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How do fire behavior and fuel consumption vary between dormant and early growing season prescribed burns in the southern Appalachian Mountains?

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Abstract

Background: Despite the widespread use of prescribed fire throughout much of the southeastern USA, temporal considerations of fire behavior and its effects often remain unclear. Opportunities to burn within prescriptive meteorological windows vary seasonally and along biogeographical gradients, particularly in mountainous terrain where topography can alter fire behavior. Managers often seek to expand the number of burn days available to accomplish their management objectives, such as hazardous fuel reduction, control of less desired vegetation, and wildlife habitat establishment and maintenance. For this study, we compared prescribed burns conducted in the dormant and early growing seasons in the southern Appalachian Mountains to evaluate how burn outcomes may be affected by environmental factors related to season of burn. The early growing season was defined as the narrow phenological window between bud break and full leaf-out. Proportion of plot area burned, surface fuel consumption, and time-integrated thermocouple heating were quantified and evaluated to determine potential relationships with fuel moisture and topographic and meteorological variables.

Results: Our results suggested that both time-integrated thermocouple heating and its variability were greater in early growing season burns than in dormant season burns. These differences were noted even though fuel consumption did not vary by season of burn. The variability of litter consumption and woody fuelbed height reduction were greater in dormant season burns than in early growing season burns. Warmer air temperatures and lower fuel moisture, interacting with topography, likely contributed to these seasonal differences and resulted in more burn coverage in early growing season burns than in dormant season burns.

Conclusions: Dormant season and early growing season burns in southern Appalachian forests consumed similar amounts of fuel where fire spread. Notwithstanding, warmer conditions in early growing season burns are likely to result in fire spread to parts of the landscape left unburnt in dormant season burns. We conclude that early growing season burns may offer a viable option for furthering the pace and scale of prescribed fire to achieve management objectives.

Keywords: Fire weather, Fuel moisture, Time-integrated heating, Litter, Duff, Woody fuels, Topography

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Resumen

Antecedentes: A pesar del uso generalizado de las quemas prescriptas a través de muchas zonas del sureste de los EEUU, las consideraciones temporales sobre el comportamiento del fuego y sus efectos todavía permanecen poco claras. La oportunidad de quemar dentro de ventanas de prescripción meteorológica varía estacionalmente y a lo largo de gradientes biogeográficos, particularmente en terrenos montañosos donde la topografía puede alterar el comportamiento del fuego. Los gestores frecuentemente buscan expandir el número de días disponibles para quemar para cumplir con sus objetivos de manejo, como la reducción de combustibles peligrosos, el control de la vegetación no deseada, y el establecimiento y mantenimiento del hábitat para la fauna. Para este estudio, comparamos las quemas prescriptas conducidas en la estación de dormición y en la de crecimiento temprano en las Montañas Apalaches del sur para evaluar como los resultados de las quemas pueden ser afectados por la estación de quema. La estación de crecimiento temprano fue definida como la angosta ventana fenológica entre el rompimiento del crecimiento de los meristemas de crecimiento y la aparición de las hojas. La proporción de la parcela quemada, el consumo de combustible superficial, y la integral entre el tiempo y el calor recibido medido con termocuplas fueron cuantificados y evaluados para determinar relaciones potenciales con la humedad el combustible y variables topográficas y meteorológicas.

Resultados: Nuestros resultados sugieren que tanto la integral entre tiempo y el calor recibido por la termocupla y su variabilidad fueron mayores en las quemas al inicio de la temporada de crecimiento que en las quemas en estado de dormición. Esas diferencias fueron notables aún cuando el combustible consumido no varió entre estaciones de quemas. La variabilidad en el consumo de broza y la reducción de la carga superficial de combustible de leñosas fueron mayores en la estación de dormición que en las quemas al inicio de la estación de crecimiento. Las temperaturas del aire más cálidas y la menor humedad del combustible, interactuando con la topografía, probablemente contribuyeron a esas diferencias estacionales y resultaron en mayores coberturas de quema in las quemas realizadas en la estación de crecimiento que en la estación de dormición.

Conclusiones: Las quemas prescriptas realizadas tanto durante la dormición como al inicio de la estación de crecimiento en las montañas Apalaches del Sur consumieron similares cantidades de combustible con el avance del fuego. A pesar de ello, las condiciones más cálidas en la estación de crecimiento temprano parecen resultar en la propagación del fuego a partes del paisaje que quedaban sin quemar en quemas realizadas durante la dormición. Concluimos que las quemas prescriptas al inicio de la estación de crecimiento pueden ofrecer una opción viable para avanzar en ritmos y escalas de quemas prescriptas para alcanzar objetivos de manejo.

Palabras clave: Meteorología de fuegos, Humedad del Combustible, Integral tiempo-temperatura, broza, mantillo, combustibles leñosos, topografía

Background

Fire is firmly embedded in the natural history and human experience of the American Southeast. Evidence suggests that fire has been prevalent in the Southeast for millennia, from the written accounts of explorers who described pervasive smoke and open woodlands (Fowler and Konopik 2007), to reconstructions of past fire occurrence using physical measurements synthesized by researchers (Delcourt and Delcourt 1998; Lafon et al. 2017). Humans before and after Euro-American settlement in the 1700s and 1800s used fire to cultivate habitat for their livelihood (Owsley 1949; Stewart 2002; Abrams and Nowacki 2008), fostering a culture of burning that may inform our present treatment of fire. Recognizing that decades of fire suppression in the 1900s often led to hazardous fuel accumulation and forest “mesophication” (Nowacki and Abrams 2008), policymakers and land managers have increasingly endorsed and implemented prescribed fire in recent decades to reduce wildfire risk and promote ecosystem health and resiliency (Pyne 1982; Rothman 2007; Waldrop and Goodrick 2012). Today, more area is treated with prescribed fire on an annual basis in the Southeast than in any other region of North America (Wade et al. 2000; Kobziar et al. 2015; Melvin 2018).

Wildland fire is thought to have occurred more often in different seasons prior to fire suppression than it does today, particularly in the Southeast’s most fire-prone environments (Komarek 1965, 1974; Lafon 2010). Habitats favorable to forage and harvest could have been maintained by humans burning in a variety of seasons (Eldredge 1911; Jurgelski 2008). Historically, lightning ignitions may have occurred in drier fuels under more open canopies, a potential source of fire following spring and summer thunderstorms (Barden and Woods 1974; Cohen et al. 2007). Lightning-ignited fires in the southern Appalachians were unlikely to have been common, however, and wet weather would typically constrain their spread (Lafon et al. 2017). Wildland fire extent in largely deciduous forests of the southern Appalachians today is inversely related to vegetation greenness (Haines et al. 1975; Norman et al. 2019), with most area burned either in late winter (dormant season) and spring before complete leaf expansion (early growing season) or in the fall following leaf abscission (Schroeder and Buck 1970). Fire seasonality is further confounded in mountainous topography with less predictable fire behavior due to more heterogeneous temperature and moisture conditions across the landscape (Stambaugh and Guyette 2008; Lesser and Fridley 2016).

