scale of variation in fuels has been quantified as typically occurring at 0.5 m^2 or less (e.g. Hiers et al. 2009, Loudermilk et al. 2012). By analyzing data within plots, we have begun to uncover interesting connections with both patterns in fuels and fire, but also potentially causal mechanisms. For example Figure 13 displays the both an oblique and nadir visual image of two of the herbicide treatment plots. The oblique angle gives a superficial impression of fuel uniformity that disappears with the nadir view. Fire behavior data illustrated the large differences in radiant heat release in the two plots (Figure 14). Two patterns became apparent: the differences between these two plots was driven not only by obvious dissimilarities in residence time and

total
Figure 13. Oblique and nadir view of two herbicide plots.

radiant energy release, but also in the type of combustion occurring. The presence of fuels with longer duration combustion is evident in lower left panel (at 5 minutes after fire entered the plot) in Figure 14. An analysis of the spatial variation within the plots shows both that the magnitude of variability in fire behavior was dramatically greater in plot 4, but that the range of spatial autocorrelation was similar (Figure 15). For instance, regardless of degree of spatial variability, little spatial autocorrelation of energy released occurred beyond 20 cm distance within both plots. This variation is driven by within stand variation in overstory derived fine fuels such as pine needles and cones. The cones were especially important in driving the variability shown in figure 14 because of their long smoldering combustion. Fire behavior within these forests is highly variable within just a few meters and exhibit large spatial autocorrelation. How long-term fuel treatments may influence this fine-scale variability in fire behavior is relatively unknown. We tested for and modeled the spatial dependencies (autocorrelation) within each plot. Moran's I was calculated using 'ape' (v 3.0-10) library package in the R programming language (v 3.0.1, (R Core Team, 2013)) to test for plot level spatial autocorrelation. To assess the range of spatial correlation and magnitude of spatial variability of energy released (J) and residence time (sec) within plots, we modeled the semivariance (spatial autocorrelation function) using the 'geoR' (v 1.7-4) and 'StatDA' (v 1.6.7) library package in the R. An isotropic spherical or exponential autocorrelation function (Goovaerts, 1997) was fit to the empirical semivariance, with a maximum range of 2 m (~ 1/2 plot distance). An individual nugget parameter was fit to each model, while sill and range parameters were automated within R.

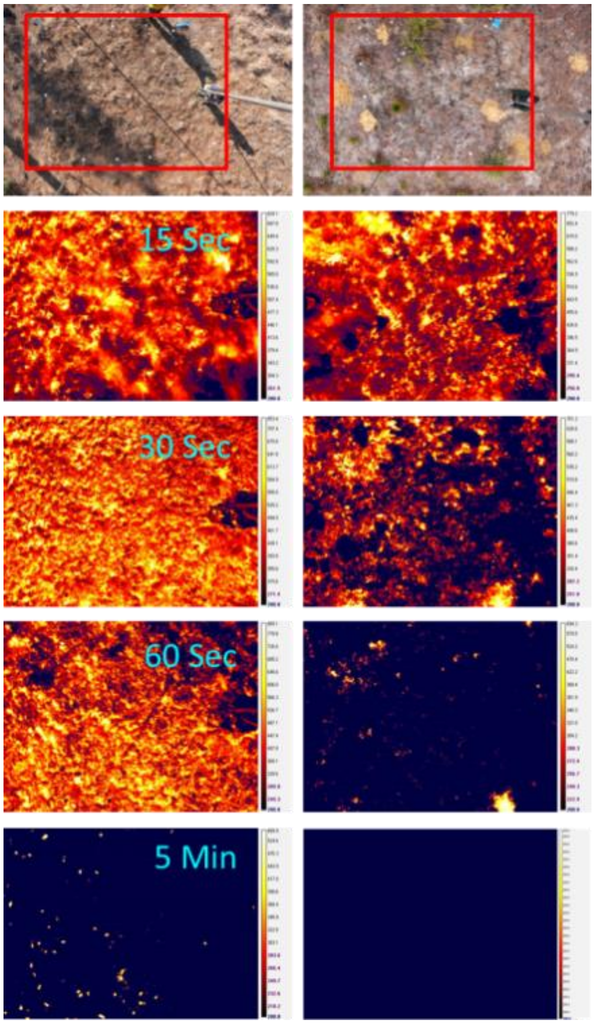


Figure 14. Visual and infrared imagery of fire progression in two herbicide plots. Herbicide plot 4 appears in the left column, herbicide plot 3 in the right. The red boxes in the top visual images indicate the approximate field of view of the thermal imagery. The labels in the infrared panels indicate the time since the fire first entered the plots.

