Forest Ecology and Management 354 (2015) 318–333

Contents lists available at ScienceDirect

Forest Ecology and Management

journal homepage: www.elsevier.com/locate/foreco

Effects of dormant and growing season burning on surface fuels and potential fire behavior in northern Florida longleaf pine (*Pinus palustris*) flatwoods

James B. Cronan [a,*], Clinton S. Wright [b], Maria Petrova [a]

[a] University of Washington, School of Environmental and Forest Sciences, Box 352100, Seattle, WA 98195-2100, USA
[b] USDA Forest Service, Pacific Northwest Research Station, 400 N. 34th St., Suite 201, Seattle, WA 98103, USA

ARTICLE INFO

Article history:
Received 22 November 2014
Received in revised form 13 May 2015
Accepted 13 May 2015
Available online 23 June 2015

Keywords:
Fuels management
Hazardous fuels
Fire behavior
Herbs
Shrubs

ABSTRACT

Prescribed fire is widely used to manage fuels in high-frequency, low-severity fire regimes including pine flatwoods of the southeastern USA where prescribed burning during the growing season (the frost-free period during the calendar year) has become more common in recent decades. Growing season prescribed fires address ecological management objectives that focus on increasing herb cover and decreasing shrub cover. The shift from shrub to herb dominance due to burning in the growing season corresponds to a change in surface fuels that could affect fire behavior, yet little has been done to assess the potential effects. We examined the effects of season-of-burn on shrub and herbaceous fuel layers and predicted fire behavior at replicate plots on frequently burned mesic pine flatwoods for two season-of-burn treatments (growing and dormant season prescribed fires) in two geographic regions in northern Florida. The Fuel Characteristic Classification System was used to construct a representative fuelbed for each plot at each sampling time to predict fire behavior. Predicted fire behavior was tested for correlation with measured surface fuel properties to determine if there was an effect from differences in fuels characteristics across treatments. In addition, fire temperature was measured *in situ* as a proxy for fire intensity and tested for treatment effects on the re-growth of live surface fuels. Compared to single dormant season burns, our single growing season burns caused no changes to live understory fuels and had no detectable effect on fire behavior, although predicted rate of spread and flame length were significantly reduced after all prescribed burns. Shrub cover and predicted fire behavior were, however, significantly different between geographic regions, and shrub height was significantly affected by fire temperature. Predicted fire behavior was strongly correlated with measures of the litter and herb strata. Results from this study suggest that land managers should not initially expect large changes in understory fuel properties or potential fire behavior from a shift to burning during the growing season and show that geographic location and fire intensity had significant effects on live fuels and potential fire behavior.

1. Introduction

Throughout the USA, prescribed fire is used to manage fuels (Schwilk et al., 2009; Stephens et al., 2012) and is recommended to counter the negative ecological effects of human activities, such as fire suppression and climate change, in ecosystems with high-frequency, low-severity fire regimes (Stephens and Ruth, 2005; Ryan et al., 2013). Using prescribed fire requires an understanding of how variation in its application affects ecosystem properties, fuel characteristics, and potential fire behavior (Agee and Skinner, 2005; O'Brien et al., 2010). Shifting season-of-burn from the dormant season to the growing season has been gaining attention as a treatment option because doing so can affect vegetation dynamics and produce ecological benefits (Knapp et al., 2009). In the southeastern USA, prescribed fire is widely used to control fuels, particularly understory shrubs and hardwood trees in fire-adapted pine forests (Melvin, 2012). While much research has been focused on the ecological effects of season-of-burn (e.g. Robbins and Myers, 1992), scant attention has been given to the effects on fuels and fire hazard, important considerations given that managing fire potential is often a primary goal of prescribed burning in this region (Marshall et al., 2008; O'Brien et al., 2010).

The pine flatwoods ecosystem is widespread throughout the coastal plain of the southeastern USA. When frequently burned,

* Corresponding author. Tel.: +1 206 732 7800; fax: +1 206 732 7801.
E-mail addresses: jcronan@u.washington.edu (J.B. Cronan), cwright@fs.fed.us (C.S. Wright), mpetrova@u.washington.edu (M. Petrova).

http://dx.doi.org/10.1016/j.foreco.2015.05.018
0378-1127/

it is characterized by an open canopy of pines, most commonly longleaf pine (*Pinus palustris* Mill.), and a biologically diverse understory of herbs and shrubs (Hardin and White, 1989). Prior to European settlement, the mean fire-return interval for longleaf pine forests was 2.2–3.2 years, with a shorter median, and most fires occurred during the growing season (Bale, 2009; Henderson, 2006; Stambaugh et al., 2011). Fire frequency drives understory composition in pine flatwoods with herbs favored at shorter fire-return intervals (Brockway and Lewis, 1997). This effect is enhanced by growing season fires when fire-return intervals are less than two years, however, the magnitude of the seasonal effect appears to vary geographically (Haywood et al., 2001; Glitzenstein et al., 2003).

The use of prescribed fire in the pine flatwoods ecosystem has shifted seasonally over the past several decades. The dormant season was the preferred burning period when fire was reintroduced as a management tool in the 1940s (Stanturf et al., 2002). Burns during the dormant season were favored because dry air and predictable winds following wetting rains produced manageable fire behavior and good smoke dispersion. A more recent focus on endangered species preservation and maintenance of biological diversity has prompted land management agencies to increase the frequency of burning and extend burning operations into the growing season with the goal of reducing the shrub component and increasing abundance of bunchgrasses and other herbaceous species (Ferguson, 1998; McWhite et al., 1999). This shift in understory composition is desirable because herb-dominated understories have greater plant diversity (Glitzenstein et al., 2012), and provide habitat for the gopher tortoise (*Gopherus polyphemus*; Cox et al., 1987) and the red cockaded woodpecker (*Picoides borealis*; Van Balen and Doerr, 1978; James et al., 1997), two vulnerable keystone species (Eisenberg, 1983; Conner et al., 2004); and the bobwhite quail (*Colinus virginianus*), an important game species (Schroeder, 1985).

Manipulating season-of-burn to alter the understory has implications for potential fire behavior because the amount and structure of surface fuels differ between shrub- and herb-dominated types (Anderson, 1982). Measures of fire behavior can be high for shrub-dominated vegetation (Saglam et al., 2008; Hough and Albini, 1978; Andreu et al., 2012). Because biomass of fine-dead and volatile-live fuels accumulates rapidly, shrub-dominated fuelbeds can support intense fires that are difficult to control. In forested areas, taller shrub-dominated fuelbeds decrease the gap between surface fuels and the tree canopy, increasing the probability of crown fire. In pine flatwoods, the shrub understory component can be managed with regular prescribed burning. Without regular burning, however, the rapid growth of shrubs (Fig. 1) contributes to surface fuel levels that can support high-intensity fires (Brose and Wade, 2002; Kreye et al., 2014). In contrast, herb-dominated fuel types tend not to support high-intensity fires because herb biomass does not accumulate to the same level as shrubs and fuel height remains relatively low (Yospin et al., 2012). Herb-dominated fuel types can affect fire behavior in other respects, however. Higher surface area-to-volume (SAV) ratio and near-optimal packing of continuous herbaceous fuelbeds can support high rates of fire spread. In addition, as herbaceous fuels cure and their moisture content decreases toward the end of their phenological growth cycle, they can have a high probability of ignition.

The goal of this study was to determine how season-of-burning influences live fuel characteristics and therefore potential fire behavior in the pine flatwoods ecosystem. The objectives were: (1) to quantify the effects of prescribed burning in the dormant and growing seasons on post-burn fuel loading, cover, and height of live understory fuels, and (2) to determine the extent to which differences in post-burn live surface fuel recovery influences fire behavior in stands managed with prescribed fire in different seasons.

We hypothesized that, relative to dormant season burns, growing season burns would cause a small shift toward herbs and away from shrubs with a similarly minor decline in fire behavior. The hypothesized direction and magnitude of expected change in live understory fuels was based on results from other published experiments in similar ecosystems in the southeastern USA where the effects of dormant season and growing season burns have been compared. Although the effects were minor, single growing season burns were found to increase herb production in an upland longleaf pine forest in central Louisiana (Grelen and Epps, 1967), decrease understory hardwoods in an oak-hickory (*Quercus–Carya*) forest in central Virginia (Brose, 2010), and decrease saw palmetto (*Serenoa repens* (W. Bartram) Small) in pine flatwoods in central and southern Florida (Willcox and Giuliano, 2010). The direction and magnitude of our hypothesized shift in live understory fuels is also suggested by long-term studies of season-of-burning in fire-adapted loblolly (*Pinus taeda* L.) and longleaf pine ecosystems (Waldrop et al., 1987; Haywood et al., 2001; Glitzenstein et al., 2003). These long-term studies show that individual growing season fires cause incremental shifts that favor herbs, and when applied consistently at short intervals, in some cases, can cause a large shift from shrub- to herb-dominated understory vegetation. Relative to dormant season fires we expect predicted fire behavior following growing season fires to decline based on known differences in fire behavior between shrub- and herb-dominated fuel types, namely that herbaceous fuel loading is typically lower than shrub fuel loading which tends to reduce measures of fire intensity (Brose and Wade, 2002; Kreye et al., 2014).

2. Methods

2.1. Study area

The study area encompasses mesic, mature pine flatwoods on federally managed lands in northern Florida (Fig. 2). The climate in northern Florida is humid-subtropical (Kottek et al., 2006) and temperatures range from an average minimum of 5 °C in January to an average maximum of 33 °C in July. Average annual precipitation is 1525–1650 mm with peak rainfall in July associated with convective thunderstorm activity. Dry periods occur in October–November and April–May. Eglin Air Force Base (EAFB) is characterized by broad plateaus dissected by dendritic streams to the north and flat coastal lowlands to the south; soils in pine flatwoods are generally somewhat poorly to moderately well-drained Entisols (Overing and Watts, 1989; Overing et al., 1995). Topography of the Apalachicola National Forest and St. Marks National Wildlife Refuge (APSM) is flat and, where pine flatwoods are present, soils are commonly poorly drained sandy Spodosols (Sanders, 1981; Allen, 1991). Pine flatwoods in the study area are characterized by an overstory dominated by longleaf pine, an open midstory, and an understory of shrubs and herbs, including saw palmetto, gallberry (*Ilex glabra* (L.) A. Gray), dwarf live oak (*Quercus minima* (Sarg.) Small), Darrow's blueberry (*Vaccinium darrowii* Camp), wiregrass (*Aristida stricta* Michx.), bluestem (*Andropogon* L. and *Schizachyrium* Nees), hairy trilisa (*Carphephorus paniculatus* (J.F. Gmel.) Herb.), and silk-grass (*Pityopsis graminifolia* (Michx.) Nutt.).

2.2. Study design

Growing and dormant season burn treatments were replicated eight times across the study and evenly allocated between two geographic regions (i.e., four replicates per region; Fig. 2). Repeated measurements of understory fuels were conducted during the dormant season no more than five months before treatment, and immediately (within one month), one year, and two years post-treatment. The dormant season was defined as the

Fig. 1. Prescribed burn demonstration plot at St. Marks National Wildlife Refuge, Florida, USA showing biennially burned (left) and unburned (right) fuels in mesic longleaf pine flatwoods.