The use of prescribed fire has expanded substantially in the southern Appalachians in recent decades amid widespread efforts to reduce hazardous fuel loads, restore woodland and savannah communities, and increase native oak (*Quercus* L.) and yellow pine (*Pinus* L.) regeneration (Van Lear and Waldrop 1989; Waldrop and Brose 1999; Brose et al. 2001). Using fire for these objectives has largely occurred in the dormant season before substantial spring green-up, mirroring prescriptive patterns of fire use in the Southeast more broadly (Van Lear and Waldrop 1989; Wade and Lunsford 1989). Burning in the dormant season as opposed to the growing season may decrease the risk of fire escape, particularly in mid-late winter with lower ambient temperatures and more predictable wind patterns (Mobley and Balmer 1981; Wade and Lunsford 1989; Robbins and Myers 1992). Spring burning has also been less favored due to potential detrimental effects on wildlife species that may be more vulnerable to fire during that stage of their life history (Landers 1981; Cox and Widener 2008). In light of the prevalence of dormant season burning, potential growing season fire behavior and effects are not well understood (Knapp et al. 2009; Reilly et al. 2012). However, there is likely a window in the early growing season when dry forest floor conditions permit the combustion of fuels and spread of fire – perhaps to a greater extent than would occur under typical dormant season burning conditions. For managers in the southern Appalachians who want to expand their prescribed fire programs, growing season burning could offer an alternative to dormant season burning, allowing for increased opportunities to burn. Evidence of historical fire regimes suggests fire occurrence outside of the dormant season (Lafon et al. 2017; Stambaugh et al. 2018). It remains to be seen, however, how growing season burns compare to dormant season burns for accomplishing management objectives of reducing fuel loads and restoring habitats.

Improved knowledge of how and why fire behavior and first-order fire effects vary seasonally may improve southern Appalachian forest management. Variability in meteorological and topographic factors influencing fire behavior may suggest the extent to which prescribed fire would be effective in achieving fuel load reduction, a first-order fire effect (Reinhardt and Keane 2009; Kreye et al. 2020). Solar radiation drives the magnitude and extent of surface fuel drying and thereby influences fire behavior relative to latitude, slope, and aspect (Byram and Jemison 1943). Slope position further influences the level and duration of heating from fire along moisture gradients from sheltered coves to prominent peaks across a mountainous landscape (Reilly et al. 2012; Dickinson et al. 2016). The effects of topography on fire behavior and resulting fuel consumption may also be reinforced or overridden by changing weather patterns over phenological transitions (Norman et al. 2017). Upon longer and warmer spring days, aboveground perennial emergence and heightened plant transpiration may lead to greater variability in the distribution of live fuel moisture (Jolly and Johnson 2018). In autumn, surface winds under an open canopy following leaf fall may compound moisture loss on upper slopes and ridges, creating a fuel bed more conducive to high rates of fire spread (Dickinson et al. 2016; Kreye et al. 2020). Fuel moisture alters flammability and may suggest fine-scale differences in fire effects (Sparks et al. 2002; Slocum et al. 2003; Kreye et al. 2018).

Research questions

For this study, we compared seven prescribed burns conducted in the dormant and early growing seasons in the southern Appalachians to evaluate season of burn effects on fire behavior and fuel consumption. In situ, representative ex situ, and digital elevation model (DEM)-derived data were used to address the following questions:

1. How do meteorological conditions influencing surface fuel moisture and proportion of plot area burned vary by season of burn?
2. How do time-integrated thermocouple heating, surface fuel consumption, and the relationship between these variables differ by season of burn?
3. How are slope position and solar heat load related to fire behavior in dormant and early growing season burns?

For Question #1, we hypothesized that diurnal solar radiation and average ambient temperatures would be higher in the early growing season, resulting in lower surface fuel moisture and a greater proportion of treatment area burned than in the dormant season. For Question #2, we hypothesized that the degree and variability of time-integrated heating would be greater in early growing season burns than in dormant season burns. We also hypothesized that the degree and variability of litter and fine woody fuel consumption would be greater in early growing season burns, driven by variations in fuel moisture. Furthermore, we expected that litter and duff consumption would rise at a greater rate with increasing time-integrated heating (have a steeper slope between these variables) in dormant season burns than in early growing season burns. For Question #3, we hypothesized that bole char height would rise at a greater rate with both increasing slope position and increasing solar heat load (have steeper slopes between these pairs of variables) in dormant season burns than in early growing season burns. Furthermore, we expected that bole char height would be more strongly correlated with both slope position and solar heat load in dormant season burns than in early growing season burns.

Methods

Study area

This study was conducted along the southern Blue Ridge Escarpment of the Appalachian Mountains in the southeastern USA. Treatment replicates were located in both the Chattooga River (CR) Ranger District of the Chattahoochee National Forest in Rabun and Stephens Counties, Georgia, as well as the Andrew Pickens (AP) Ranger District of the Sumter National Forest, in Oconee County, South Carolina (Fig. 1). Unit elevations ranged from 222 to 1430 m, encompassing a variety of landforms from lower slopes in sheltered coves to exposed ridges and upper slopes of high peaks. Mean monthly temperatures ranged from 4 °C in January to 24 °C in July, with mean annual precipitation of 159 cm distributed relatively evenly throughout the year (NCEI 2020). Ultisols, Inceptisols, and Entisols were common soil orders found within the study area, mostly underlain by metamorphic bedrock (e.g. granitic gneiss and schist) (Griffith et al. 2001, 2002).

Pre-treatment fuel characteristics were quantified prior to treatment (Table 1; see the "Fuel loads and depths" section below). Forest cover consisted primarily of oaks