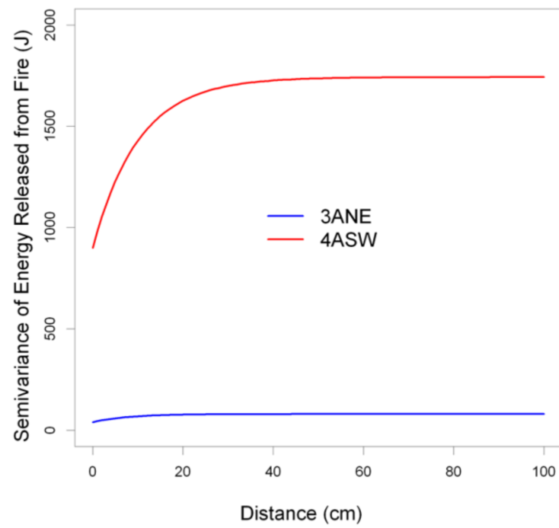
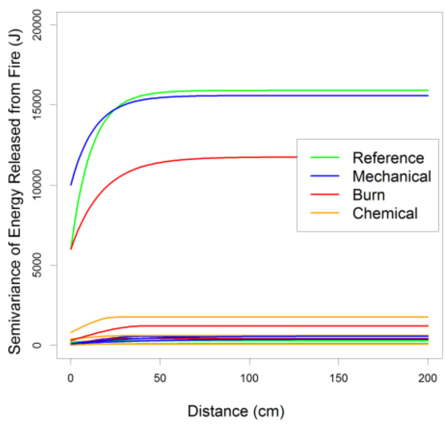


Figure 15. Semivariogram of fire intensity in the two herbicide plots displayed in Figure 14. The red line indicates the left column (plot 4) and the blue line represents the right column (plot 3) in Figure 14.

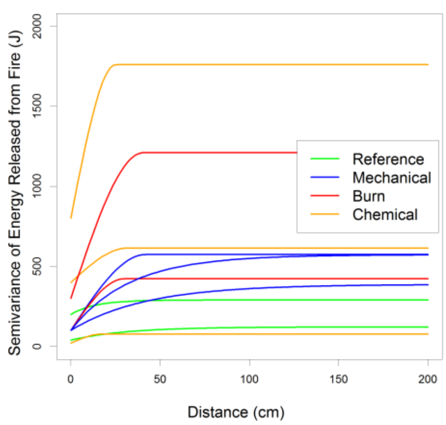
Table 4. Moran's I values of energy released (J) calculated for each study plot. Each plot illustrated significant (p<0.05) positive spatial autocorrelation.

Plot	**Trmt**	**Moran's I**
2ASE	Burn	0.05
4ASE	Burn	0.06
6ASW	Burn	0.07
2ASW	Chemical	0.07
3ANE	Chemical	0.07
4ASW	Chemical	0.06
2ANE	Mechanical	0.08
3ASE	Mechanical	0.12
4ANE	Mechanical	0.16
6ASE	Mechanical	0.04
1CE	Reference	0.04
1CW	Reference	0.03
2CW	Reference	0.07

All plots illustrated significant spatial autocorrelation of energy released (Moran's I: 0.03-0.16, $p<0.05$, Table 4) and residence time, and the range (distance) of spatial variability among plots were within 1 m, and often within 0.5 m (Figures 16, 17). There was no distinction, however, in magnitude of spatial variability (semivariance) among treatments. The spatial variability of fire behavior within and among plots can be influenced by many factors, such as fuel loading and type, fuel structure, including fuel continuity, and local weather (wind, ambient temperature, relative humidity). We found that there was no relationship between energy released (nor magnitude of spatial variability) from fire and recorded fuel loadings. There was, however, a significant linear relationship between the magnitude of spatial variability of energy released (partial sill of semivariogram) and total energy released from fire (R^2=0.62). The same was found for residence time (R^2=0.62). This suggests that other factors, such as local weather and fuel type and structure may play a stronger role in determining fire behavior than alterations in fuel loading caused by various fuel treatments. It is likely that the loading measured within treatments was highly variable and not entirely representative of within plot characteristics. Furthermore, other factors, such as pine overstory density – which has a significant influence on fuelbed characteristics – created another layer of layer of complexity to the dataset.