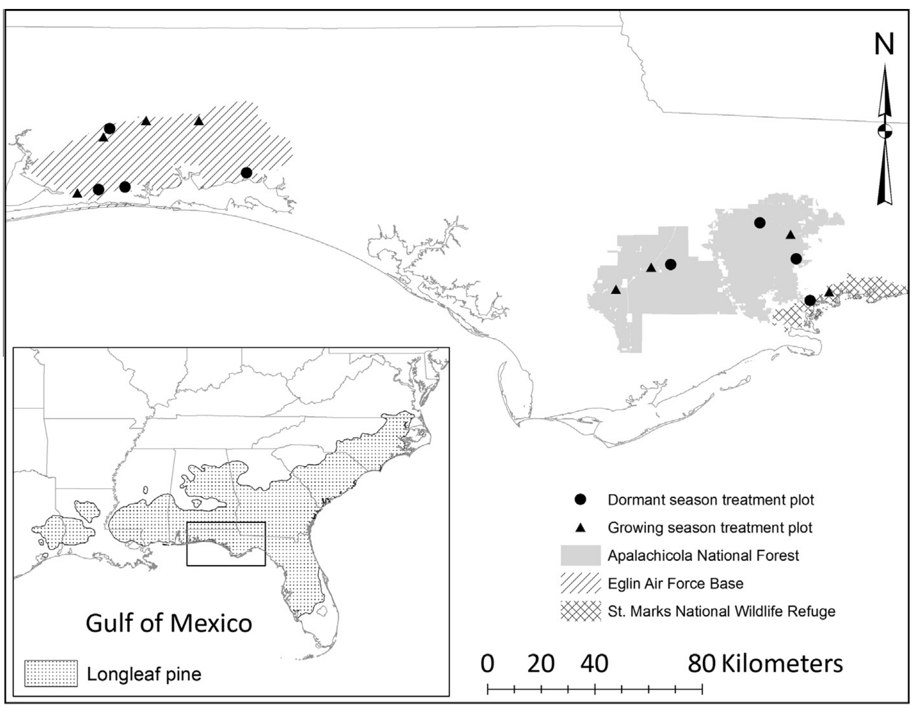

Fig. 2. Location of 2–4.5 ha mesic longleaf pine flatwoods season-of-burn treatment plots in northern Florida. Inset: box shows general area of treatment plots relative to the historic distribution of longleaf pine in the southeastern USA.

period between October 15 and March 14, and the growing season was March 15 to October 14, which corresponds to the typical frost-free period for northern Florida. Burns were conducted between December 2009 and July 2010 (Table 1). Replicates, or treatment plots, ranged from 2 to 4.5 ha in area and were located in mature, mesic longleaf pine stands that were at least 2 ha and were part of larger (10s to 100s of ha) administrative units. To reduce the influence of confounding variables, plots were located in stands with similar age, vegetation composition (characteristic mesic pine flatwoods vegetation, as described above), time-since-last-fire, and disturbance history that included at least 20 years of prescribed burning at 3–5 year intervals and no evidence of other past disturbances (i.e., high severity fires, grazing, silvicultural treatments, or agriculture). This study utilized operational prescribed burns conducted on administrative units as treatments. We identified and measured pre-fire fuels in 22 stands of mature longleaf pine that met these selection criteria throughout the study area. Six stands were excluded from the analysis because burns were not conducted within the treatment window ($n = 3$), were conducted on the same day ($n = 2$), or plots were burned again before the final repeated measurement was conducted ($n = 1$). Within each plot, subplot markers ($n = 20$) were systematically established on a 40-m grid arranged to provide a buffer of the same distance from sources of edge effect including stand boundaries (e.g., changes in forest age, composition, or structure) and roads (Fig. 3). As we were interested in how vegetation and fuels recover following fires in different seasons, immediate post-burn data were not used in this study.

Table 1
Geographic region, fire history, burn date, season-of-burn, day-of-burn weather, and thermocouple data ($\bar{x} \pm$ SE) for season-of-burn treatment plots in northern Florida, USA. Except where noted ambient temperature data were collected on site from portable weather stations. A total of 15 thermocouples were deployed at each plot.

Plot no.	Geographic region	Fire history[a]		Treatment burn						
		Season-of-last-burn	Time-since-last-fire (years)	Burn date	Season-of-burn	Air temp. (°C)[b]	Relative humidity (%)	MTT (°C)[c]	Residence time (s)[c]	Thermocouples exposed to flame
1[d]	EAFB	Dormant	2.9	12 January 2010	Dormant	9	46	437 ± 26	29 ± 3	13
2[e]	EAFB	Growing	4.5	23 December 2009	Dormant	17	73	400 ± 33	25 ± 5	2
3	EAFB	Dormant	1.9	23 January 2010	Dormant	14	85	356 ± 42	20 ± 10	14
4	EAFB	Growing	4.9	21 February 2010	Dormant	3	33	504 ± 33	41 ± 5	12
5	EAFB	Dormant	3.2	8 May 2010	Growing	29	70	332 ± 57	19 ± 8	8
6	EAFB	Dormant	2.1	30 March 2010	Growing	21	28	371 ± 23	20 ± 3	13
7	EAFB	Dormant	2.2	8 May 2010	Growing	30	65	438 ± 32	35 ± 7	9
8	EAFB	Dormant	5.2	19 March 2010	Growing	20	41	395 ± 45	28 ± 6	10
9	APSM	Dormant	3.3	18 February 2010	Dormant	14	27	430 ± 42	34 ± 8	7
10	APSM	Dormant	5.0	11 February 2010	Dormant	6	52	389 ± 42	22 ± 4	11
11[d]	APSM	Dormant	2.9	14 January 2010	Dormant	12	58	485 ± 24	31 ± 3	14
12	APSM	Dormant	2.3	17 February 2010	Dormant	8	42	522 ± 35	34 ± 4	15
13	APSM	Dormant	2.3	19 May 2010	Growing	26	65	472 ± 37	33 ± 5	10
14	APSM	Dormant	2.6	2 June 2010	Growing	29	66	332 ± 28	20 ± 5	8
15	APSM	Growing	2.0	22 July 2010	Growing	34	57	460 ± 27	31 ± 4	13
16	APSM	Dormant	2.5	9 July 2010	Growing	36	47	423 ± 40	30 ± 5	13

[a] Information about most recent prescribed fire prior to treatment burn.
[b] Air temperature at time of burn treatment.
[c] Maximum thermocouple temperature (MTT) and residence time is the average value from thermocouples exposed to flame.
[d] Weather data collected with handheld instruments.
[e] Weather data from Eglin Air Force Base Remote Automated Weather Station B-75 (N30°33.22′ W86°45.61′) located 9.8 km from plot.

2.3. Fuel sampling

Data were collected to test the effect of season-of-burn treatments on live surface fuels. Fuel loading of understory vegetation by life form (i.e., shrubs and herbs), litter, and 1-h (<0.64 cm diameter) and 10-h (0.64–2.54 cm diameter) timelag fuel classes for downed-woody fuels was inventoried using standard destructive methods (Wright, 2013) from 20 biomass subplots at each of the four sampling times. Biomass subplots were located 10 m apart along a 40 m line between subplot markers and assignment of sampling time was based on consecutive order (Fig. 3). The sampling area for biomass subplots varied (0.5 m^2, 1 m^2, and 4 m^2) according to the fuel type to balance precision, accuracy, and sampling effort. Coverage of understory vegetation by life form, and 100-h (2.54–7.62 cm) and 1000-h (>7.62 cm) timelag fuel classes for downed-woody fuel loading were measured at each sampling time on two 20-m transects of random azimuth originating from subplot markers by using line intercept (Canfield, 1941; Stephenson and Buell, 1965) and planar intersect (Brown, 1974) sampling methods, respectively. Transect endpoints were marked so that they could be remeasured at each sampling time. Three points were established along each transect (for a total of 120 points per treatment plot) to estimate litter and duff depth, vegetation height by life form, and canopy cover at each sampling time. Vegetation height was estimated as the average height of plants within a one meter radius of the measurement point (Burgan and Rothermel, 1984) and canopy cover was estimated by using the vertical tube method (Johansson, 1985). Subplot data were averaged for each sampling time for each treatment plot.

2.4. Fire weather and in-fire temperature observations

To document day-of-burn weather conditions, temperature, relative humidity, wind speed, and wind direction were measured adjacent to each plot using portable weather stations (WatchDog 2000 Series, Spectrum Technologies Inc., Aurora, IL). In three instances observations were collected with handheld instruments (Kestrel® 4000, Nielsen-Kellerman, Birmingham, MI) or inferred from nearby remote automated weather stations (Table 1). To adjust for the effects of fire intensity on post-fire herb and shrub growth, in-fire temperature was recorded *in situ* at each plot with an array of 15 thermocouples. Thermocouples provide a useful gauge of the physiological effects of fire by recording heat duration and flame temperature (Kennard et al., 2005). During burn treatments temperature was measured at 3–5 s intervals with 20-gauge wire, type-K thermocouples insulated with ceramic fiber (XCIB-K-2-7-3, OMEGA® Engineering, Stamford, CT) connected to single-channel data loggers (EL-USB-TC-LCD, Lascar Electronics, Ltd., Salisbury, UK; HOBO® U12-014, Onset® Corp., Bourne, MA). Thermocouples were arrayed systematically 3 m from the first 15 subplots and sensors were suspended 5 cm above the litter surface (Fig. 3). Temperature time series were used to calculate flame residence time (RT), defined as seconds with temperature readings above 300 °C (Wotton et al., 2012), and maximum thermocouple temperature (MTT; Wally et al., 2006). RT and MTT were averaged for each treatment plot for all thermocouples exposed to flame.

2.5. Fire behavior predictions

The Fuels Characteristic Classification System (FCCS; Ottmar et al., 2007) was used to construct custom fuelbeds from measured surface fuel characteristics and to predict fire behavior for each plot at pre-fire, 1-year, and 2-year post-fire sampling times (48 custom fuelbeds). Reaction intensity (RI; kW m^{-2}), rate-of-spread (ROS; m min^{-1}), and flame length (FL; m) were compared between treatments and geographic regions over time. The FCCS is a fire management decision support tool that includes a surface fire behavior prediction model based on a reformulation of the Rothermel quasi-steady-state fire spread model (Rothermel, 1972; Sandberg et al., 2007). The FCCS surface fire spread model differs from the Rothermel model by explicitly modeling the heat sink and heat source for each surface fuel stratum, providing a framework to evaluate differences in fire behavior among fuelbeds constructed with field data as direct inputs (Sandberg et al., 2007). FCCS fuelbeds are divided into six strata that represent unique combustion environments and include tree canopies, shrubs, herbs, woody fuels, litter, and duff (Riccardi et al., 2007).

To characterize fuelbeds we used an existing FCCS fuelbed, "Longleaf pine-slash pine (*Pinus elliottii* Engelm.)/gallberry forest" (FCCS fuelbed 191), as a template for the canopy fuel stratum

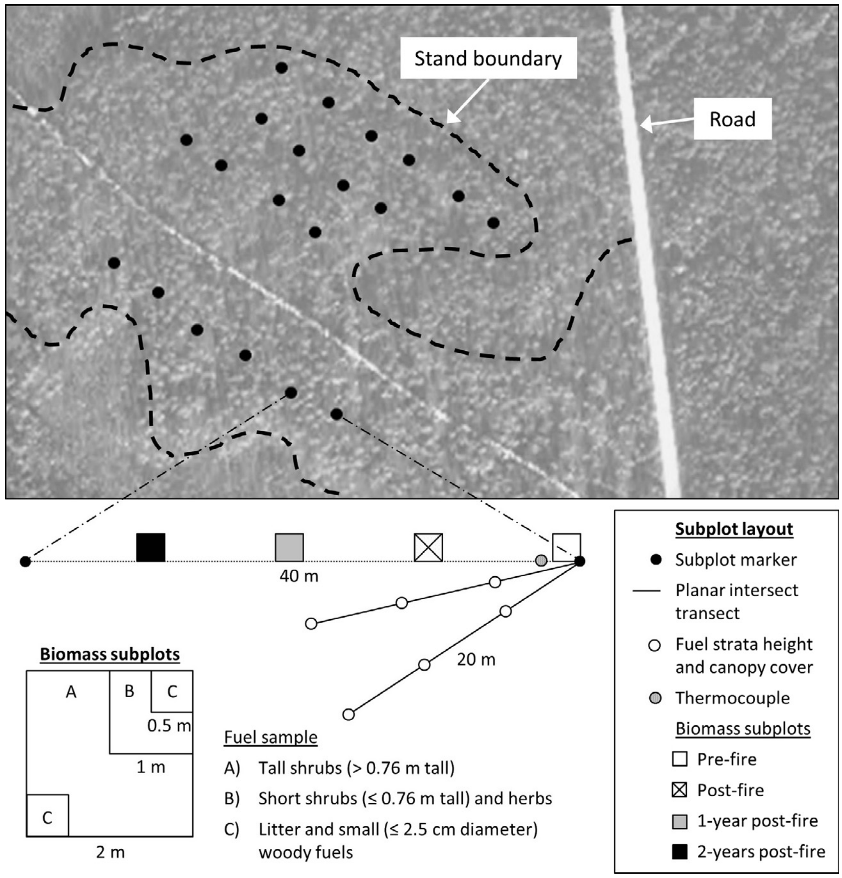

Fig. 3. Aerial photo showing systematic location of subplots ($n = 20$) within stand boundaries of a mesic pine flatwoods plot. Schematic illustration shows fuel sampling design within a subplot.

and for intrinsic fuel properties such as heat content and bulk density. This fuelbed was selected because its characteristics were a close match to the dominant overstory and understory species, and the 20-year mean fire-return interval (4.3 years) at our plots. We customized the inputs of the surface fuel strata for each fuelbed with our fuel inventory measurements (Table 2). All input data for plots were averaged from subplots and are included in Appendix A. Fire behavior was simulated for all resulting fuelbeds under the same benchmark environmental conditions of no slope, 6.4 km h^{-1} wind speed, and fuel moisture contents of 6% for 1-h fuels, 7% for 10-h fuels, 8% for 100-h fuels, 60% for graminoids and forbs, and 90% for shrubs (i.e., the D2L2 scenario of Scott and Burgan, 2005). Benchmark environmental conditions were used so that we could compare relative differences in fire behavior associated with differences in fuels; predictions do not necessarily represent prescribed burning conditions.