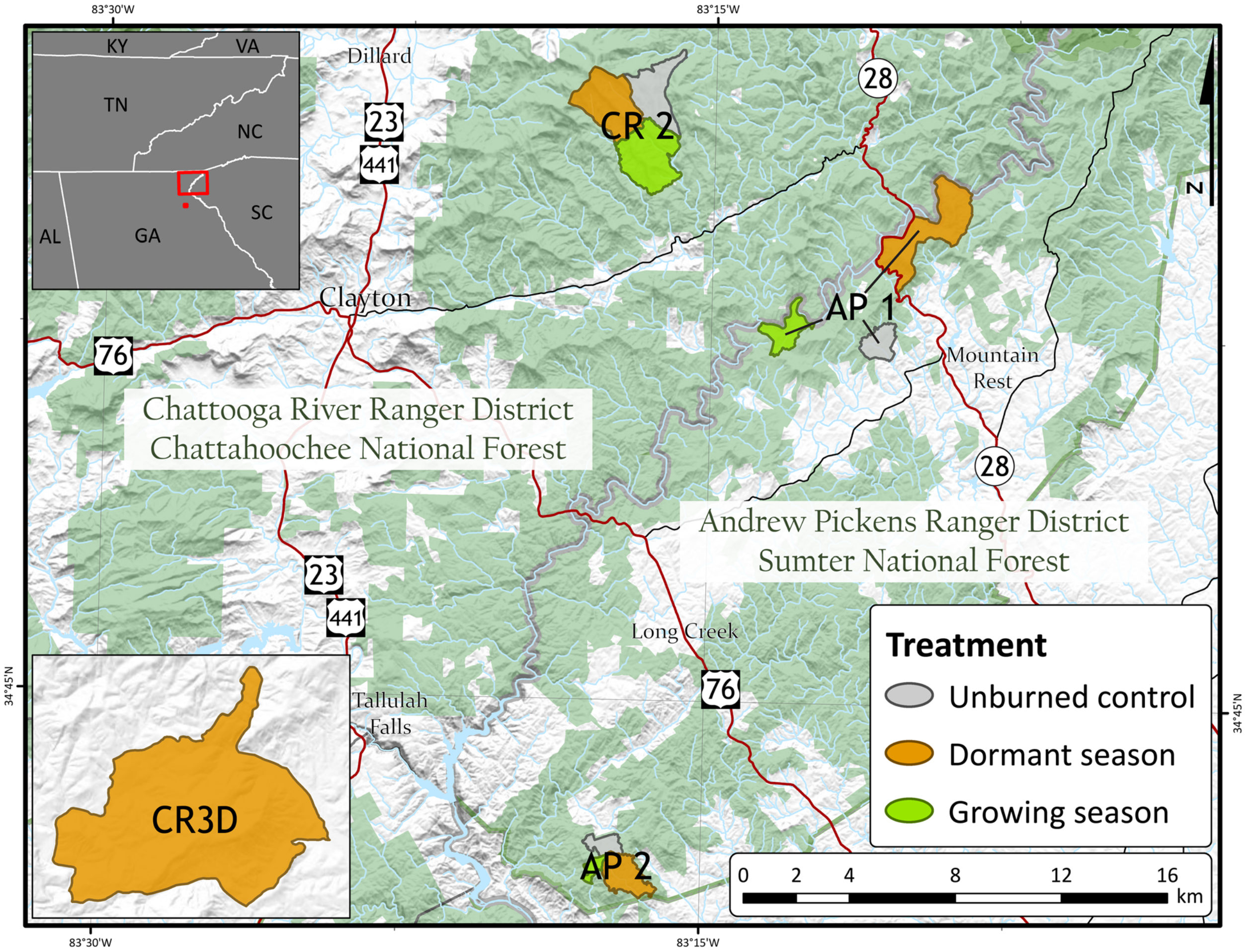

Fig. 1 Map depicting the replicates comprised of treatment units with plots established in this study. "AP" refers to replicates in the Andrew Pickens Ranger District whereas "CR" refers to replicates in the Chattooga River Ranger District. See Table 2 for further information on treatment units

Table 1 Summary of pre-treatment fuel characteristics between designated treatments across all study plots

Woody fuel characteristic (Brown 1974)	Designated treatment	Mean (± SE)	Overall mean (± SE)
Litter load [kg ha^{-1}]	C	6707.2 (± 330.2)	6684.4 (± 179.7)
	DS	6876.7 (± 292.2)	
	GS	6453.1 (± 315.4)	
Woody fuelbed height [cm]	C	13.0 (± 1.2)	14.1 (± 0.7)
	DS	14.7 (± 1.3)	
	GS	14.6 (± 1.1)	
1-h woody load [kg ha^{-1}]	C	551.1 (± 26.8)	604.4 (± 19.8)
	DS	619.1 (± 32.1)	
	GS	642.0 (± 41.8)	
10-h woody load [kg ha^{-1}]	C	1662.0 (± 127.2)	1881.7 (± 90.9)
	DS	2191.3 (± 174.2)	
	GS	1765.9 (± 157.7)	
100-h woody load [kg ha^{-1}]	C	3493.8 (± 390.0)	4941.0 (± 421.0)
	DS	6355.4 (± 1,014.9)	
	GS	4856.0 (± 519.4)	
1000-h woody load [kg ha^{-1}]	C	6356.4 (± 1,189.2)	5457.6 (± 540.6)
	DS	5480.3 (± 887.6)	
	GS	4534.0 (± 665.0)	

(*Quercus* L.), hickories (*Carya* L.), and pines (*Pinus* L.) across the following ecozones (Simon et al. 2005; Simon 2015): Dry-Mesic Oak-Hickory Forest, Shortleaf Pine-Oak Forest and Woodland, Mixed Oak/Rhododendron Forest, and Montane Oak-Hickory Forest. Substantial midstory encroachment was present from mesophytic hardwoods [e.g., red maple (*Acer rubrum* L.)], mountain laurel (*Kalmia latifolia* L.), and great rhododendron (*Rhododendron maximum* L.).

Study design

The study was established as a randomized complete block design, with treatments of dormant season burn (d), growing season burn (g), and an unburned control (c) replicated (blocked) three times. A fourth, standalone, dormant season burn in a planned, additional replicate was also included to equal a total of 10 treatment units. Treatment units ranged in area from 43 to 567 ha, with a mean area of 293 ha (Table 2). Twenty plots were stratified across a variety of slope, aspect, and landscape positions within each treatment unit (except for 5 plots in the standalone unit). This yielded 180 plots with usable data that were included in analyses, with 5 plots in burn treatment units lost due to construction of control lines which contained different areas than had been anticipated. Each plot was 30 m × 30 m (900 m^2),

Table 2 Listing of treatment units used in this study by replicate and corresponding treatment, with area, date of burn (if applicable), and elevation range. Firing methods included both hand ignition and remote aerial ignition, with a spot fire technique used for hand ignitions when possible to simulate aerial ignition

Replicate	Treatment	Unit	Area (ha)	Date of burn	Elevation range (m)
AP 1	Unburned control (C)	AP1C	133.8	n/a	498–625
	Dormant season burn (DS)	AP1D	538.1	01/31/18	480–772
	Growing season burn (GS)	AP1G	160.5	04/18/18	454–560
AP 2	Unburned control (C)	AP2C	80.8	n/a	360–470
	Dormant season burn (DS)	AP2D	205.3	03/18/19	275–468
	Growing season burn (GS)	AP2G	43.3	04/21/18	312–462
CR 2	Unburned control (C)	CR2C	323.2	n/a	704–1157
	Dormant season burn (DS)	CR2D	441.5	04/05/18	724–1430
	Growing season burn (GS)	CR2G	435.3	04/24/19	622–963
CR 3	Dormant season burn (DS)	CR3D	566.5	03/03/18	222–386

subdivided into nine 10 m × 10 m (100 m^2) subplots delineated by 16 grid point intersections and oriented with outer boundaries running magnetic north (0°) and east (90°) from its point of origin (Fig. 2). Surface fuel transects (15.24 m in length) were superimposed on each plot, separated by 20° magnetic azimuth emanating from the plot origin.

Prescribed burns were implemented by US Forest Service fire practitioners as a part of official burn plans and coordinated with Clemson University for purposes of this study. Dormant season burns were defined as those occurring after autumn leaf-fall and before spring green-up (typically before last frost), whereas growing season burns were considered as those occurring in the early spring green-up period (typically after last frost) before complete overstory leaf-out. At the elevations of the study area, green-up typically begins in early April, with full leaf-out occurring by May. Burn treatments occurred between January 31–April 5 (dormant season) and April 18–24 (growing season) in 2018 and 2019 (Table 2). Firing methods included hand ignition using drip torches as well as remote aerial ignition using delayed aerial ignition devices launched from a helicopter on some burns. A spot fire technique was used for hand ignitions when possible in order to simulate aerial ignitions.

Field sampling and data preparation

Fuels were measured before and after each burn to determine changes in surface fuel load across all plots. Complementary measurements of litter and duff consumption were taken at a greater sampling density in a subset of plots (see “Fuel loads and depths” section below). Fuel moisture was sampled the morning of burns and levels of heating were recorded throughout each burn day in situ in the same subset of “fire behavior plots.” Measurements of bole char height were taken in all plots following each burn. Visual evidence of the presence or absence of fire (y/n) was noted at grid point intersections, with a 50% threshold of grid points indicating the presence of fire used to qualify burn treatments for plot-level variables. The proportion of plot area burned was calculated by dividing the number of grid points with evidence of charred material by the total number of grid point intersections within a plot.