(a)



(b)

Figure 16. Semivariance of energy released within each plot across treatments. All plots (a), plots with sill lower than 2000 J (for clarity) (b).

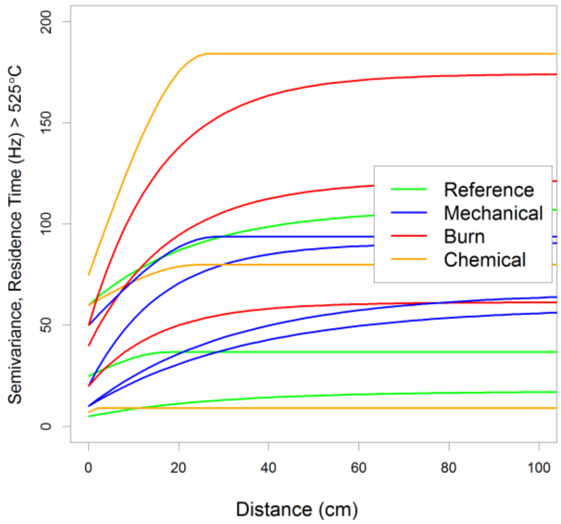


Figure 17. Semivariance of residence time within each plot across treatments.

Stem Heating

The initial data acquisition on the first three stems was unsuccessful due to thermocouple failure. After improving our methods, we were able to collect data on the remaining six stems. The analyses of these data are preliminary. We provide here a few examples of the kinds of data that were collected. Figure 18 shows the time-temperature profile of surface heating versus cambium temperatures in a single stem.

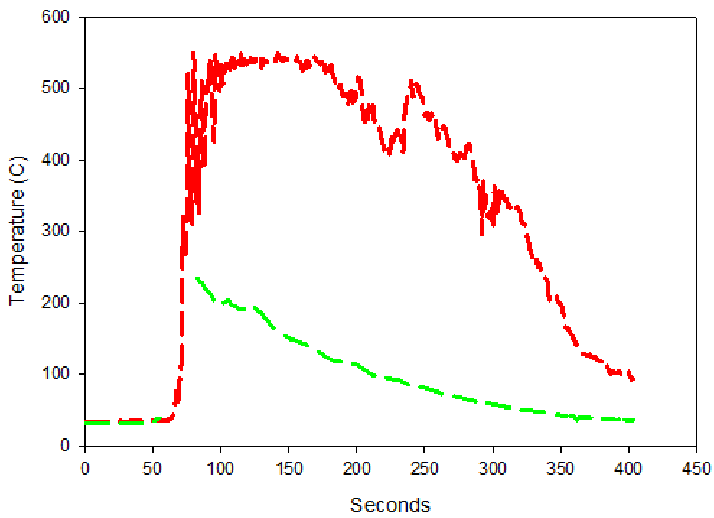


Figure 18. Plot of surface temperature (red line) and cambium temperature (green line) in a 3cm diameter turkey oak stem.

The probes were removed and needles inserted to the same depth as the probes. The stem sections containing the probes were collected for further processing. On three separate trees of the same species and approximately the same DBH, additional cookies were collected for tissue moisture content analysis. These samples were sectioned, weighed, dried and then reweighed. These data are currently being analyzed to improve FireStem2D (Chatziefstratiou et al. 2013) and to explore the three-dimensional aspects of heat transfer through woody stems.

Conclusions

Our results showed that the within treatment variation in multiple measures of fire behavior swamped any legacies of the original treatment effects. The occurrence of frequent low intensity fires in the treatments appeared to have driven a convergence of fuel characteristics in plots with and without management interventions in as little as 16 years. Our results were similar to those of Kirkman et al. (2013) who illustrated no differences in vegetation characteristics within the same treatments and the same convergence patterns. The results of Hiers et al. 2007 showed similar results with understory vegetation response: the impact of frequent, low intensity fires alone had a greater effect than oak stem densities than any treatment effect. Future analyses may provide information on fuel and vegetation structural legacies, similar to (Kirkman et al. 2013). It is likely that the mechanical treatment has created an even sized cohort of oaks, yet this structure seems to have little impact on fire behavior. Similarly, in the herbicide plots, oak densities were lower than the other treatments, but again, this did not seem to impact patterns of fire behavior.

