Do structural and compositional shifts in mixed pine-oak forests alter fuels and fire behavior?

by

Steven Michael Cabrera

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Approved by

Heather D. Alexander, Chair, Associate Professor of Forest Ecology
Christopher J. Anderson, Professor of Wetland Ecology
John L. Willis, Research Forester USDA Forest Service

Abstract

The lack of fire disturbances throughout the 20th century has contributed to forest structural and compositional shifts, resulting in the encroachment of shade-tolerant and often fire-sensitive hardwood species in fire-dependent forests. Upland forests in the southeastern U.S. are adapted to frequent, low-intensity surface fires, but encroaching species pose a risk to fire efficacy due to their generally fire suppressing leaf litter and crown traits. To evaluate whether encroaching species impact fire behavior through changes in fuels, we described stand characteristics and fuel loads across a gradient of *Pinus* dominance, then performed a manipulative field experiment testing the effects of targeted midstory thinning on fuels and fire behavior. In general, encroaching species occurred at relatively high midstory densities and in dominant overstory positions, thus rendering midstory thinning targeting these species largely ineffective at altering fire behavior through minor changes in understory light availability and fuels.

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List of Abbreviations

ANOVA	analysis of variance
CRAT	Cherokee Ridge Alpine Trail
CWD	coarse woody debris
DBH	diameter at breast height
ED	early dormant season
FOFEM	First Order Fire Effects Model
FWD	fine woody debris
GS	growing season
KPNC	Kreher Preserve & Nature Center
LD	late dormant season
MOTDF	Mary Olive Thomas Demonstration Forest
QMD	quadratic mean diameter
SA:V	surface area to volume ratio
TANF	Talladega National Forest
TPHA	trees per hectare
TUNF	Tuskegee National Forest
U.S. or USA	United States of America

Chapter 1: Encroachment of fire-intolerant hardwoods into historically fire-dependent pine-oak forests homogenizes stand and fuel characteristics

Abstract

Oak (*Quercus*) and pine (*Pinus*) are foundational species in forest ecosystems throughout the eastern and central U.S. and are adapted to frequent, low-intensity surface fires. Oak and pine species frequently co-occur across this range as mixed pine-oak stands, but successful fire exclusion has contributed to encroachment from shade-tolerant and often fire-sensitive species with leaf litter traits (thin, flat leaves with low curl and high surface area to volume ratios) and crown structures (wide, deep crowns with high leaf area) often associated with lower flammability compared to traits of pine and upland oaks. However, most work documenting how leaf litter or crown traits influence flammability along a fire-promoting to suppressing spectrum focus on single rather than mixed species fuelbeds, which are increasingly common across the region. This research quantifies stand characteristics (composition, density, canopy cover) and fuel loads (herbaceous, shrub, litter, duff, fine and coarse woody debris, total) in 97 plots with a fire return interval greater than 3 years across five sites in east-central Alabama, USA in 2022. We characterized plots into different stand types based on the relative percent contribution of *Pinus* species to total basal area as either hardwood (0 – 30%; n = 8), mixed pine-oak (30 – 70%; n = 68), or pine (70 – 100%; n = 21). We found that across the gradient of *Pinus* basal area, pine and upland oaks were the dominant overstory species, but encroaching species (e.g., *Liquidambar styraciflua* and *Quercus nigra*) occurred in both mid- and overstory size classes (20.4 ± 0.7 cm quadratic mean diameter; QMD) at relatively high densities (364 ± 25 trees ha^{-1}) compared to pines and oaks, likely contributing to high canopy cover (92.3 ± 0.5%) across stand

types. All stand types had similar total fuel loads, ranging from 23 – 25 Mg ha^{-1}, but leaf litter fuel loads in pine and mixed pine-oak stands were 1.7 Mg ha^{-1} and 1.3 Mg ha^{-1} greater compared to hardwood stands, respectively. In general, leaf litter fuelbeds in all stand types consisted of 22 – 30% leaf litter by mass of encroaching species, indicating encroachment in the absence of management is an issue within these stands with unknown consequences for flammability. Our characterizations coupled with fuel load assessments of these mixed stands are critical to understanding impacts to future fire potential, because without disturbance, southeastern forests are susceptible to becoming increasingly hardwood dominated with increased shade and less flammable leaf litter fuels due to encroaching species proliferation.

Introduction

Fire-dependent pine (*Pinus* spp.) and upland oak (*Quercus* spp.) forests require frequent, low-intensity surface fires to maintain and restore landscapes across the central and eastern U.S., but prescribed fire use as a management tool is potentially becoming less effective due to increased encroachment and dominance from opportunistic shade-tolerant and often fire-sensitive species in response to decades of successful fire exclusion (Nowacki and Abrams 2008). Shifts in forest composition and structure resulting from fire exclusion induced encroachment could suppress forest flammability by altering fuel loads and/or traits that influence fire behavior (Kreye et al. 2018; Babl et al. 2020). While there has been considerable effort to document differences in leaf litter traits and their influence on flammability among individual species on the fire-promoting/fire-suppressing spectrum (Kane et al. 2021; Varner et al. 2021), there has been less effort to assess characteristics of fuel mixtures (Varner et al. 2015). Understanding mixed fuelbeds are important because: 1) pine and oak frequently co-occur as mixed stands within their range, where no one species represents > 75% dominance by stand basal area (Helms 1998), 2) mixed species fuelbeds are becoming increasingly complex with the addition of hardwood species encroachment in mid- and understory strata beneath pine and oak overstories, and 3) gradients in canopy openness due to spatial heterogeneity or dominance of pine and oak species likely impact their relative contribution to total fuel loads. Consequently, compositional and structural shifts due to fire exclusion (Hanberry 2013a; Knott et al. 2019) could have stark consequences for flammability, leaving the future role of fire in these forests unknown.