Fuel loads and depths

Fuel measurements of woody fuelbed height and fine woody debris counts (1-h, 10-h, and 100-h) were taken in the growing season pre- and post-burn using a modified version of Brown’s Planar Intercept Method (Brown 1974; Stottlemyer 2004; Coates et al. 2019). This method was utilized in all plots within the treatment units (3

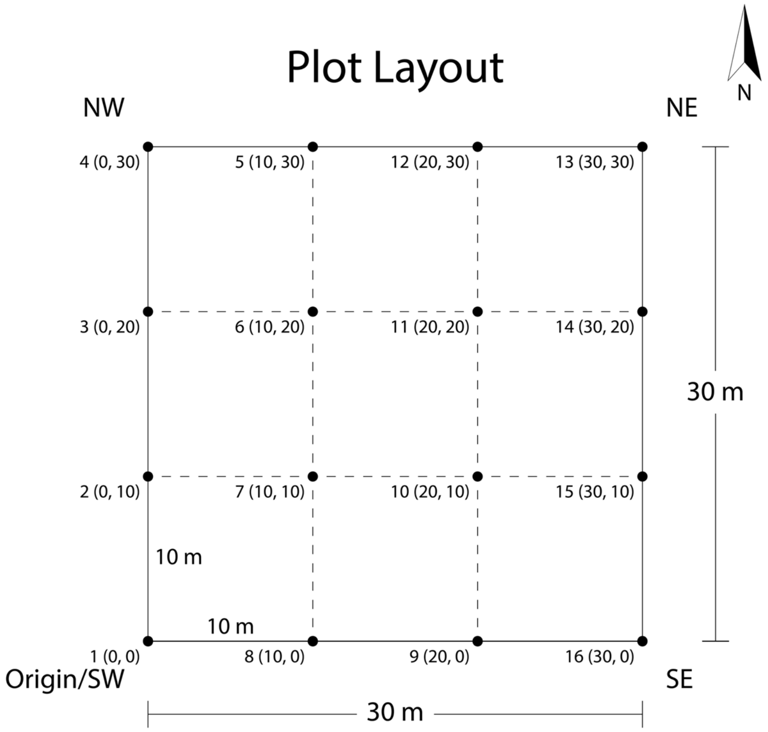

Fig. 2 Representative diagram indicating the layout, orientation, and dimensions of each plot with interior grid point intersections. The (*x*, *y*) Cartesian coordinate pairs for each grid point represent the longitudinal (*x*) and latitudinal (*y*) distance from the origin

transects per plot; n = 60 measurement units per treatment unit), which included measurements taken at designated intervals along transects emanating from the plot origin (3.66 m, 7.62 m, and 12.19 m). Slope values were derived from a digital elevation model along lines representing the length and orientation of each transect in a geographic information system (Esri 2019). Measurements of litter and duff consumption were taken at grid point intersections within a subset of 5 fire behavior plots per burn treatment (16 litter and 16 duff nails per plot; n = 80 measurement units for each fuel class per treatment unit) using depth reduction measurements on 30 cm nails. Nails for this purpose were driven into the ground prior to ignition so that the heads were at the same pre-burn height as the fuel class being measured. Post-burn fuel height was marked on the nail within 24 h after burn completion to determine changes in litter and duff depth. All fuel depth and height measurements were recorded to the nearest 0.64 cm.

Raw fuel measurements were used to estimate fuel weight per area (load) for each fuel class, calculated by plot (Brown's protocol) or grid point (nail method). Fuel consumption was used as the metric of response. The average change in fuel height or load for each fuel class in unburned control units was subtracted from the change in fuel height or load in corresponding burn treatments in the same replicate to account for fuel changes in the absence of fire. Bulk density, quadratic mean diameter, specific gravity, and non-horizontal correction coefficients were chosen from representative values for the region and forest type (Ottmar and Andreu 2007; B. Buchanan, United States Forest Service, Roanoke, VA, USA, unpublished report). The degree and variability of surface fuel consumption as quantified by changes in woody fuelbed height (cm); 1-h, 10-h, and 100-h woody fuel load (kg ha^{-1}); and litter and duff load (kg ha^{-1}) were compared between dormant and growing season burn treatments.

Fuel moisture

Fuel moisture was measured in situ for litter and 1-h woody (pooled) as well as 10-h woody fuels in the fire behavior plots on the day of burn prior to ignition. Grab samples for this purpose (approx. 20 g) were collected from each plot corner and center (origin/SW, NW, NE, SE, and center), with disturbance of the surface fuel bed minimized at sampling locations [(5) litter/1-h woody and (5) 10-h woody fuel samples per plot; n = 25 measurement units for each fuel class per treatment unit]. All samples were sealed in 946 mL bags and weighed in the lab upon unsealing (wet mass), dried to constant weight at 75 °C (48 h), and re-weighed after drying (dry mass). Fuel weight measurements for this purpose were recorded to the nearest 0.01 g. Relative moisture content for these fuels (%) was calculated using the formula $\frac{\text{wet mass} - \text{dry mass}}{\text{dry mass}} \times 100$ (Cannon and Parkinson 2019) and averaged by plot. Moisture content for coarser fuels and duff was not measured, as these materials are generally not consumed under typical prescribed fire conditions in the region.

Fire behavior

Temperature was recorded continuously in situ before, during, and after passage of flaming fronts on each burn day using thermocouple probes. Onset Computer Corporation (Bourne, MA, USA) HOBO Type K Thermocouple data loggers were programmed to log temperature at a 1-s interval throughout the burn day (recording period 9 h 1 min 58 s), which were then attached to Cole-Parmer Instrument Company Digi-Sense Type K thermocouple probes (Vernon Hills, IL, USA), packaged, and buried in the ground approximately 15 cm deep prior to ignition. Probes protruded aboveground (sheath length = 30.48 cm) and were oriented such that the tip (sheath diameter = 0.1016 cm) faced downward at a uniform height of 2.54-5.08 cm above the litter surface (Fig. 3). Thermocouples were positioned to record temperatures at each grid point intersection within the subset of 5 fire behavior plots per unit coincident with nail measurements of litter and duff consumption (16 probes per plot; n = 80 measurement units per treatment unit). Data logger and probe packages were retrieved within 48 h after deployment with temperature measurements subsequently downloaded from each device. Data from loggers showing abnormal temperature profiles uncharacteristic of passage of a flaming front (i.e., suggesting recording failure) were excluded from analyses.

Metrics of fire behavior were derived from thermocouple temperature profiles, calculated via different approaches and thresholds using an automated script in MATLAB R2020a Update 5 (MathWorks 2020). Following initial comparisons of these metrics, the time integral of absolute temperature above 60 °C (ABS60 approach) was chosen as the representative thermocouple heating metric relative to fire intensity for subsequent analysis. The time integral of temperature is the Riemann sum approximation of the product of time step and temperature, representing both the relative degree and residence time (i.e., "dose") of fire-induced heating experienced at a thermocouple probe tip. A threshold of 60 °C was chosen as the temperature at or above which thermocouple recordings would not only represent ambient heating, but a level of heating reached as a result of contact with the flaming front (Dickinson and Johnson 2004; Bova and Dickinson 2008). Temperature thresholds were also distinguished by their relative

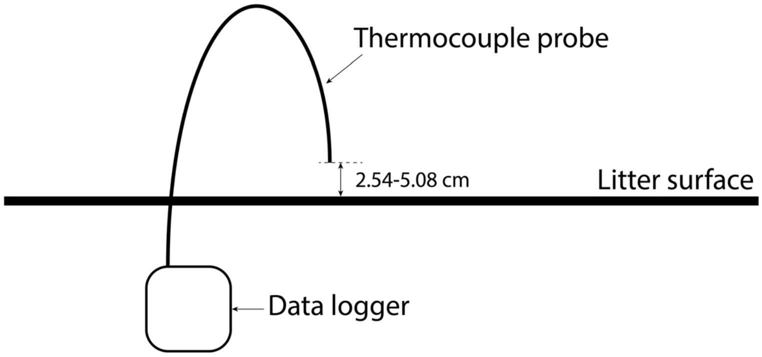

Fig. 3 Diagram of thermocouple setup deployed at each plot grid point intersection. Data loggers were buried belowground in order to be shielded from fire temperatures aboveground. Probes attached to and extending from the data loggers were arranged with the tip at a uniform height and orientation above the litter surface

sensitivity in predicting surface fuel consumption during and after passage of a flaming front. The degree and variability of time-integrated thermocouple heating (ABS60 approach: ∫ABS60; °C s) as well as the relationship between pooled litter and duff consumption (nail method; kg ha^{-1}) vs. ∫ABS60 at plot grid point intersections (aggregated as plot averages) were compared between dormant and growing season burn treatments.