2.6. Data analysis

Repeated measures analysis of variance (Crawley, 2007) with season-of-burn and geographic region as explanatory variables, and sampling time as a repeated measure was used to test the effect of dormant and growing season burns on the difference between pre- and post-fire shrub and herb fuels and measures of predicted fire behavior. Interaction terms were limited to two-way interactions (i.e., season-of-burn × time, region × time, season-of-burn × region). Tukey's Honestly Significant Difference post hoc multiple comparison tests (Tukey, 1973) were conducted to examine change within treatment levels across sampling time and between treatment levels for each sampling time. MTT was assessed for significant correlation with live fuel variables and incorporated into the repeated measures model as a covariate when significant. Model residuals were assessed for homogeneity of variance and normality; assumptions were met for each. Outliers were identified by flagging absolute standardized residuals that lie outside the 95% confidence interval of the standard normal distribution. If outliers were present, statistical tests were repeated without them to determine their influence on model interpretation. To determine if fire intensity was different between the season-of-burn treatments or geographic region, MTT for each variable was tested with a two-sample t test (Appendix B). Because of its high correlation with MTT ($\rho = 0.915$, $P < 0.001$), RT was not used as a proxy for fire intensity. The effect of live fuels on predicted fire behavior over the range of sampled conditions was studied using correlation and regression analysis. Litter fuel loading is calculated as a function of depth, type, and coverage in FCCS v 2.2 (Riccardi et al., 2007) and therefore excluded from the correlation analysis as the FCCS did not accept direct input of measured litter loading. Phenological differences (i.e., the presence of leaves on deciduous species) in live fuels at plots burned and sampled in the growing season introduced a potentially confounding variable that was assessed by adjusting live fuel measurements with paired plot data (see Appendix C).

Given the small sample size and high probability of Type II error, statistical significance for tests was evaluated at $\alpha = 0.1$. A Bonferroni correction was made on t tests and Tukey P values in instances where two analyses were conducted on the same data (i.e., separate tests for the effect of season-of-burn and region on MTT and separate post hoc tests for the effect of season-of-burn × time and region × time interactions on shrub

Table 2
Data source and measurement unit by input variable used to build FCCS fuelbeds to represent treatment plots at different sampling times in northern Florida (see Appendix A for input values).

Input variables	Data source	Measurement units
Fuelbed FCCS191: Longleaf pine-slash pine/gallberry forest (2–3 year prescribed fire rotation)	Selected based on vegetation type, mean fire rotation period, and mean canopy cover for treatment plot from measured values from canopy cover points	
Canopy	Used default values for FCCS191	
Shrubs		
Cover	Mean cover value for treatment plot from measured values from line intercept transects	%
Height	Mean height value from height sampling points	Meters
Loading	Mean biomass for treatment plots from 1 m^2 and 4 m^2 biomass subplots	Megagrams $hectare^{-1}$
Herbs		
Cover	Mean cover value for treatment plot from measured values from line intercept transects	%
Height	Mean height value from height sampling points	Meters
Loading	Mean biomass for treatment plots from 1 m^2 biomass subplots	Megagrams $hectare^{-1}$
Woody fuels		
1-h and 10-h loading	Mean loading value for treatment plot from 0.5 m^2 biomass subplots	Megagrams $hectare^{-1}$
100-h and 1000-h loading	Mean loading value for treatment plot from measured planar intersect inventory	Megagrams $hectare^{-1}$
Litter		
Cover	Mean cover value for treatment plot from measured values from line intercept transects	%
Depth	Mean depth value from depth sampling points	Millimeters
Loading	Calculated from cover and depth	Megagrams $hectare^{-1}$
Duff		
Cover	Percent of depth sampling points with duff present (depth > 1 mm)	%
Depth	Mean depth value from depth sampling points	Millimeters

cover, shrub height, ROS, and FL). Thus, $\alpha = 0.1 \div 2$, or 0.05, was used as a level of significance. Statistical analyses were conducted with R version 3.1.1 (R Development Core Team, 2014). Except when noted, results are presented as the plot mean ± standard error.

3. Results

3.1. Shrub fuels

Pre-fire shrub cover did not differ (Tukey $P = 1.000$; Fig. 4) between plots burned in the dormant (41.2 ± 3.3%) and growing (42.6 ± 4.0%) seasons. There was a season-of-burn × time interaction ($P = 0.057$) indicating that reduction of shrub cover one year after treatment was slightly greater at plots burned in the growing season, but variability within each season-of-burn treatment group was high and, as a result, the slightly greater reduction of shrub cover at plots burned during the growing season was not significant (Tukey $P \geqslant 0.955$). An interaction between geographic region and time ($P < 0.001$) suggested that prescribed burning reduced shrub cover more at EAFB (Fig. 5). Within each region changes in shrub cover over time were not significant (Tukey $P = 0.307$). There was, however, a significant difference between regions. A nonsignificant difference between APSM (44.7 ± 4.7%) and EAFB (39.1 ± 1.5%) before (Tukey $P = 0.876$) and one year after (Tukey $P = 0.110$) treatment became significant the second year after treatment (Tukey $P = 0.004$) when shrub cover was 19.9 ± 6.3% lower at EAFB. MTT did not explain a significant amount of variation in post-fire shrub cover ($P = 0.609$) and was not included as a covariate in the test for the effect of season-of-burn.

Pre-fire shrub fuel loading averaged across all plots was 2.59 ± 0.28 Mg ha^{-1} and there was no season-of-burn treatment effect on post-fire shrub growth; season-of-burn alone and season-of-burn × time and season-of-burn × region interactions were not significant ($P \geqslant 0.221$; Fig. 4). For geographic region, pre-fire shrub fuel loading was not different (Tukey $P = 1.000$) between APSM (2.60 ± 0.46 Mg ha^{-1}) and EAFB (2.58 ± 0.35 Mg ha^{-1}) but there was a significant region × time interaction ($P = 0.091$). Mean shrub fuel loading appeared to decline more at EAFB after burning (Fig. 5), but variability among plots was high and post hoc testing showed that the change in shrub fuel loading over time was not significant for either geographic region (Tukey $P \geqslant 0.232$) and that shrub fuel loading the first and second years after treatment at EAFB was not lower than APSM (Tukey $P \geqslant 0.559$). MTT did not explain a significant amount of variation in post-fire shrub fuel loading ($P = 0.160$) and was not included as a covariate in season-of-burn tests.

Pre-fire shrub height averaged across all plots was 0.58 ± 0.03 m. Season-of-burn alone and season-of-burn × time and season-of-burn × region interactions were not significant ($P \geqslant 0.265$; Fig. 4). Shrub height differed significantly regionally ($P = 0.057$), based on significant differences for the second year after treatment (Tukey $P = 0.026$), when mean shrub height was 0.48 ± 0.03 m at APSM and 0.56 ± 0.02 m at EAFB. Mean shrub height at APSM was lower than at EAFB across all times (Fig. 5), which was the opposite of the regional trend that was observed for shrub cover and fuel loading. Although mean shrub height was slightly lower at APSM before and one year after treatment, these differences were not significant (Tukey $P \geqslant 0.158$). As one might expect, shrub height declined significantly by 0.09 ± 0.02 m at APSM (Tukey $P = 0.016$) and by 0.15 ± 0.04 m at EAFB (Tukey $P = 0.004$) from pre-fire to 1-yr post-fire. By the second year after treatment, however, mean shrub height was no longer significantly different from pre-fire means for either geographic region (Tukey $P \geqslant 0.262$). MTT explained a significant amount of variation in post-fire shrub height ($P = 0.060$), which declined with increasing MTT, and was included as a covariate in season-of-burn tests.

3.2. Herb fuels

Pre-fire herb cover averaged across treatments was 20.3 ± 3.8%. Season-of-burn alone and season-of-burn × time and season-of-burn × region interactions were not significant ($P \geqslant 0.462$; Fig. 4). Mean herb cover tended to decrease after burning and, although time was a significant term in the overall model

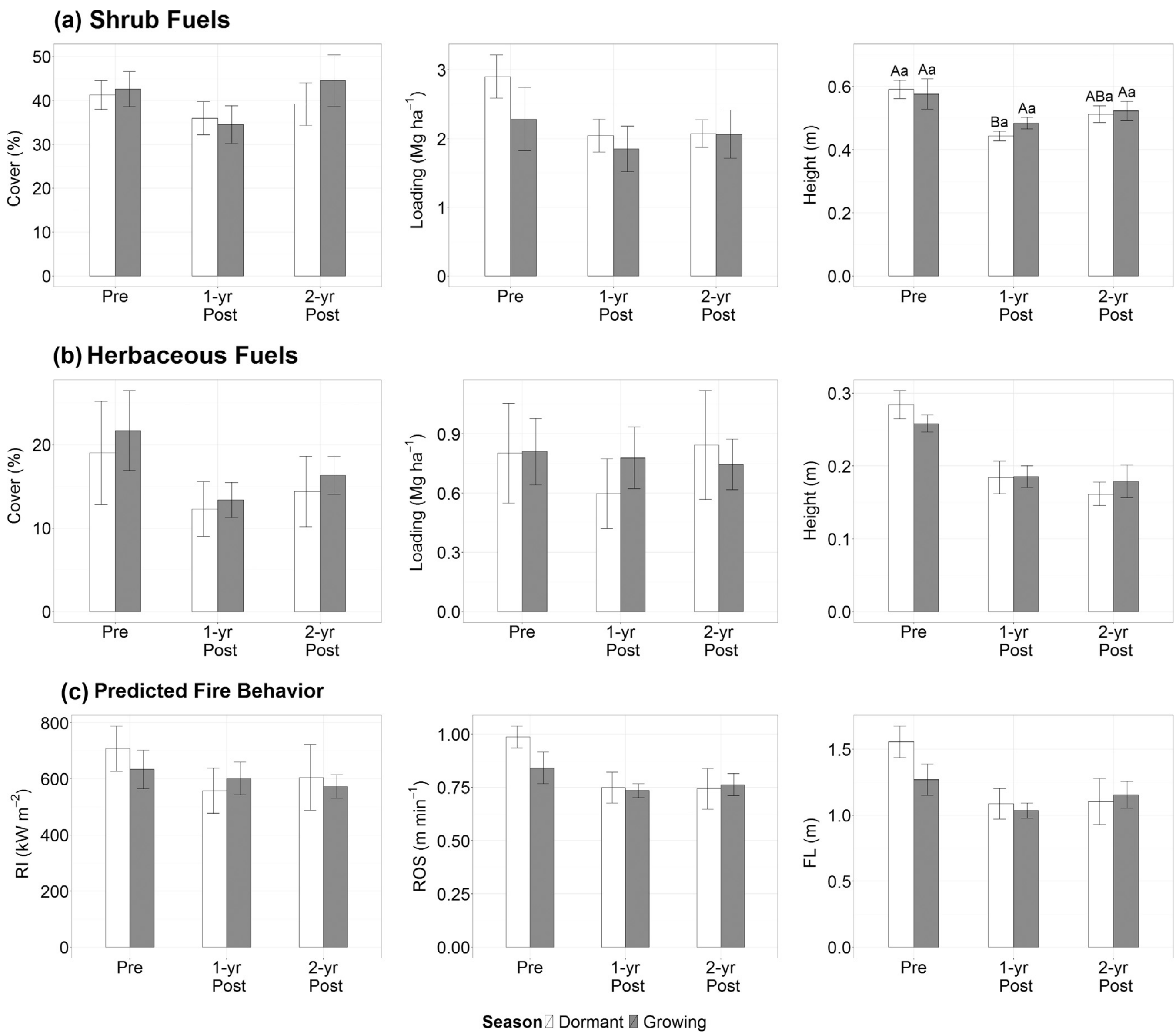

Fig. 4. Live fuel cover, loading, and height for understory (a) shrub and (b) herbaceous fuel layers, and (c) fire behavior predictions from custom FCCS fuelbeds for pre-fire, 1-year post-fire, and 2-years post-fire at treatment plots grouped by season-of-burn. Means with the same uppercase letter are not significantly different among sample times within season-of-burn treatments and means with the same lowercase letter are not significantly different between season-of-burn treatments for a sample time (Tukey $P \leqslant 0.1$). Bars without letters are not significantly different.