One of the more interesting results of this study was our ability to exploit spatially explicit fuel and fire sampling to understand the complex patterns of fire behavior and by extension, fire effects that we observed. Within stand variation in overstory derived fuels appeared to be driving fire behavior. These data have important implications for integrating silviculture with fire management (see Mitchell et al. 2009). The results of this research were critical for developing a successfully funded large scale study that aims to mechanistically test ecological theories that will also link fire behavior with fire effects (Department of Defense, Strategic Environmental Research and Development Program RC-2243).

Our initial stem heating results indicate that at least in species with rough bark, heat transfer is much more complex and necessitates the incorporation of three-dimensional information into the development of accurate tissue heat transfer and damage models. The data we have collected will allow us to make those improvements. We have developed a promising means (photogrammetry coupled with IR imagery) to rapidly capture the fine scale tissue topography and heating of stems useful for improving models.

Research Linkages

This research will be complementary to a number of on-going pursuits, including and evaluation of burn severity patterns and vegetation response in sand pine scrub, ecological forestry, and red cockaded woodpecker management.

Table 5. Current and pending research grants linked to this project.

Grant Program	Project or Proposal Description/Identification	Funding Amount	Project Completion Date
SERDP	Dynamic Reference Conditions at Eglin AFB	$1.3 Million	2013
JFSP	Data Set for Fuels, Fire Behavior, Smoke, and Fire Effects Model Development and Evaluation – the RxCADRE Project.	$1.8 Million	2014
SERDP	Patterns and processes: monitoring and understanding diversity in frequently burned longleaf landscapes.	$2.5 Million	2018

Science Delivery and Application

Traditional scientific outlets, including professional workshops, peer-reviewed publications, and reports will summarize research and modeling results; however, active distribution of information will be accomplished through a series of manager workshops offered by the Georgia Forestry Commission and the Air Force Wildland Fire Center at Eglin. Workshops will address State, Private, and Federal fire managers together as targets of these training workshops. In particular, we will leverage existing partnerships in the region represented by the Georgia Prescribed Fire Council, and North Florida Prescribed Fire Council.

Deliverables

This study represented a large re-sampling effort to understand life cycles in southern fuels, and it leverages the vast quantity of existing data from before and after the extensive fuel treatments across an important forest type common in Florida and the Southeast. While we are still analyzing the data we showed that frequent fire seems to have had the same effect as more intensive management interventions such as herbicide and mechanical treatments with respect to fire behavior. This work will be part of a growing body of knowledge on these types of treatments (Kirkman et al. 2013, Hiers et al. 2007) and is the first to quantitatively assess fire behavior in response to long term treatment legacies in longleaf sandhills. As such we intend to disseminate these results in at least three research publications, two in peer reviewed journals and one white paper. We have also produced several other forms of delivery summarized in Table 6, and intend to continue presenting our results as analyses are completed.

Table 6. Deliverable, description and delivery dates.

Deliverable Type	Description	Delivery Dates
Presentation (6)	Three invited presentations, 2 conference papers with published abstracts, 1 conference poster.	2010-2014
Manuscripts (5)	"Integrating multidimensional variables for predicting stem heating during wildland fires." In preparation.	January 2014
	"Impact of hardwood fuels on fire behavior and long-term treatment effectiveness." In preparation.	February 2014
	"A system for capturing in situ high spatial and temporal resolution wildland fire behavior measurements." In preparation.	March 2014
	Loudermilk, E.L., Achtemeier, G.L., O'Brien, J.J., Hiers, J.K., Hornsby, B. Fire behavior in heterogeneous surface fuels: observations of high-resolution combustion. Submitted to International Journal of Wildland Fire.	August 2013
	Achtemeier, G. L., Goodrick, S. A., & Liu, Y. 2012. Modeling Multiple-Core Updraft Plume Rise for an Aerial Ignition Prescribed Burn by Coupling Daysmoke with a Cellular Automata Fire Model. Atmosphere, 3(3), 352-376.	July 2012
Webpage	All publications, tools, metadata, and data will be linked to FRAMES Southern Fire Portal.	September 2014
Final Report	JFSP project final report	September 2013
Mortality Model	Improvements on the FireStem tree mortality prediction tool.	June 2014

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