Bole char height, an estimate of flame length related to thermocouple temperatures, was measured on hardwood tree species (e.g., *Quercus* spp., *Acer* spp., *Liriodendron tulipifera*) at all plot grid point intersections within burn units (Pomp et al. 2008). Measurements of bole char height were taken on the nearest charred bole (2.54 cm precision) within 3.05 m of each grid point (16 points per plot; n = 320 measurement units per treatment unit). Plot averages were obtained from these measurements. Bole char heights likely underestimated true flame length (Cain 1984) and were not measured on yellow pines [e.g., pitch pine (*Pinus rigida* Mill.) or shortleaf pine (*Pinus echinata* Mill.)] due to the increased likelihood of fire spread on the bark of these trees irrespective of surface flame heights.

Meteorological variables

Meteorological conditions represented by solar radiation, wind velocity, air temperature, fuel temperature, and relative humidity (RH) were gathered ex situ from the nearest Remote Automatic Weather Station (RAWS) at similar elevation to each treatment unit (MesoWest 2019). Weather information for each burn day was derived from the Andrew Pickens (Station ID: WLHS1), Tallulah (Station ID: TULG1), and Chattooga (Station ID: CHGG1) stations in northwestern South Carolina and northeastern Georgia. These weather stations were located within 21 km of corresponding burn locations. Solar radiation was summed and remaining variables were averaged between 08:00 and 19:59 local time, adjusted relative to daylight savings time clock forward dates on March 11, 2018, and March 10, 2019 (12 measurements of each variable at 1-h increments on the hour). Additionally, the reported Keetch-Byram Drought Index (KBDI) was gathered for each corresponding burn day, accessed through the Weather Information Management System (WIMS) (WIMS 2019). The degree and variability of both meteorological conditions (RAWS/WIMS) and fuel moisture (grab samples) on burn days were quantified for total solar radiation (KW-h/m^2), air temperature (°C), fuel temperature (°C), wind speed (m/s), RH (%), KBDI, pooled litter and 1-hr woody fuel moisture (%), and 10-h woody fuel moisture (%) to compare between dormant and growing season burn treatments.

Topographic variables

Topographic variables were derived from a digital elevation model (DEM) in a geographic information system (GIS) to evaluate topographic effects on fire behavior. A DEM covering the study area was downloaded as part of the National Elevation Dataset from the U.S. Geological Survey's The National Map Viewer at a spatial resolution of 1/9 arc-second and transformed to a Universal Transverse Mercator (UTM) Zone 17 projected coordinate system (3.18 m cell size) (Esri 2019). The DEM had pits removed using TauDEM and was clipped to the necessary extent for analysis in ArcGIS Desktop 10.7.1 (Tarboton 2015; Esri 2019). Each index variable was normalized to a scale of 0-1 using the Raster Calculator tool and extracted using the Extract Multi Values to Points tool (Esri 2019).

Topographic Position Index (TPI) was used to quantify slope position, based on the relative difference between a given point's elevation and the average elevation of its surrounding terrain within a defined window (Guisan et al. 1999; De Reu et al. 2013). Lower values represented more sheltered parts of the landscape whereas higher values represented greater exposure. A rectangular window of 1000 m × 1000 m was chosen to define the focal area, with its average elevation subtracted from each cell in the DEM using the ArcGIS Geomorphometry and Gradient Metrics Toolbox to derive TPI (Evans et al. 2014a, b; A. Evans, Texas A&M University, College Station, TX, USA, personal communication; Esri 2019). Heat Load Index (HLI) was used to quantify solar radiation as a function of aspect, further incorporating the effects of slope and latitude to linearize compass azimuth such that it ranges from the lowest values on northeast-facing slopes to the highest values on southwest-facing slopes (Beers et al. 1966; McCune and Keon 2002). HLI was derived from the DEM using the ArcGIS Geomorphometry and Gradient Metrics Toolbox (Evans et al. 2014b; Esri 2019). TPI and HLI were averaged by plot area and related to bole char height (m) as topographic predictors of fire behavior, compared between dormant and growing season burns by individual burns and treatment means.

Statistical analyses

A statistical model was developed that related the means of the continuous dependent variables to the treatments. Model effects included treatment (fixed), replicate (random), replicate crossed with treatment (random), and/or plot nested within treatment and replicate (random). Analysis of variance (ANOVA) techniques were used to evaluate the model terms and specifically test for treatment effects. For some variables, the model residuals did not follow a normal distribution with stable variance across treatments, and therefore either a Kruskal-Wallis rank-based ANOVA (Boos and Brownie 1992) or a generalized linear model with an exponential distribution was used to test the treatment effect on responses.

A statistical model was also developed that related response variability to the treatments. Response variability was quantified as the coefficient of variation (CV). Model effects for this model included treatment (fixed) and/or replicate (random). Either a Wilcoxon rank sum test (Mann-Whitney U test) or a generalized linear model with an exponential distribution was used to test the treatment effects on the response CVs.

Ordinary least squares regression modeling was used to estimate the slope and associated root mean square error (RMSE) between selected pairs of response variables within each treatment unit. A log transformation was used on heavily skewed distributions when estimating the bivariate relationships. The slopes were included in a statistical model to relate to the treatments including model effects of treatment (fixed), replicate (random), and replicate crossed with treatment (random). A one-way ANOVA was used to test for the treatment effect in this model. The RMSEs were related to treatments with a statistical model including treatment (fixed) and replicate (random) only, also with a one-way ANOVA used to test for the treatment effect.

Across all models of treatment effects, response variable observations were aggregated at different levels with the overall objective of producing independent observations to be used in the model analyses. Statistical significance was evaluated either at the α = 0.05 level (non-ranked values) or α = 0.10 level (ranked values). All analyses were performed using JMP Pro 15.1.0 and/or RStudio Desktop (up to v. 1.4.1717) within the R programming language and software environment (up to 4.1.0) (SAS 2019; R Core Team 2021; RStudio 2021).

Results

Meteorology, fuel moisture, and proportion of plot area burned

The early growing season was characterized by greater solar radiation, warmer air temperatures, and warmer fuels relative to the dormant season. While air temperatures were cooler in the dormant season, they were more variable. This, however, did not translate to greater variation in fuel temperatures in the dormant season. Other meteorological parameters (wind speed, relative humidity, KBDI) did not significantly differ between seasons. Woody fuel moisture, for both 1-h and 10-h lag classes, was greater in the dormant season – but variation in fuel moisture did not vary between seasons (Table 3). The proportion of plot area burned was significantly greater, and less variable, in early growing season burns than in dormant season burns (Fig. 4), with burned area correlating with fuel moisture (Fig. 5).

Time-integrated heating and fuel consumption

Time-integrated thermocouple heating (∫ABS60) was more than 5x greater in the early growing season than in the dormant season and was also more variable (Fig. 6). This pattern was largely driven by an increase in heating from fire midday and onward (Fig. 7).