($P = 0.005$), variability among plots was high and post hoc testing was unable to identify significant changes in herb cover among sampling times (Tukey $P \geqslant 0.149$). Mean herb cover was slightly lower at APSM for each sampling time (Fig. 5) but this difference was not significant ($P = 0.316$). MTT did not explain a significant amount of variation in post-fire herb cover ($P = 0.867$) and was not included as a covariate to test for the effect of season-of-burn.

Pre-fire herb fuel loading averaged across all plots was 0.81 ± 0.15 Mg ha^{-1}. Season-of-burn alone and season-of-burn × time and season-of-burn × region interactions were not significant ($P \geqslant 0.189$; Fig. 4). Sampling time was not significant ($P = 0.243$) and suggested that herb fuel loading recovered to pre-treatment levels within the first post-treatment sampling time. As with herb cover, mean herb fuel loading was consistently lower at APSM for all sampling times (Fig. 5), however, this difference between geographic regions was not significant ($P = 0.246$). MTT did not explain a significant amount of variation in post-fire herb fuel loading ($P = 0.585$) and was not included as a covariate in season-of-burn tests.

Pre-fire herb height averaged across treatments was 0.27 ± 0.10 m. Season-of-burn alone and season-of-burn × time and season-of-burn × region interactions were not significant ($P \geqslant 0.168$; Fig. 4). Mean herb height tended to decrease after burning and post hoc testing showed that herb height the first (0.18 ± 0.01 m) and second (0.17 ± 0.01) years after treatment was significantly lower (Tukey $P < 0.001$) than pre-fire herb height. As with herb cover and fuel loading, mean herb height was slightly lower at APSM for each sampling time (Fig. 5), but this difference was not significant ($P = 0.179$).

3.3. Predicted fire behavior

Prior to treatment, predicted RI, ROS, and FL averaged across all plots was 670 ± 52 kW m^{-2}, 1.41 ± 0.09 m min^{-1}, and

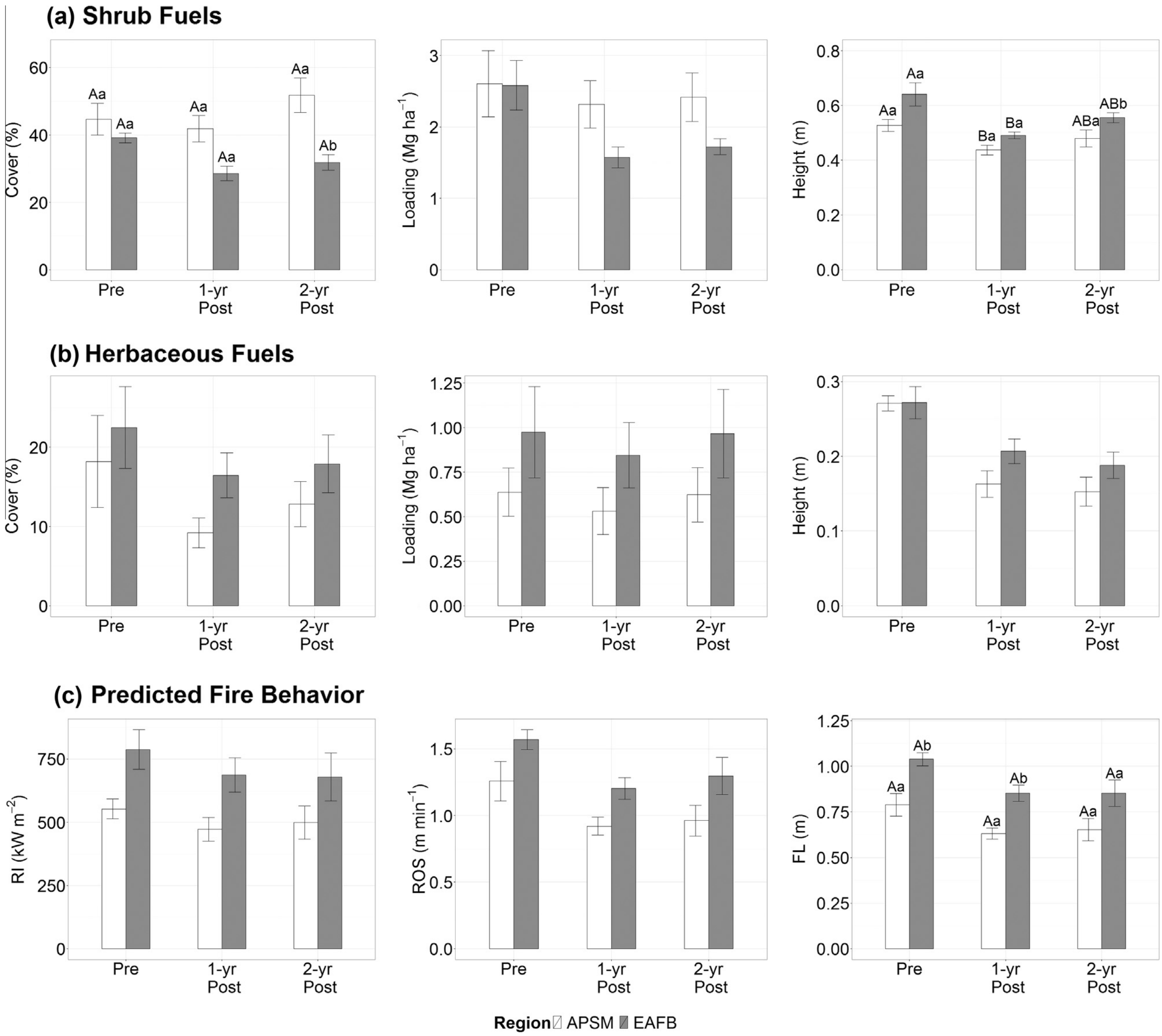

Fig. 5. Live fuel cover, loading, and height for understory (a) shrub and (b) herbaceous fuel layers, and (c) fire behavior predictions from custom FCCS fuelbeds for pre-fire, 1-year post-fire, and 2-years post-fire at treatment plots grouped by geographic region. Means with the same uppercase letter are not significantly different among sample times within geographic region and means with the same lowercase letter are not significantly different between geographic regions for a sample time (Tukey $P \leqslant 0.1$). Bars without letters are not significantly different.

0.91 ± 0.05 m, respectively. All three predicted fire behavior metrics decreased after burning but season-of-burn alone and season-of-burn × time and season-of-burn × region interactions were not significant ($P \geqslant 0.126$; Fig. 4). Predicted RI, ROS, and FL differed significantly regionally ($P \leqslant 0.035$). For all sampling times the mean predicted RI, ROS, and FL at APSM were lower than at EAFB (Fig. 5), however post hoc testing showed that, except for predicted FL, these differences were not significant (Tukey $P \geqslant 0.165$). Relative to EAFB, predicted FL at APSM was 0.25 ± 0.07 m lower before treatment (Tukey $P = 0.021$) and 0.22 ± 0.07 m lower the first year after treatment (Tukey $P = 0.055$). Although predicted FL at APSM was 0.20 ± 0.11 m lower than EAFB the second year after treatment, this difference was not significant (Tukey $P = 0.105$).

3.4. In-fire temperatures

Distribution of MTT and RT were weakly bimodal and the average MTT was 423 °C with a range of 332–522 °C (Table 1). Average RT was 28 s and ranged from 19 to 41 s. No differences in MTT were observed between dormant season and growing season burns or between geographic regions (see Appendix B).

3.5. Correlation between predicted fire behavior and surface fuel properties

Measures of the litter and herb fuel strata were most strongly correlated with predicted fire behavior, while correlation coefficients for the shrub layer were consistently low (Table 3). Herbaceous fuel loading was strongly correlated with predicted RI. Cover of herbs and litter, which were additive categories in our sample data, had opposite relationships with predicted RI. Other surface fuel measures correlated with predicted RI included litter depth and herb height. Litter depth was well correlated with predicted ROS, however, predicted ROS stopped increasing when litter depth exceeded 20 mm. Other fuel variables correlated with predicted ROS included 1-h and 100-h downed woody fuel loading and duff depth. Litter depth was strongly correlated with predicted FL, however, the relationship between litter depth and predicted FL did not flatten as was observed with litter depth and ROS. Other fuel variables correlated with predicted FL included 1-h, 10-h, and 1000-h downed woody fuel loading and duff depth. No live fuel measures were strongly correlated with predicted ROS or FL.

4. Discussion

4.1. Shrub fuels

We did not detect a difference in the shrub fuel stratum between single dormant and growing season burns in mature pine flatwoods. This result agrees with past studies in which observed individual growing season burns in pine flatwoods had only small (Willcox and Giuliano, 2010; Robertson and Hmielowski, 2014) or negligible (Hughes and Knox, 1964; Boyer, 1990; Olson and Platt, 1995) negative effects on the shrub layer relative to dormant season burns. Growing season burning is thought to have a greater negative effect on shrubs than dormant season burning in fire-adapted pine forests of the southeastern USA because fires in the growing season coincide with a period of low carbohydrate reserves in root structures of understory shrubs. When plants are top-killed by fire during this time of the year less energy is available for regrowth, and recovery is delayed (Ferguson, 1957). Reduced recovery following growing season burning relative to burns in the dormant season has been observed for saw palmetto (Willcox and Giuliano, 2010) in pine flatwoods, and deciduous hardwoods in mixed southern pine woodlands (Robertson and Hmielowski, 2014), but not gallberry in slash pine forests (Hughes and Knox, 1964). Carbohydrate reserves for saw palmetto and gallberry, two of the most common shrub species at our plots in both geographic regions, are lowest during the mid- to late-summer (Hughes and Knox, 1964; Hough, 1968). The growing season burns at our plots occurred in spring and early summer and did not align well with the period of depleted carbohydrate reserves, which could help to explain the lack of a significant effect

Table 3
Correlation of FCCS fire behavior predictions with fuel characteristics measured at season-of-burn treatment plots by sampling time.

Input variable	Reaction intensity (kW m^{-2})	Rate of spread (m min^{-1})	Flame length (m)
Shrubs			
Percent cover	−0.425**	0.005	−0.172
Fuel loading	−0.132	0.289*	0.237
Height	0.321*	0.227	0.325*
Herbs			
Percent cover	0.693***	−0.137	0.162
Fuel loading	0.871***	−0.169	0.215
Height	0.481***	0.343*	0.480***
Litter			
Percent cover	−0.743***	0.098	−0.229
Fuel loading	–	–	–
Depth	0.487***	0.919***	0.927***
Duff			
Percent cover	−0.087	0.465***	0.364*
Depth	0.099	0.597***	0.554***
Woody fuels			
1-h fuel loading	0.094	0.514***	0.500***
10-h fuel loading	0.143	0.479***	0.500***
100-h fuel loading	0.067	0.548***	0.490***
1000-h fuel loading	0.428**	0.404**	0.562***

* Significance level: $0.01 < P < 0.05$.
** Significance level: $0.001 < P < 0.01$.
*** Significance level: $P < 0.0001$.

in our results. Higher fire intensity during the growing season has also been suggested as a possible cause of shrub reduction relative to dormant season burning (Waldrop et al., 1987), although other studies have found that dormant season fires burn at higher intensity than those in the growing season (Sparks et al., 2002). We did not detect a difference in MTT, used as a proxy measure for fire intensity, between season-of-burn treatments, so were unable to examine the putative relationships between shrub response and seasonally influenced fire intensity.