Woody fuelbed height; and 1-h, 10-h, and 100-h woody fuel consumption as measured using Brown's Planar Intercept Method were not significantly different between burn treatments. Likewise, using the nail method, litter consumption was not significantly different between burn treatments. While mean differences were not statistically different between treatments, there was greater variability in the change in woody fuelbed height and litter consumption in dormant season burns. However, duff consumption (nails) was significantly greater in growing season burns, with no measurable duff consumption observed in dormant season burns (Table 4). Slope of the linear line of best fit between pooled litter and duff consumption and log-transformed ∫ABS60 did not differ significantly between burn treatments, nor was

Table 3 Summary of statistical comparisons of meteorological conditions from Remote Automatic Weather Stations (RAWS) or as reported in the Weather Information Management System (WIMS) and fuel moisture collected in the field (grab samples) on burn days by variable and burn treatment. Statistical analyses were performed using a non-parametric Kruskal-Wallis rank-based standard least squares ANOVA aggregated by plot (grab samples) or unit (RAWS/WIMS) with fixed effect of treatment and random effects of replicate and/or replicate crossed with treatment (response) or fixed effect of treatment and random effect of replicate (variability of response). Response variables include both the mean (± standard error) and coefficient of variation (CV; %). Tests with statistical significance (α = 0.10) are reported in boldface

Response variable (*α = 0.10)	**Burn treatment**	**Mean (± SE)**	**CV (%)**
Meteorological conditions (RAWS/WIMS)			
Total solar radiation [KW-h/m^2] Mean: $F_{1,\ 2.4} = 7.24$, $P =$ ***0.09**	DS	**5.4 (± 0.8)**	n/a
	GS	**6.7 (± 0.5)**	n/a
Air temperature [°C] Mean: $F_{1,\ 2.0} = 12.00$, $P =$ ***0.07** CV: $F_{1,\ 3.2} = 10.07$, $P =$ ***0.05**	DS	**10.6 (± 1.8)**	**48.4**
	GS	**21.7 (± 2.3)**	**21.3**
Fuel temperature [°C] Mean: $F_{1,\ 1.8} = 36.07$, $P =$ ***0.03** CV: $F_{1,\ 1.5} = 9.96$, $P = 0.12$	DS	**14.1 (± 2.8)**	59.9
	GS	**26.0 (± 2.2)**	32.2
Wind speed [m/s] Mean: $F_{1,\ 2.4} = 0.54$, $P = 0.53$ CV: $F_{1,\ 3.2} = 0.88$, $P = 0.41$	DS	1.5 (± 0.3)	50.6
	GS	1.6 (± 0.4)	34.1
Relative humidity (RH) [%] Mean: $F_{1,\ 3.2} = 0.38$, $P = 0.58$ CV: $F_{1,\ 2.6} = 0.07$, $P = 0.81$	DS	27.2 (± 1.4)	49.4
	GS	31.4 (± 3.1)	40.7
Keetch-Byram Drought Index (KBDI) Mean: $F_{1,\ 2.8} = 2.51$, $P = 0.22$	DS	23.8 (± 12.6)	n/a
	GS	61.7 (± 13.4)	n/a
Fuel moisture (grab samples)			
Litter and 1-h woody [%] Response: $F_{1,\ 2.0} = 71.08$, $P =$ ***0.01** Variability: $F_{1,\ 2.4} = 3.75$, $P = 0.17$	DS	**39.2 (± 6.3)**	36.0
	GS	**17.9 (± 2.7)**	27.1
10-h woody [%] Response: $F_{1,\ 2.6} = 9.79$, $P =$ ***0.06** Variability: $F_{1,\ 3.2} = 1.83$, $P = 0.26$	DS	**38.9 (± 8.0)**	39.6
	GS	**14.6 (± 1.0)**	20.9

there a difference in the root mean squared error (RSME) between treatments.

Topographic effects on fire behavior

Heat load index and bole char height were positively correlated. While the slope of this regression was steeper in dormant season burns compared to growing season burns (2.2 vs. 1.4), these differences were not statistically significant. Likewise, there were no statistically significant treatment effects for root mean squared errors or proportion of variance. A summary of bivariate comparisons of bole char height vs. topographic position and heat load indices by unit and treatment can be found in Fig. 8.

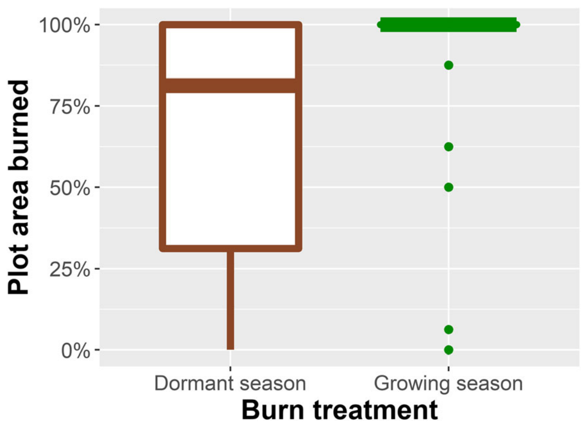

Fig. 4 Boxplot of proportion of plot area burned (*y*-axis; %) by burn treatment (*x*-axis). Proportions were calculated based on the number of grid points indicating evidence of fire presence per plot

Discussion

This study examined factors of the fire environment related to season of burn to gain a better understanding of how these parameters influence prescribed fire behavior and first-order effects. Relating fire behavior and fire effects to environmental mechanisms representative of burning season may promote meaningful interpretations

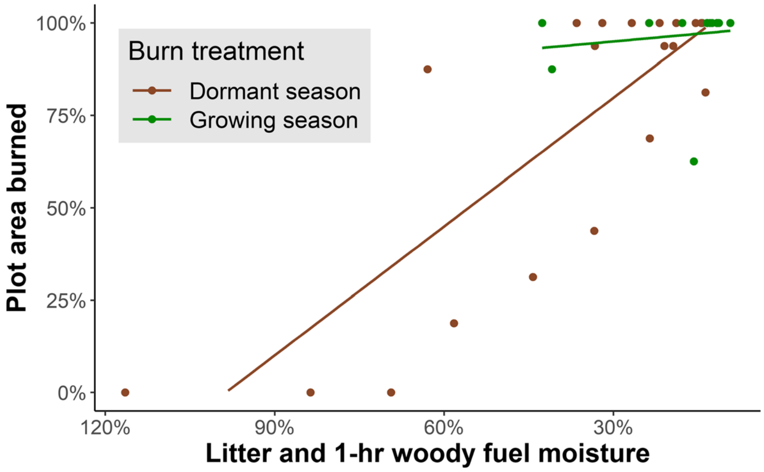

Fig. 5 Scatterplot with linear regression of proportion of plot area burned (*y*-axis; %) vs. pooled litter and 1-hr woody fuel moisture (*x*-axis, reversed; %) in subset of fire behavior plots by burn treatment (series). Proportions were calculated based on the number of grid points indicating evidence of fire presence per plot

of prescribed fire seasonality for both scientists and managers (O'Brien et al. 2018; Hiers et al. 2020).

Following the winter solstice in the Northern Hemisphere, ambient temperatures begin to increase as a result of increasing photoperiod from a more direct sun angle (Schroeder and Buck 1970). Reflecting this trend and supporting our hypothesis, diurnal solar radiation and mean ambient temperatures (both of air and fuel) were greater, and fuels were drier, in early growing season burns. Warmer, precipitation-free periods typically increase in frequency by late winter in the Southeast, with favorable atmospheric conditions for fire spread following passage of cold fronts (Robbins and Myers 1992; Chiodi et al. 2018). Other key prescription window parameters influencing fire behavior (wind speed, RH, and KBDI) did not vary by season of burn, however. Consistently low KBDI values reflect long-term trends in the southern Appalachians for the period of January-April in which burns were conducted for this study (Keetch and Byram 1968). These results suggest that seasonal variability of prescribed fire behavior in southern Appalachian forests before complete overstory leaf-out may be influenced by solar radiation and fuel moisture more so than other environmental conditions that remained similar between seasons.