We found that other factors, aside from the season of burn, influence post-fire recovery of the shrub fuel layer in pine flatwoods. Greater reduction of shrubs at EAFB relative to APSM suggests that prescribed fires can have differential effects on post-fire shrub dynamics in pine flatwoods across geographic regions. Differences in post-fire recovery of shrubs in longleaf pine forests between geographic regions and habitat types have been observed and attributed to fire intensity (Liu et al., 2004), soil moisture (Olson and Platt, 1995), and soil texture (Glitzenstein et al., 2003). Differences in MTT were not observed between plots at APSM and EAFB and therefore it is unlikely that fire intensity contributed to our observed differences in shrub cover reduction. Olson and Platt (1995) observed that shrubs at upland pine savanna sites were slower to recover after burning relative to shrubs at more poorly drained seepage savannas while Glitzenstein et al. (2003) noted that pine flatwoods understory shrub cover was unaffected by high-frequency repeated burning at sites on Spodosols in northern Florida and significantly reduced at sites on more finely textured Ultisols in South Carolina. Our results are consistent with the observation by Glitzenstein et al. (2003) that shrubs growing on Spodosols are less affected by burning, but inconsistent with their hypothesis that coarser soil texture increases resistance of shrubs to stress as soils at EAFB soils are generally more well-drained and coarsely textured than Spodosol soils at APSM. For our study, post-fire recovery of the shrub layer was slower on coarse-textured, well-drained soils (e.g. EAFB) and reflects observations by Olson and Platt (1995). The relationship between soils and post-fire shrub recovery at our plots is equivocal, however, as we lack specific soil typing and, are relying on published soil surveys which may not accurately represent the actual soil type at our treatment plots owing to the spatial variability within geographic regions.

The shrub stratum is an important determinant of fire behavior in southeastern pine forest types (Andreu et al., 2012). Relevant characteristics of this stratum include fuel loading, cover, and height (Hough and Albini, 1978; Brose and Wade, 2002). In pine flatwoods, resprouting shrub stems recover height and accumulate biomass quickly following disturbance, which, over several years without burning can contribute a large fraction to the surface fuel load (McNab et al., 1978; Kreye et al., 2014). In stands with a shrub-dominated understory, as is typical for pine flatwoods, potential fire behavior can increase to undesirable levels within five years of treatment due to high fuel loading of shrubs and litter (Brose and Wade, 2002). To control accumulations of hazardous fuels, including shrubs, management activities focus on: (1) continually top-killing shrubs to keep fuel loading and heights low, or (2) contributing to shrub mortality to reduce the capacity of vegetation to fully recover and thereby reduce the maximum level of accumulation that is possible between treatments. Frequent prescribed burning over the past 20 years at our plots has maintained relatively low loading and height of shrubs relative to long-unburned pine flatwoods where shrub fuel loading can be considerably higher (Kreye et al., 2014). Given the recent management history of our plots, initial fuel loads, and therefore the total amount that could be reduced following prescribed burns, were well below those associated with a high difficulty of fire suppression (Brose and Wade, 2002). Changes in shrub cover before and after treatment for growing and dormant season burns (Fig. 4) were also well below Hough and Albini's (1978) 15%, 50%, and 85% palmetto cover categories that correspond to saw palmetto quantities above which marked changes in fire behavior are expected. Furthermore, pre- and post-treatment shrub cover for both season-of-burn treatments was not significantly different, suggesting shrub cover returns to pre-fire levels rapidly.

4.2. Herb dynamics

Measures of the herb fuel layer did not differ between season-of-burn treatments. Other studies in southeastern pine-dominated ecosystems show there to be wide variability in herb response to single burns (e.g., Hiers et al., 2000; Brewer, 2006) suggesting that it can be difficult to assess a treatment effect when species with different phenologies and responses to fire are grouped together by life form. Variability in post-fire regrowth has also been observed within a single species (Sparks et al., 1998) suggesting that multiple factors can influence herb growth following a single fire. While we attempted to control for some factors by selecting compositionally comparable plots and using in-fire temperature measurements to adjust for differences in fire intensity, other confounding factors may have been present. For instance, our study locations were substantially colder and wetter than normal during the dormant season burn treatments, and warmer and slightly drier than normal during the growing season burn treatments (Fig. 6). Since precipitation during the growing season is known to affect herb growth in pine flatwoods (Grelen and Lohrey, 1978), effects of season-of-burn may have been overwhelmed by a departure from normal precipitation levels from the dormant to the growing season. In addition, we may not have detected a season-of-burn effect on herbaceous fuels due to the coarse temporal scale (i.e., annual) of our post-treatment measurements. Although one year is a relevant time-step for prescribed fire and fuels management, detecting the effect of a single season-of-burn treatment on herbs may require weekly or monthly sampling as was conducted in other studies that did observe effects related to season-of-burning (Platt et al., 1988; Hiers et al., 2000; Shepherd et al., 2012).

Potential fire behavior is unlikely to be affected by the small variations in the herb layer we observed because, as with the shrub layer, herb cover, fuel loading, and height were well below thresholds known to produce extreme fire behavior. By virtue of its overall lower fuel loading, the herb fuel stratum in pine flatwoods does not contribute to fire behavior to the same degree as other fuels that comprise a greater portion of the total fuelbed such as shrubs and litter. Fire behavior observations in grasslands (Cheney et al., 1998; Setterfield et al., 2010) and laboratory settings (Kreye et al., 2013) show that fuel loading must change by several megagrams per hectare to substantially affect fire behavior. At our plots herb loading ranged from 0.10 to 2.39 Mg ha^{-1} and on average comprised only 13.7 ± 1.4% of the total fine fuel loading.

4.3. Predicted fire behavior

Predicted fire behavior for post-treatment fuelbeds for plots burned in the dormant and growing seasons were not different. This not only reflects the nonsignificant effects of season-of-burn on the recovery of live fuels at our plots, but also the relatively low loading of total fine surface fuels in frequently burned pine flatwoods. The range of biomass of total fine surface fuels (i.e., shrubs, herbs, litter, and downed-woody fuels < 2.54 cm in diameter) for all plots and sampling times in this study ranged from 4.25 to 10.41 Mg ha^{-1} and represents the lower end of sampled fuel conditions in studies that have assessed fire behavior in forested ecosystems in the USA. For instance, Brose and Wade (2002) sampled fuels before and after fuels reduction treatments in pine plantations and pine flatwoods in northern Florida and found that total fine surface fuel loading ranged from 4.46 to 60.87 Mg ha^{-1}. They also report that predicted fire behavior would result in low

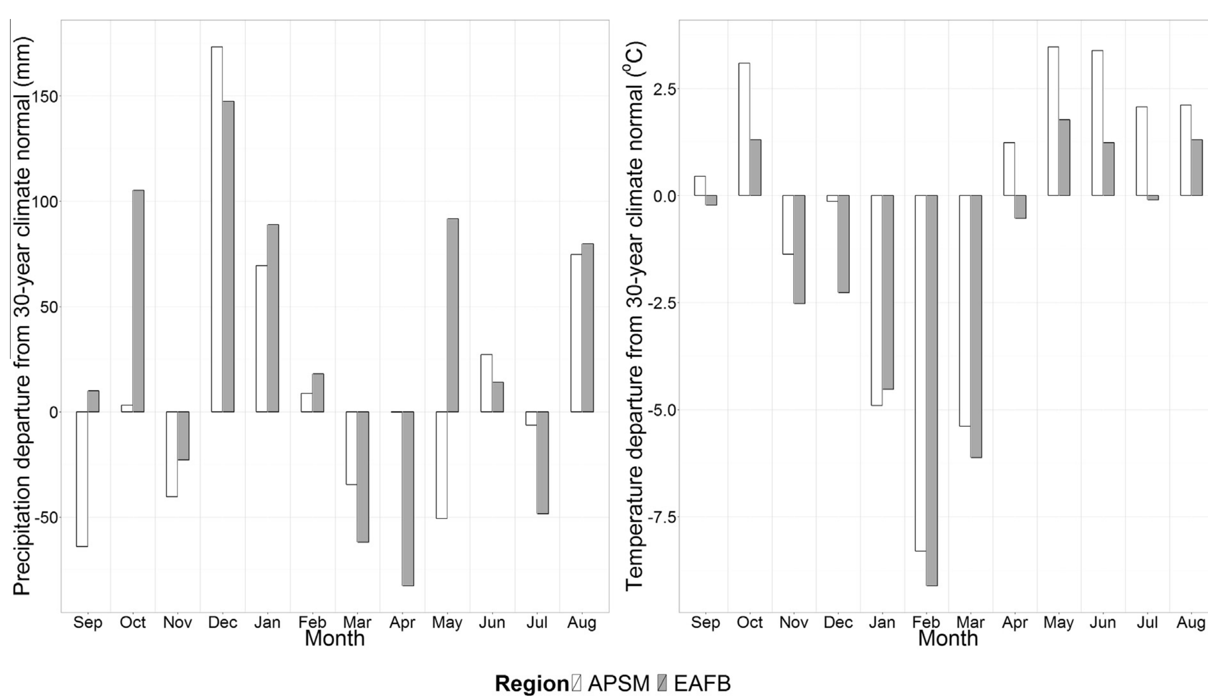

Fig. 6. Departure from 1971 to 2000 precipitation and temperature climate normals (National Oceanic and Atmospheric Association (NOAA), 2002) for APSM (NOAA Cooperative Station ID 088758, Tallahassee, Florida) and EAFB (NOAA Cooperative Station ID 086240, Niceville, Florida) in study area during a 12 month period surrounding the burn treatments from September 2009 to August 2010.

difficulty of fire suppression for plots with total fine surface fuel loading up to 26.77 Mg ha^{-1}. Other studies throughout the USA have examined the effect of fuel treatments on fire behavior and found that substantial differences in fire behavior were associated with changes in total fine surface fuel loading on the order to 10s of Mg ha^{-1} (Youngblood et al., 2008; McGinnis et al., 2010), further highlighting the narrow range of sampled fuel conditions and fire potential at the low end of the continuum that our plots represent. In their current state the fuels on our plots are what would be considered well-managed and any changes associated with season-of-burn treatments would not influence fire behavior on a scale likely to affect fire control efforts.

The litter layer plays an important role in fire behavior for fuel types with a longleaf pine overstory (Wahlenburg, 1946; Mitchell et al., 2009), such as pine flatwoods, and in pine-dominated ecosystems with a low severity fire regime, in general (Agee, 1998). Pine litter is important in the longleaf pine flatwoods fuel type because needles have high energy content (Reid and Robertson, 2012) and the overstory can quickly produce enough litterfall annually to create a continuous fine dead fuel layer that will readily carry fire. There is also a synergistic effect with the herb fuel layer, primarily bunchgrasses, which, when dominant, can loft litter and orient individual needles vertically (Hendricks et al., 2002). This orientation of the litter increases the rate of litter drying (Nelson and Hiers, 2008) and the probability of ignition. Litter depth was highly correlated with predicted ROS and FL and litter fuel loading, while not a direct input into FCCS, would have been highly correlated with these measures of fire behavior. Cover of litter was less correlated with predicted fire behavior because there was little variation in coverage (86.3 ± 1.6%) among plots for each sampling time. For this study litter was the dominant fine surface fuel, accounting for 47.9 ± 1.7% of total fine surface fuel loading on average. In other studies of fuels in pine flatwoods, litter accounted for an even larger fraction of total fine surface fuels. Kreye et al. (2014) recorded litter fuel loading of 11.1 Mg ha^{-1} and 14.3 Mg ha^{-1} which was 74.1% and 69.4% of total fine surface fuel loading, 1 year and 2 years after mowing treatments, respectively, in burned, mature pine flatwoods on the Osceola National Forest in northern Florida, USA, approximately 170 km east of our easternmost plots. The high correlation we observed between herb cover and loading with RI is surprising as herbs were a relatively minor component of the surface fuel complex on our plots. The high herb layer correlation with predicted RI was a function of the manner in which the FCCS fire spread model partitions RI calculations by individual fuelbed strata making it sensitive to different fuel moisture levels for each stratum. In our environmental benchmark scenario, herb fuel moisture was lower than shrub fuel moisture (60% vs. 90%), which may have over-weighted the influence of the herb fuel layer.