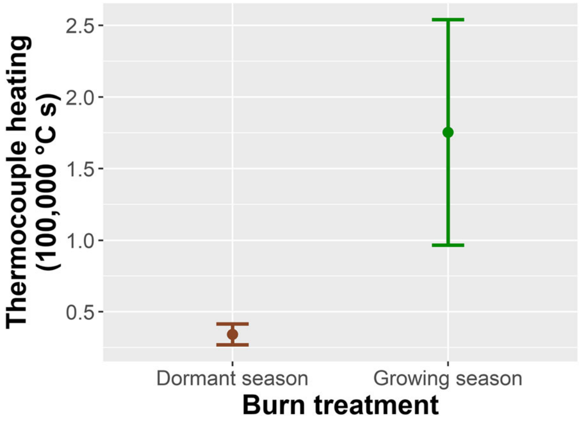

Fig. 6 Plot of means of the time integral of thermocouple probe temperature (ABS60 approach) with error bars representing associated standard error (*y*-axis; °C s) by burn treatment (*x*-axis)

Patterns of the proportion of plot area burned showed significant differences that may provide evidence for seasonal effects on fire spread. While the area and topographic heterogeneity of dormant season burn units (mean area = 363.5 ha) was greater than that of early growing season burn units (mean area = 190.6 ha), proportion of plot area burned was significantly greater in the growing season than in the dormant season. Observed patterns indicate that ignition probability is greater in the early growing season, but do not necessarily suggest that other fire behavior parameters will be more uniform when prescribed burns are implemented in this season. Variable fire behavior in the dormant season created a mosaic of burned and unburned areas, which may be a desirable outcome if habitat heterogeneity is an objective.

Temperatures recorded by thermocouple probes are related to fireline intensity and were used in this study as an index of heating (Kennard et al. 2005; Bova and Dickinson 2008). Both the degree and variability of time-integrated thermocouple heating were greater in early growing season burns than in dormant season burns. Similar to a nearby study with burns conducted at the same time of year, differences in ambient air temperature by season of burn likely influenced fire

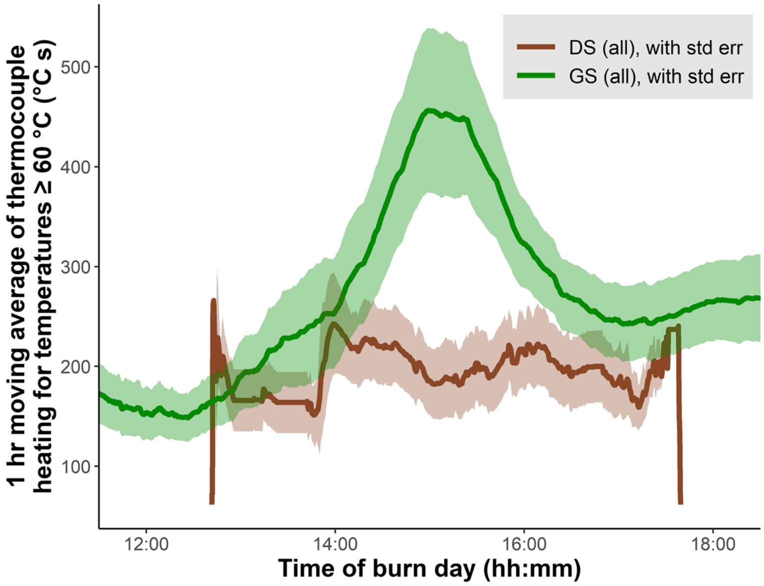

Fig. 7 Plot of 1 h, centered rolling mean (moving average) of the time integral of thermocouple probe temperature (ABS60 approach) (*y*-axis; °C s) vs. time of day (*x*-axis; hh:mm), by burn treatment from 11:30 am to 6:30 pm on burn days. Time of day was adjusted to account for daylight savings time clock forward dates in March 2018 and March 2019. Series include error bars (shaded area) representing associated standard error around the mean

Table 4 Summary of statistical comparisons of fuel consumption by sampling protocol, fuel class, and burn treatment. Statistical analyses were performed using a non-parametric Kruskal-Wallis rank-based standard least squares ANOVA aggregated by plot with fixed effect of treatment and random effects of replicate, replicate crossed with treatment, and plot nested within treatment and replicate (response) or fixed effect of treatment and random effect of replicate (variability of response). Response variables include both the mean (± standard error) and coefficient of variation (CV; %). Tests with statistical significance ($\alpha = 0.10$) are reported in boldface

Response variable ($*\alpha = 0.10$)	**Burn treatment**	**Mean (± SE)**	**CV (%)**
Woody fuel consumption (Brown 1974) [$\lvert\Delta\rvert$]			
Woody fuelbed height [cm] Mean: $F_{1,\ 2.2} = 0.30$, $P = 0.63$ CV: $F_{1,\ 2.0} = 23.88$, $P = *$**0.04**	DS	5.0 (± 2.4)	**629.2**
	GS	3.9 (± 3.5)	**256.9**
1-h woody [kg ha^{-1}] Mean: $F_{1,\ 2.1} = 0.34$, $P = 0.61$ CV: $F_{1,\ n/a} = 0.00$, P = n/a	DS	66.5 (± 231.3)	83.7
	GS	217.2 (± 133.1)	400.9
10-h woody [kg ha^{-1}] Mean: $F_{1,\ 3.1} = 0.03$, $P = 0.86$ CV: $F_{1,\ 3.2} = 4.19$, $P = 0.13$	DS	298.6 (± 870.1)	141.3
	GS	296.3 (± 323.0)	627.4
100-h woody [kg ha^{-1}] Mean: $F_{1,\ 2.7} = 0.41$, $P = 0.57$ CV: $F_{1,\ 2.8} = 0.29$, $P = 0.63$	DS	4160.0 (± 2,691.6)	128.0
	GS	2701.4 (± 1,075.9)	271.3
Litter and duff consumption (nail method) [$\lvert\Delta\rvert$]			
Litter [kg ha^{-1}] Mean: $F_{1,\ 3.1} = 3.34$, $P = 0.16$ CV: $F_{1,\ 2.5} = 27.17$, $P = *$**0.02**	DS	2664.6 (± 372.9)	**94.4**
	GS	4365.0 (± 394.0)	**41.1**
Duff [kg ha^{-1}] Mean: $F_{1,\ 2.0} = 11.34$, $P = *$**0.08** CV: $F_{0,\ 0.0}$ = n/a, P = n/a	DS	**0.0 (± 0.0)**	n/a
	GS	**135.6 (± 113.7)**	n/a