4.4. Management implications

Existing literature consistently points to the length of the fire-free interval as a driver of fuel composition and amount, and of potential fire behavior in pine flatwoods (Hough and Albini, 1978; Brose and Wade, 2002; Kreye et al., 2014), and suggests that land managers should prioritize frequent burning (<5 years) to maintain low fuel loading (O'Brien et al., 2010). Our results showed that a single growing season prescribed fire did not affect live fuel recovery or predicted fire behavior differentially than a dormant season prescribed fire for up to two years following burning for frequently burned pine flatwoods. Based on this study, managers should not expect dramatic changes in fuel amounts, composition, structure, or fire behavior in this ecosystem regardless of season-of-burn following a single prescribed fire.

This study examined the effects of burning in the dormant and growing seasons on fuel recovery and found only subtle differences; management decisions should carefully weigh treatment goals, not just on the effects on potential fire behavior. For instance, the decision to use prescribed fire in pine flatwoods to restore or maintain habitat characteristics or understory plant diversity may take precedence over simply maintaining low fuel loading levels. An open understory with a large wiregrass component is desirable for some rare species that prefer an open herbaceous understory such as the red-cockaded woodpecker (Van Balen and Doerr, 1978; James et al., 1997) and gopher tortoise (Cox et al., 1987). For ecological goals such as these, a single growing season burn may produce beneficial effects. For example, Shepherd et al. (2012) found that relative to dormant season burning, a single growing season burn increased seed production for some grass species common to pine savannas. While decades of dormant season prescribed burning have shown that hazardous fuels in pine flatwoods can be managed effectively with prescribed fire, incorporating growing season prescribed fire may help to achieve ecological goals while maintaining acceptable surface fuel levels if burns can be conducted with sufficient frequency (i.e., at least once every five years).

Pine flatwoods typically occur as part of a mosaic of multiple vegetation types with different fire regimes and management goals within operation prescribed fire boundaries. Design and implementation of prescribed fire burning regimes should incorporate frequency and season-of-burn, and should consider management objectives for all vegetation types.

Based on other published work (Haywood et al., 2001; Glitzenstein et al., 2003) we expect that multiple burns spaced at short intervals (1–3 years) and consistently applied in the growing season may incrementally change the composition, amount, and structure of live surface fuels and alter potential fire behavior. While changes associated with growing season burning may initially be subtle, managers should monitor live fuels as cumulative incremental changes may produce a fuel complex with different fire behavior characteristics. Over longer periods of time, however, repeated burning at short fire-return intervals (1–2 years) has been shown to substantially reduce shrubs (Brockway and Lewis, 1997), especially for burns conducted in the growing season in some geographic regions in the pine flatwoods ecosystem (Haywood et al., 2001; Glitzenstein et al., 2003).

Acknowledgements

We acknowledge funding from the Joint Fire Science Program under Project No. 09-1-01-2. We are grateful for the support and cooperation of numerous agencies and individuals who worked with us to incorporate research plots into existing prescribed fires, specifically K. Hiers and B. Williams at Eglin Air Force Base, E. Watkins at Apalachicola National Forest, and G. Titus and J. Hinckley at St. Marks National Wildlife Refuge. We also thank C. Balog, C. Burke, B. Cassell, J. Crowder, J. Dvorak, T. Freed, L. Grand, S. Griscom, K. Jacobson, R. Jones, I. Kostick, J. Landburg, A. Lundquist, J. McDuffey, K. Moffit, J. Restaino, S. Savage, A. Sengsirirak, D. Shoemaker, M. Simmons, and J. Smith for their help with field data collection and data entry. P. Eagle developed the database structure and data entry application. M. Kennedy and A. Steele provided statistical advice. B. Vihnanek coordinated field logistics.

Appendix A. Inputs for FCCS custom fuelbeds for each treatment plot at each sampling period

See Tables A1–A4.

Table A1
Mean understory live fuel variables for each treatment plot at each sampling time at EAFB in mesic longleaf pine flatwoods in northern Florida, USA used as inputs to create custom FCCS fuelbeds.

Plot no.	Sample time	Shrubs			Herbs		
		Cover (%)	Biomass (Mg ha^{-1})	Height (m)	Cover (%)	Biomass (Mg ha^{-1})	Height (m)
Dormant season plots							
1	Pre	39	4.48	0.75	13	0.44	0.32
	1-year post	27	1.90	0.47	12	0.62	0.24
	2-years post	34	1.80	0.60	12	0.84	0.13
2	Pre	32	2.67	0.67	48	1.96	0.35
	1-year post	20	1.16	0.49	29	1.53	0.25
	2-years post	21	1.10	0.63	39	2.39	0.23
3	Pre	41	2.10	0.57	23	1.51	0.33
	1-year post	39	2.32	0.50	21	0.71	0.26
	2-years post	30	2.17	0.52	21	1.33	0.23
4	Pre	44	3.46	0.60	7	0.14	0.20
	1-year post	34	1.63	0.45	6	0.23	0.14
	2-years post	34	1.69	0.52	7	0.25	0.17
Growing season plots							
5	Pre	36	1.55	0.53	7	0.21	0.19
	1-year post	31	1.32	0.50	6	0.34	0.21
	2-years post	35	1.55	0.50	8	0.20	0.17
6	Pre	43	2.56	0.87	19	0.60	0.25
	1-year post	24	1.04	0.55	15	0.54	0.17
	2-years post	33	1.97	0.61	15	0.59	0.11
7	Pre	36	1.57	0.63	24	1.13	0.24
	1-year post	24	1.48	0.51	19	1.33	0.22
	2-years post	43	1.77	0.55	23	1.10	0.25
8	Pre	42	2.26	0.51	38	1.80	0.29
	1-year post	29	1.74	0.44	22	1.46	0.15
	2-years post	26	1.71	0.50	19	1.03	0.23

Table A2
Mean understory live fuel variables for each treatment plots at each sampling time at APSM in mesic longleaf pine flatwoods in northern Florida, USA used as inputs to create custom FCCS fuelbeds.

Plot no.	Sample time	Shrubs			Herbs		
		Cover (%)	Biomass (Mg ha^{-1})	Height (m)	Cover (%)	Biomass (Mg ha^{-1})	Height (m)
Dormant season plots							
9	Pre	31	1.75	0.51	42	1.36	0.22
	1-year post	35	1.59	0.38	15	1.09	0.18
	2-years post	39	2.36	0.40	20	1.24	0.16
10	Pre	52	2.78	0.60	4	0.10	0.25
	1-year post	46	3.28	0.43	2	0.13	0.11
	2-years post	58	2.43	0.51	3	0.22	0.11
11	Pre	57	3.58	0.53	4	0.22	0.29
	1-year post	54	2.62	0.44	4	0.19	0.10
	2-years post	61	2.99	0.48	4	0.22	0.11
12	Pre	35	2.40	0.51	10	0.68	0.32
	1-year post	32	1.83	0.39	8	0.28	0.19
	2-years post	37	2.03	0.44	8	0.26	0.16
Growing season plots							
13	Pre	43	1.61	0.43	34	0.79	0.27
	1-year post	39	1.95	0.42	11	0.75	0.22
	2-years post	46	1.68	0.44	14	0.78	0.18
14	Pre	28	0.94	0.52	37	0.78	0.25
	1-year post	29	1.37	0.48	17	0.99	0.24
	2-years post	40	1.28	0.48	25	1.14	0.27
15	Pre	45	2.62	0.50	9	0.64	0.28
	1-year post	40	1.83	0.42	11	0.54	0.14
	2-years post	54	2.11	0.42	20	0.84	0.12
16	Pre	67	5.15	0.63	6	0.53	0.29
	1-year post	61	4.06	0.54	5	0.28	0.13
	2-years post	80	4.43	0.67	8	0.28	0.12

Table A3
Mean understory dead fuel variables for each treatment plot at each sampling time at EAFB in mesic longleaf pine flatwoods in northern Florida, USA used as inputs to create custom FCCS fuelbeds.

Plot no.	Sample time	Litter			Duff		Woody fuel biomass			
		Cover (%)	Biomass (Mg ha^{-1})	Depth (mm)	Cover (%)	Depth (mm)	1-h (Mg ha^{-1})	10-h (Mg ha^{-1})	100-h (Mg ha^{-1})	1000-h (Mg ha^{-1})
Dormant season plots										
1	Pre	89	3.67	23	48	35	0.21	0.97	1.45	10.00
	1-year post	88	2.39	18	56	23	0.10	0.76	1.13	8.83
	2-years post	92	3.09	23	42	23	0.07	0.59	1.30	7.53
2	Pre	53	2.66	25	25	11	0.13	0.51	0.77	5.52
	1-year post	70	1.77	15	28	12	0.05	0.54	0.74	4.66
	2-years post	61	2.07	15	22	11	0.09	0.37	0.62	4.25
3	Pre	78	3.13	20	68	23	0.13	0.72	1.07	4.77
	1-year post	79	3.54	23	45	19	0.10	0.70	0.76	4.81
	2-years post	80	4.39	25	68	19	0.08	0.42	0.82	2.65
4	Pre	92	3.77	28	77	40	0.20	0.55	1.04	0.22
	1-year post	93	2.42	15	45	33	0.16	0.67	1.05	0.22
	2-years post	93	3.08	18	46	49	0.10	0.53	1.19	0.36
Growing season plots										
5	Pre	96	4.90	20	44	9	0.07	0.71	0.66	1.65
	1-year post	97	2.22	15	52	16	0.08	0.45	0.59	0.74
	2-years post	96	2.92	13	42	15	0.05	0.52	0.59	0.84
6	Pre	80	3.99	25	48	42	0.15	0.96	1.36	4.53
	1-year post	88	2.18	15	34	27	0.13	0.89	0.88	4.11
	2-years post	89	4.09	20	49	36	0.21	0.59	1.05	3.40
7	Pre	79	3.19	20	29	14	0.06	1.00	0.31	0.65
	1-year post	82	1.88	15	20	13	0.09	0.54	0.42	0.49
	2-years post	78	2.49	13	8	13	0.02	0.33	0.36	0.58
8	Pre	63	3.12	23	18	17	0.07	0.57	0.43	0.75
	1-year post	78	1.14	13	24	7	0.06	0.22	0.43	0.58
	2-years post	82	2.29	13	15	17	0.04	0.17	0.51	0.11

Table A4
Mean understory dead fuel variables for each treatment plot at each sampling time at APSM in mesic longleaf pine flatwoods in northern Florida, USA used as inputs to create custom FCCS fuelbeds.

Plot no.	Sample time	Litter			Duff		Woody fuels			
		Cover (%)	Biomass (Mg ha^{-1})	Depth (mm)	Cover (%)	Depth (mm)	1-h (Mg ha^{-1})	10-h (Mg ha^{-1})	100-h (Mg ha^{-1})	1000-h (Mg ha^{-1})
Dormant season plots										
9	Pre	57	2.11	15	8	13	0.04	0.36	0.32	0.26
	1-year post	85	1.06	8	2	4	0.02	0.48	0.29	0.37
	2-years post	81	2.59	8	46	2	0.04	0.39	0.39	0.36
10	Pre	94	4.80	20	35	9	0.03	0.32	0.73	2.86
	1-year post	96	1.47	10	10	16	0.04	0.34	0.71	2.22
	2-years post	96	2.93	8	44	4	0.04	0.29	0.88	2.27
11	Pre	98	4.90	23	62	19	0.22	0.41	0.57	1.19
	1-year post	99	2.00	10	34	6	0.06	0.57	0.62	1.11
	2-years post	99	3.93	10	78	8	0.08	0.50	0.66	0.83
12	Pre	91	6.52	23	41	8	0.08	0.73	0.54	0.61
	1-year post	92	2.34	15	24	12	0.12	0.64	0.51	0.63
	2-years post	92	4.71	10	65	5	0.15	0.79	0.51	0.51
Growing season plots										
13	Pre	76	2.66	13	2	4	0.00	0.24	0.68	1.48
	1-year post	93	1.53	13	3	10	0.01	0.35	0.57	1.05
	2-years post	91	2.33	10	22	4	0.01	0.38	0.62	0.96
14	Pre	73	4.01	15	18	7	0.01	0.37	0.80	1.43
	1-year post	91	2.21	13	20	10	0.00	0.54	0.51	2.04
	2-years post	87	3.36	15	17	10	0.01	0.74	0.53	1.58
15	Pre	95	2.50	13	12	8	0.06	0.32	0.59	1.37
	1-year post	96	1.51	10	16	7	0.02	0.62	0.45	0.97
	2-years post	94	2.57	18	32	9	0.07	0.61	0.54	0.75
16	Pre	95	2.74	13	58	18	0.25	0.29	0.20	1.07
	1-year post	98	1.37	10	54	13	0.10	0.50	0.29	0.76
	2-years post	97	1.96	15	38	21	0.16	0.67	0.43	0.53

Table B1
Season-of-burn (growing vs. dormant season) and geographic region (APSM vs. EAFB) comparisons of MTT ($\bar{x} \pm$ SE).

Treatment	MTT (°C)	P
Season-of-burn		
Growing season	403 ± 19	0.190
Dormant season	443 ± 22	
Geographic region		
APSM	439 ± 21	0.299
EAFB	407 ± 21	

Appendix B. Ancillary statistical test results

See Table B1.

Appendix C. Paired plot sampling to adjust for phenological differences of live fuels

Post-fire sampling times were spaced at annual increments after treatment burns to allow for a full growing season for vegetation recovery, which resulted in plots being sampled from January to July. This provided equal periods of recovery among our plots but phenological differences in live fuels between plots sampled in the dormant and growing seasons may have been present and could have affected hypothesis testing. Differences in live fuels between the dormant and growing seasons have been observed elsewhere in the southeastern USA (Sparks et al., 2002). We felt that phenological differences in shrubs were minor and limited to cover. At our plots the majority of understory shrubs (i.e. saw palmetto, gallberry, dwarf live oak, and Darrow's blueberry) were evergreen and unlikely to express strong phenological differences that would affect our response variables. As such, changes in loading and height would be attributable completely to growth rather than seasonal changes and were not tested. However, some deciduous species were present in small numbers including huckleberry (*Gaylussacia* Kunth), gopher apple (*Licania michauxii* Prance), and highbush blueberry (*Vaccinium corymbosum* L.) and this could have significantly influenced cover estimates beyond increases attributable only to growth. The herb layer was dominated by wiregrass which retains foliage throughout the year and phenological differences would likely be limited to height as plants tend to flatten during the dormant season. Some perennial forbs, whose foliage decomposes rapidly after the plant enters dormancy, were also present at our plots. Phenology of these plants could affect cover, fuel loading, and height of the herb layer.

To account for these differences we sampled 10 paired February (sampled before leaf emergence) and May (leaves fully emerged) subplots at two plots in each region in 2012. Odd numbered subplots from the main study were used as paired plots. Shrub cover and herb cover and height data were sampled along subplot transects before (February) and after (May) leaf emergence. For herb fuel loading, additional biomass subplots were paired with existing subplots (within 2 m) at locations where density and structure of live fuels were visually similar. Measurements of shrub and herb cover, biomass, and height were collected by using the same methods outlined in the methods (Section 2.3). A paired *t* test was conducted to determine whether differences in fuel variables existed between the February and May sampling times (Table C1). Shrub cover, and herb cover, loading, and height were adjusted by applying the ratio of mean February-to-May values on a weighted scale according to time-since-leaf emergence to plots for which sample times fell between initial leaf emergence (defined as March 15, the beginning of the growing season) and full leaf emergence (defined as May 15) to remove phenological effects. For instance, to adjust a hypothetical plot measured on April 15 with 45% shrub cover for phenological differences, the adjustment ratio of 0.822 (Table C1; February shrub cover divided by May shrub cover from paired plots), is scaled to mid-April by adding it to the product of the ratio of time to full leaf emergence from the sampling date (30 days) to time between initial and full leaf emergence (61 days) and the inverse of the adjustment ratio (1–0.822). This gives a time-weighted adjustment ratio of 0.910 $(0.822 + (0.492 \times 0.178))$ and an adjusted shrub cover of 41%. Live fuels analyses were re-calculated with adjusted data to test whether the phenological differences in fuels we detected had an

Table C2
Comparison of significant terms for overall repeated measures ANOVA statistical tests for raw data and data adjusted for phenological differences in shrub cover and herb cover, and height.

Fuel stratum	Term	P	
		Raw data	Adjusted data
Shrubs			
Cover (%)	Region	0.026	0.031
	Time	<0.001	<0.001
	Season × time	0.057	0.043
	Region × time	<0.001	<0.001
Herbs			
Cover (%)	Time	0.009	0.002
Loading (Mg ha^{-1})	No significant terms	n.a.	n.a.
Height (m)	Time	<0.001	<0.001

Table C3
Comparison of significant terms for Tukey's HSD multiple comparison statistical tests for raw data and data adjusted for phenological differences in shrub cover and herb cover and height.

Fuel stratum	Term	P	
		Raw data	Adjusted data
Shrubs			
Cover (%)	APSM – 2-year post EAFB – 2-year post	0.004	0.007
Herbs			
Cover (%)	n.a.		
Height (m)	n.a.		

Table C1
Live fuel ($\bar{x} \pm$ SE) cover, loading, and height for paired February (before leaf emergence) and May (after leaf emergence) plots, results of Student's *t*-test, and adjustment ratio used for fuels sampled after leaf out (mean ratio value applied on weighted scale based on time-since-leaf emergence).

Fuel layer	Fuel property	February	May	P	Adjustment ratio
Shrub	Cover (%)	42.00 ± 9.60	51.00 ± 9.40	<0.001	0.822 (0.901)
	Loading (Mg ha^{-1})	2.24 ± 0.83	2.42 ± 0.88	0.298	n.a.
	Height (m)	1.30 ± 0.30	1.50 ± 0.30	0.011	n.a.
Herbaceous	Cover (%)	17.20 ± 5.60	21.20 ± 5.00	<0.001	0.811 (0.893)
	Loading (Mg ha^{-1})	0.84 ± 0.54	1.05 ± 0.53	0.039	0.798 (0.890)
	Height (m)	0.60 ± 0.20	0.70 ± 0.20	0.080	0.906 (0.946)

effect on statistical results. There was no change in significance for terms in the overall repeated measures analysis of variance tests or post hoc multiple comparison tests for any live fuel variable (Tables C2 and C3).

References

Agee, J.K., 1998. Fire and pine ecosystems. In: Richardson, D.M. (Ed.), Ecology and Biogeography of *Pinus*. Cambridge University Press, Cambridge, pp. 193–218.

Agee, J.K., Skinner, C.N., 2005. Basic principles of forest fuel reduction treatments. For. Ecol. Manage. 211, 83–96.

Allen, W.J., 1991. Soil Survey of Wakulla County, Florida. USDA Soil Conservation Service, Washington, DC.

Anderson, H.E., 1982. Aids to Determining Fuel Models for Estimating Fire Behavior. USDA Forest Service, Gen. Tech. Rep. INT-122, Ogden, Utah.

Andreu, A.G., Shea, D., Parresol, B.R., Ottmar, R.D., 2012. Evaluating fuel complexes for fire hazard mitigation planning in the southeastern United States. For. Ecol. Manage. 273, 4–16.

Bale, A.M., 2009. Fire Effects and Litter Accumulation Dynamics in a Montane Longleaf Pine Ecosystem. M.S. Thesis, University of Missouri, Columbia, Missouri.

Boyer, W.D., 1990. Growing-season Burns for Control of Hardwoods in Longleaf Pine Stands. USDA Forest Service, Res. Pap. SO-256, New Orleans, Louisiana.

Brewer, J.S., 2006. Long-term population changes of a fire-adapted plant subjected to different fire seasons. Nat. Areas J. 26, 267–273.

Brockway, D.G., Lewis, C.E., 1997. Long-term effects of dormant-season prescribed fire on plant community diversity, structure and productivity in a longleaf pine wiregrass ecosystem. For. Ecol. Manage. 96, 167–183.

Brose, P.H., 2010. Long-term effects of single prescribed fires on hardwood regeneration in oak shelterwood stands. For. Ecol. Manage. 260, 1516–1524.

Brose, P., Wade, D., 2002. Potential fire behavior in pine flatwood forests following three different fuel reduction techniques. For. Ecol. Manage. 163, 71–84.

Brown, J.K., 1974. Handbook for Inventorying Downed Woody Material. USDA Forest Service, Gen. Tech. Rep. INT-16, Ogden, Utah.

Burgan, R.E., Rothermel, R.C., 1984. BEHAVE: Fire Behavior Prediction and Fuel Modeling System: FUEL Subsystem. USDA Forest Service, Gen. Tech. Rep. INT-167, Ogden, Utah.

Canfield, R.H., 1941. Application of the line interception method in sampling range vegetation. J. For. 39, 388–394.

Cheney, N.P., Gould, J.S., Catchpole, W.R., 1998. Prediction of fire spread in grasslands. Int. J. Wildland Fire 8, 1–13.

Conner, R.N., Saenz, D., Rudolph, D.C., 2004. The red-cockaded woodpecker: interactions with fire, snags, fungi, rat snakes and pileated woodpeckers. Tex. J. Sci. 56, 415–426.

Cox, J., Inkley, D., Kautz, R., 1987. Ecology and Habitat Needs of Gopher Tortoise (*Gopherus Polyphemus*) Populations Found on Lands Slated for Large-scale Development in Florida. Florida Game and Fresh Water Fish Commission, Nongame Wildlife Program Technical Report No. 4, Tallahassee, Florida.

Crawley, M.J., 2007. Mixed Effect Models. In: The R book. Wiley, Chichester, England, pp. 627–660.

Eisenberg, J., 1983. The gopher tortoise as a keystone species. In: Bryant, R.J., Franz, R. (Eds.), The Gopher Tortoise: A Keystone Species: Proceedings of the 4th Annual Meeting of the Gopher Tortoise Council. Gopher Tortoise Council, Valdosta, Georgia, pp. 1–4.

Ferguson, E.R., 1957. Stem-kill and sprouting following prescribed fires in a pine-hardwood stand in Texas. J. For. 55, 426–429.

Ferguson, J.P., 1998. Prescribed fire on the Apalachicola Ranger District: the shift from dormant season to growing season and effects on wildfire suppression. In: Pruden, T.L., Brennan, L.A. (Eds.), Fire in Ecosystem Management: Shifting the Paradigm from Suppression to Prescription, Tall Timbers Fire Ecology Conference Proceedings No. 20. Tall Timbers Research Station, Tallahassee, Florida, pp. 120–126.

Glitzenstein, J.S., Streng, D.R., Wade, D.D., 2003. Fire frequency effects on longleaf pine (*Pinus palustris*, P. Miller) vegetation in South Carolina and northeast Florida, USA. Nat. Areas J. 23, 22–37.

Glitzenstein, J.S., Streng, D.R., Masters, R.E., Robertson, K.M., Hermann, S.M., 2012. Fire-frequency effects on vegetation in north Florida pinelands: another look at the long-term Stoddard Fire Research Plots at Tall Timbers Research Station. For. Ecol. Manage. 264, 197–209.

Grelen, H.E., Epps, E.A., 1967. Season-of-burning affects herbage quality and yield on pine-bluestem range. J. Range Manage. 20, 31–33.

Grelen, H.E., Lohrey, R.E., 1978. Herbage Yield Related to Basal Area and Rainfall in a Thinned Longleaf Plantation. USDA Forest Service, Res. Note SO-232, New Orleans, Louisiana.

Hardin, E.D., White, D.L., 1989. Rare vascular plant taxa associated with wiregrass (*Aristida stricta*) in the southeastern United States. Nat. Areas J. 9, 234–245.

Haywood, J.D., Harris, F.L., Grelen, H.E., Pearson, H.A., 2001. Vegetative response to 37 years of seasonal burning on a Louisiana longleaf pine site. South. J. Appl. For. 25, 122–130.

Henderson, J.P., 2006. Dendroclimatological Analysis and Fire History of Longleaf Pine (*Pinus palustris* Mill.) in the Atlantic and Gulf Coastal Plain. Dissertation, University of Tennessee, Knoxville, Tennessee.

Hendricks, J.J., Wilson, C.A., Boring, L.R., 2002. Foliar litter position and decomposition in a fire-maintained longleaf pine-wiregrass ecosystem. Can. J. For. Res. 32, 928–941.

Hiers, J.K., Wyatt, R., Mitchell, R.J., 2000. The effects of fire regime on legume reproduction in longleaf pine savannas: is a season selective? Oecologia 125, 521–530.

Hough, W.A., 1968. Carbohydrate reserves of saw-palmetto: seasonal variation and effects of burning. For. Sci. 14, 399–405.