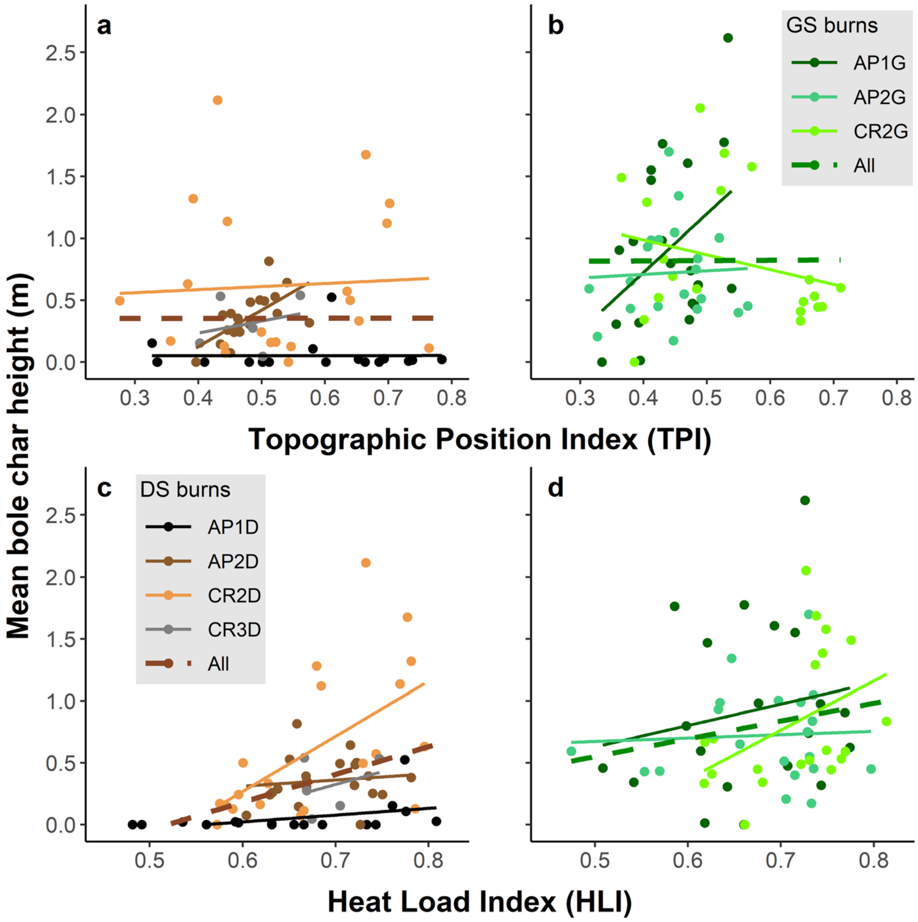

Fig. 8 Scatterplots with linear regressions of mean bole char height (*y*-axis; m) vs. landscape indices Topographic Position Index (TPI) and Heat Load Index (HLI) (*x*-axis) by burn treatment (columns) and index (rows) for all plots in each unit (series). Top row, left column shows mean bole char height vs. TPI for dormant season burns (**a**), top row, right column shows mean bole char height vs. TPI for growing season burns (**b**), bottom row, left column shows mean bole char height vs. HLI for dormant season burns (**c**), and bottom row, right column shows mean bole char height vs. HLI for growing season burns (**d**)

behavior (Keyser et al. 2019). Less additional heat would be required for combustion to occur with warmer air in the early growing season.

Temporal variation in the relative amount and duration of heating experienced throughout the burn day also differed by season of burn. Dormant season burns were more limited in their distribution of periods of high levels of thermocouple heating (≥ 60 °C s), with early growing season burns having such periods starting before and continuing after those of dormant season burns. These patterns suggest that surface temperatures in a prescribed fire respond more positively to the warmest and driest part of the day in the mid-late afternoon in the early growing season than those in dormant season burns. Even if recent precipitation saturates surface fuels to a similar degree as in the dormant season, greater solar radiation in the early growing season can dry forest fuels more rapidly, which may have implications for fire effects (Byram and Jemison 1943).

There was little indication based on the results of our study that surface fuel consumption in areas where fire spread varied by season of burn. Greater proportions of plot area were burned in the early growing season, but for plots with at least 50% of grid points indicating fire presence, fuel load reduction largely did not differ between burn treatments. Among fuel classes measured, only duff consumption was significantly greater in early growing season burns, which may reflect greater duff fuel availability from drier conditions at the fuelbed surface (Ferguson et al. 2002; Waldrop et al. 2010). A relationship between fuel moisture and consumption would not explain the lack of seasonal differences observed for litter and woody fuel consumption, however. We further hypothesized that the variability of surface fuel consumption would be greater in early growing season burns than in dormant season burns, but our results do not support this. Rather, while variability in woody fuel consumption (1-h, 10-h, and 100-h) did not differ by season of burn, litter consumption and woody fuelbed height reduction were more variable in dormant season burns. With less plot area burned, this result in the dormant season reflects a more bifurcated outcome at this time of year of either (a) low-moderate fuel consumption or (b) no consumption as a result of no ignition.

Our findings of surface fuel consumption ran contrary to our hypothesis as we expected warmer and drier conditions in the early growing season to result in higher levels of surface fuel consumption. In contrast, another study in the southern Appalachians found higher KBDI as a strong predictor of increased fuel consumption (Jenkins et al. 2011). The range of dates of burn and KBDI in different seasons was much greater in that study than ours, however, which may limit study comparisons. The fact that greater heat pulses did not correspond with increased surface fuel consumption in our study suggests that moisture levels did not limit combustion in either season. Indeed, in longleaf pine savannas of the Coastal Plain, a study of fire regime dynamics over several years found that fuel consumption did not correlate with eight intra-annual periods dispersed throughout the year, but fire intensity varied considerably as a function of rate of spread (Glitzenstein et al. 1995). Higher solar angles and lower fuel moisture in the early growing season likely allowed fire to spread to more variable landscape positions and burn at higher temperatures than in the dormant season while maintaining similar levels of fuel consumption.

Conclusions

Early growing season burns had a greater degree and variability of time-integrated heating induced by fire than did dormant season burns, influenced by warmer and drier burn day conditions. Differences in surface fire temperatures by season of burn were most pronounced during the mid-late afternoon on burn days. These patterns of fire behavior correlated with greater probability of fire spread within early growing season burns with fuel moisture being less of a limiting factor to fire spread. Per given area that fire spread in treatment units, however, surface fuel consumption largely did not differ by season of burn, suggesting that increased levels and duration of heating do not necessarily result in increased fuel consumption. Nevertheless, burning in a given unit in the early growing season is likely to reduce fuel loads at least as effectively as in the dormant season.

Burning in the early growing season is likely to result in not only higher levels of but also more variable thermal energy release over a greater extent than in the dormant season. This, in turn may result in greater variation in the post-fire vegetation response – possibly enhancing landscape-level community heterogeneity. Managers in the region thus may consider growing season burns as a viable addition to their existing dormant season burning regimes to enhance their ability to reduce fuels across fire-suppressed landscapes. They should be mindful, however, of how burning in the early growing season may influence non-fuels-related objectives, including those related to wildlife and smoke.

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Authors' contributions

MCV collected the data, performed the analyses, and drafted the manuscript as the first author. DLH wrote the original proposal for the project as its Principal Investigator, coordinated field data collection efforts, and served as liaison with the US Forest Service for conducting the prescribed fire treatments. WCB Jr. provided direction on statistical design and methodology. MBD refined the methodology, particularly with the use of thermocouples, and wrote the original script that was used to process the thermocouple data. TAC refined the methodology, particularly with fuels data. All authors reviewed and provided input and feedback on drafts of earlier versions of the manuscript and read and approved the final manuscript.

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Availability of data and materials

The datasets used and/or analyzed during the current study are archived at Clemson University, Clemson, SC, USA, and available from the corresponding author on reasonable request. Programming code for all analyses performed in R is archived and available online in a GitHub repository [https://github.com/gishokie95/ms1-ffb].

Declarations

Ethics approval and consent to participate

Not applicable.

Consent for publication

Not applicable.

Competing interests

The authors declare that they have no competing interests and have undergone the required agency review.

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