Hough, W.A., Albini, F.A., 1978. Predicting Fire Behavior in Palmetto-gallberry Fuel Complexes. USDA Forest Service, Res. Pap. SE-174, Asheville, North Carolina.

Hughes, R.H., Knox, F.E., 1964. Response of Gallberry to Seasonal Burning. USDA Forest Service, Res. Note SE-21, Asheville, North Carolina.

James, F.C., Hess, C.A., Kufrin, D., 1997. Species-centered environmental analysis: indirect effects of fire history on red-cockaded woodpeckers. Ecol. Appl. 7, 118–129.

Johansson, T., 1985. Estimating canopy density by the vertical tube method. For. Ecol. Manage. 11, 139–144.

Kennard, D.K., Outcalt, K.W., Jones, D., OBrien, J.J., 2005. Comparing techniques for estimating flame temperature of prescribed fires. Fire Ecol. 1, 75–84.

Knapp, E.E., Estes, B.L., Skinner, C.N., 2009. Ecological Effects of Prescribed Fire Season: A Literature Review and Synthesis for Managers. USDA Forest Service, Gen. Tech. Rep. PSW-224, Redding, California.

Kottek, M., Grieser, J., Beck, C., Rudolf, B., Rubel, F., 2006. World map of the Koppen-Geiger climate classification updated. Meteorol. Z. 15, 259–263.

Kreye, J.K., Kobziar, L.N., Zipperer, W.C., 2013. Effects of fuel load and moisture content on fire behaviour and heating in masticated litter-dominated fuels. Int. J. Wildland Fire 22, 440–445.

Kreye, J.K., Kobziar, L.N., Camp, J.M., 2014. Immediate and short-term response of understory fuels following mechanical mastication in a pine flatwoods site of Florida, USA. For. Ecol. Manage. 313, 340–354.

Liu, C.X., Harcombe, P.A., Knox, R.G., 2004. Structural changes after prescribed fire in woody plant communities of southeastern Texas. Tex. J. Sci. 56, 319–334.

Marshall, D.J., Wimberly, M., Bettinger, P., Stanturf, J., 2008. Synthesis of Knowledge of Hazardous Fuels Management in Loblolly Pine Forests. USDA Forest Service, Gen. Tech. Rep. SRS-110, Asheville, North Carolina.

McGinnis, T.W., Keeley, J.E., Stephens, S.L., Roller, G.B., 2010. Fuel buildup and potential fire behavior after stand-replacing fires, logging fire-killed trees and herbicide shrub removal in Sierra Nevada forests. For. Ecol. Manage. 260, 22–35.

McNab, W.H., Edwards, M.B., Hough, W.A., 1978. Estimating fuel weights in slash pine-palmetto stands. For. Sci. 24, 345–358.

McWhite, R.W., Furman, J., Petrick, C.J., 1999. Eglin Air Force Base Integrated Natural Resources Transitional Plan 1998–2001. U.S. Department of Defense, Air Force, Natural Resources Management Branch, Niceville, Florida.

Melvin, M.A., 2012. 2012 National Prescribed Fire Use Survey Report. Coalition of Prescribed Fire Councils Inc, Tech. Rep. 01-12, Newton, Georgia.

Mitchell, R.J., Hiers, J.K., O'Brien, J., Starr, G., 2009. Ecological forestry in the Southeast: understanding the ecology of fuels. J. For. 107, 391–397.

National Oceanic and Atmospheric Association, 2002. Monthly Station Normals of Temperature, Precipitation, and Heating and Cooling Degree Days: 1971–2000. U.S. Department of Commerce, Climatography of the United States No. 81, 08 Florida.

Nelson, R.M., Hiers, J.K., 2008. The influence of fuelbed properties on moisture drying rates and timelags of longleaf pine litter. Can. J. For. Res. 38, 2394–2404.

O'Brien, J.J., Mordecai, K.A., Wolcott, L., Snyder, J., Outcalt, K., 2010. Fuel Managers Field Guide: Hazardous Fuels Management in Subtropical Pine Flatwoods and Tropical Pine Rocklands. USDA Forest Service, Gen. Tech. Rep. SRS-123, Asheville, North Carolina.

Olson, M.S., Platt, W.J., 1995. Effects of habitat and growing-season fires on resprouting of shrubs in longleaf pine savannas. Vegetatio 119, 101–118.

Ottmar, R.D., Sandberg, D.V., Riccardi, C.L., Prichard, S.J., 2007. An overview of the Fuel Characteristic Classification System – quantifying, classifying, and creating fuelbeds for resource planning. Can. J. For. Res. 37, 2383–2393.

Overing, J.D., Watts, F.C., 1989. Soil Survey of Walton County, Florida. USDA Soil Conservation Service, Washington, DC.

Overing, J.D., Weeks, H.H., Wilson, J.P., Sullivan, J., Ford, R.D., 1995. Soil Survey of Okaloosa County, Florida. USDA Soil Conservation Service, Washington, DC.

Platt, W.J., Evans, G.W., Davis, M.M., 1988. Effects of fire season on flowering of forbs and shrubs in longleaf pine forests. Oecologia 76, 353–363.

R Development Core Team, 2014. R: A Language and Environment for Statistical Computing. R Foundation for Statistical Computing, Vienna, Austria. <http://www.R-project.org> (accessed 02.2015).

Reid, A.M., Robertson, K.M., 2012. Energy content of common fuels in upland pine savannas of the south-eastern US and their application to fire behavior modelling. Int. J. Wildland Fire 21, 591–595.

Riccardi, C.L., Prichard, S.J., Sandberg, D.V., Ottmar, R.D., 2007. Quantifying physical characteristics of wildland fuels using the Fuel Characteristic Classification System. Can. J. For. Res. 37, 2413–2420.

Robbins, L.E., Myers, R.L., 1992. Seasonal Effects of Prescribed Burning in Florida: A Review. Tall Timbers Research Inc., Miscellaneous Publication No. 8, Tallahassee, Florida.

Robertson, K.M., Hmielowski, T.L., 2014. Effects of fire frequency and season on resprouting of woody plants in southeastern US pine-grassland communities. Oecologia 174, 765–776.

Rothermel, R.C., 1972. A Mathematical Model for Predicting Fire Spread in Wildland Fuels. USDA Forest Service, Res. Pap. INT-115, Ogden, Utah.

Ryan, K.C., Knapp, E.E., Varner, J.M., 2013. Prescribed fire in North American forests and woodlands: history, current practice, and challenges. Front. Ecol. Environ. 11, E15–E24.

Saglam, B., Bilgili, E., Kucuk, O., Durmaz, B.D., 2008. Fire behavior in Mediterranean shrub species (Maquis). Afr. J. Biotechnol. 7, 4122–4129.

Sandberg, D.V., Riccardi, C.L., Schaaf, M.D., 2007. Fire potential rating for wildland fuelbeds using the Fuel Characteristic Classification System. Can. J. For. Res. 37, 2456–2463.

Sanders, T.E., 1981. Soil Survey of Leon County, Florida. USDA Soil Conservation Service, Washington, DC.

Schroeder, R.L., 1985. Habitat Suitability Index Models: Northern Bobwhite. USDI, Fish and Wildlife Service, Bio. Rep. 82 (10.104), Washington, DC.

Schwilk, D.W., Keeley, J.E., Knapp, E.E., McIver, J., Bailey, J.D., Fettig, C.J., Fiedler, C.E., Harrod, R.J., Moghaddas, J.J., Outcalt, K.W., Skinner, C.N., Stephens, S.L., Waldrop, T.A., Yaussy, D.A., Youngblood, A., 2009. The national Fire and Fire Surrogate study: effects of fuel reduction methods on forest vegetation structure and fuels. Ecol. Appl. 19, 285–304.

Scott, J.H., Burgan, R.E., 2005. Standard Fire Behavior Fuel Models: A Comprehensive Set for Use with Rothermel's Surface Fire Spread Model. USDA Forest Service, Gen. Tech. Rep. RMRS-153, Fort Collins, Colorado.

Setterfield, S.A., Rossiter-Rachor, N.A., Hutley, L.B., Douglas, M.M., Williams, R.J., 2010. Turning up the heat: the impacts of *Andropogon gayanus* (gamba grass) invasion on fire behaviour in northern Australian savannas. Divers. Distrib. 16, 854–861.

Shepherd, B.J., Miller, D.L., Thetford, M., 2012. Fire season effects on flowering characteristics and germination of longleaf pine (*Pinus palustris*) savanna grasses. Restor. Ecol. 20, 268–276.

Sparks, J.C., Masters, R.E., Engle, D.M., Palmer, M.W., Bukenhofer, G.A., 1998. Effects of late growing-season and late dormant-season prescribed fire on herbaceous vegetation in restored pine-grassland communities. J. Veg. Sci. 9, 133–142.

Sparks, J.C., Masters, R.E., Engle, D.M., Bukenhofer, G.A., 2002. Season-of-burn influences fire behavior and fuel consumption in restored shortleaf pine-grassland communities. Restor. Ecol. 10, 714–722.

Stambaugh, M.C., Guyette, R.P., Marschall, J.M., 2011. Longleaf pine (*Pinus palustris* Mill.) fire scars reveal new details of a frequent fire regime. J. Veg. Sci. 22, 1094–1104.

Stanturf, J.A., Wade, D.D., Waldrop, T.A., Kennard, D.K., Achtemeier, G.L., 2002. Background paper: fire in southern forest landscapes. In: Wear, D.N., Greis, J.G. (Eds.), Southern Forest Resource Assessment. USDA Forest Service, Gen. Tech. Rep. SRS-53, Asheville, North Carolina, pp. 607–630.

Stephens, S.L., Ruth, L.W., 2005. Federal forest-fire policy in the United States. Ecol. Appl. 15, 532–542.

Stephens, S.L., McIver, J.D., Boerner, R.E.J., Fettig, C.J., Fontaine, J.B., Hartsough, B.R., Kennedy, P.L., Schwilk, D.W., 2012. The effects of forest fuel-reduction treatments in the United States. Bioscience 62, 549–560.

Stephenson, S.N., Buell, M.F., 1965. The reproducibility of shrub cover sampling. Ecology 46, 379–380.

Tukey, J.W., 1973. The Problem of Multiple Comparisons. Princeton University Press, Princeton, New Jersey.

Van Balen, J.B., Doerr, P.D., 1978. The relationship of understory vegetation to red-cockaded woodpecker activity. In: Dimmick, R.W., Hair, J.D., Grover, J. (Eds.), Proceedings of the 32nd Annual Conference of the Southeastern Association of Fish and Wildlife Agencies. Hot Springs, Virginia, pp. 82–92.

Wahlenburg, W.G., 1946. Longleaf Pine: Its Use, Ecology, Regeneration, Protection, Growth, and Management, first ed. Charles Lathrop Pack Forestry Foundation, Washington, DC.

Waldrop, T.A., Van Lear, D.H., Lloyd, F.T., Harms, W.R., 1987. Long-term Studies of Prescribed Burning in Loblolly Pine Forests of the Southeastern Coastal Plain. USDA Forest Service, Gen. Tech. Rep. SE-45, Asheville, North Carolina.

Wally, A.L., Menges, E.S., Weekley, C.W., 2006. Comparison of three devices for estimating fire temperatures in ecological studies. Appl. Veg. Sci. 9, 97–108.

Willcox, E.V., Giuliano, W.M., 2010. Seasonal effects of prescribed burning and roller chopping on saw palmetto in flatwoods. For. Ecol. Manage. 259, 1580–1585.

Wotton, B.M., Gould, J.S., McCaw, W.L., Cheney, N.P., Taylor, S.W., 2012. Flame temperature and residence time of fires in dry eucalypt forest. Int. J. Wildland Fire 21, 270–281.

Wright, C.S., 2013. Fuel consumption models for pine flatwoods fuel types in the southeastern United States. South. J. Appl. For. 37, 148–159.

Yospin, G.I., Bridgham, S.D., Kertis, J., Johnson, B.R., 2012. Ecological correlates of fuel dynamics and potential fire behavior in former upland prairie and oak savanna. For. Ecol. Manage. 266, 54–65.

Youngblood, A., Wright, C.S., Ottmar, R.D., McIver, J.D., 2008. Changes in fuelbed characteristics and resulting fire potentials after fuel reduction treatments in dry forests of the Blue Mountains, northeastern Oregon. For. Ecol. Manage. 255, 3151–3169.