Fuel characteristics could vary across mixed pine-oak stands for a variety of reasons. For example, the relative dominance of overstory pine versus oak will dictate their relative contribution of leaf litter fuels, which range in growth form and associated chemistry and morphology, from needles to broadleaves. Increased abundance of encroaching species to the midstory and understory will further impact forest flammability due to generally fire-dampening leaf litter and crowns traits – influencing a shift from generally open canopied forests with herbaceous fuels to closed-canopy forests dominated by leaf litter fuels (Hanberry et al. 2012; Alexander et al. 2021; McDaniel et al. 2021). In general, encroaching species (i.e., *Liquidambar styraciflua, Ulmus alata*) have leaf litter with low-curl, thin leaves, and high surface area to volume ratios (SA:V) that impact the arrangement and structure of fuelbeds, influencing aeration and fuel moisture retention that are associated with lower maximum burn temperatures, rates of fire spread, and flame lengths (Kreye et al. 2013; Grootemaat et al. 2017; Babl et al. 2020; McDaniel et al. 2021). Conversely, leaf litter of fire-adapted species (i.e., pines and upland oaks) is among the most flammable in this region (high leaf curl, thick leaves, low SA:V), thereby providing the primary fuel source of surface fires (McDaniel et al. 2021). The wide, deep crowns of encroaching species (i.e., *Fagus grandifolia, Acer rubrum*) with high leaf area decrease light intensity and create shadier and cooler understory conditions compared to many fire-adapted species with more open crowns that increase solar radiation reaching the forest floor (Ray et al. 2005; Babl et al. 2020; Kreye et al. 2020). This, in turn, impacts decomposition rates of leaf litter fuels as encroaching species generally decompose more rapidly than oaks, reducing available fuel loads (Babl-Plauche et al. 2022). Not only could these crown traits directly influence fuel moisture and decomposition of leaf litter fuels, but as forest structures shift from open-canopy to closed-canopy, other fuels are also likely to change due to increased canopy cover and decreased light levels – potentially contributing to less herbaceous and shrub fuels which is especially important as herbaceous fuels are a major component of flammable fuelbeds in open forests

(Brewer 2016; Hanberry, Bragg, et al. 2020). Downed woody debris inputs and pools could also vary across a mixed forest gradient, as oak-dominated forests tend to have higher volumes of deadwood compared to pine forests (Lo Monaco et al. 2020). Generally, oak coarse woody debris tends to be denser compared to pine coarse woody debris and could influence decomposition rates (Gosz et al. 1973; Barnett and Jeronimidis 2003), but previous disturbance or management history could reduce fuels through consumption due to fire or increase fuels via residual slash following timber operations, potentially altering the longevity and structure of available woody debris fuels. When present together, the mixture of fire-suppressing and/or fire-promoting leaf litter and crown traits within stands that have heterogenous dominance of pine, oak, and encroaching species could have large variation on fuel load inputs, with potential consequences for forest flammability in the absence of management.

This research quantified a gradient of stand types from hardwood dominant, mixed pine-oak dominant, and pine dominant and their respective fuel loads (leaf litter, duff, herbaceous, shrub, fine and coarse woody debris) across a range of varying conifer (*Pinus* spp.) dominance at five sites in east-central Alabama, USA. As pine dominant woodlands and pine-hardwood mixtures are becoming increasingly occupied by encroaching species (Hanberry et al. 2012), examining a range of mixed stand composition and structure to quantify fuel mixtures can aid our understanding of prescribed fire application where dominance by encroaching shade-tolerant and fire-sensitive species is increasing. We targeted a range of pine dominance based on their contribution to stand basal area to evaluate the effect of various mixed stand compositions and structures on fuels and assessed how the encroachment of species under varying levels of pine dominance potentially alters the flammability of pine dominant woodlands and pine-hardwood mixtures. We predicted that across the distribution of pine dominance, we would observe a wide range of fuel types and loads such that: 1) leaf litter fuels correspond with stand species composition, and 2) herbaceous and shrub fuels would be more abundant in stands with high pine domniance stands due to greater understory light availability. Ultimately, fuel quantity and type across a gradient of pine dominance could promote or suppress flammability given the relative proportion of species contribution to fuels and the relationship between fuel traits and flammability. By quantifying mixed stand fuels, this study can inform future work concerning how encroaching species and their associated traits play a role in altering mixed stand structure and composition, and test the flammability of mixed fuelbeds, which are important to identifying a potential threshold where a dominance by encroaching species leads to mesophication of forests (Nowacki and Abrams 2008), and provide recommendations where applying herbicides or mechanical treatments plus repeated prescribed fire is necessary to achieve management objectives in degraded pine-oak mixtures.

Methods

Site and Stand Selection

In February and March 2022, we established 97 0.02-ha plots in hardwood, mixed pine-oak, and pine dominant stands at five sites throughout east-central Alabama, USA (Table 1) for sampling of stand and fuel characteristics: 1) Mary Olive Thomas Demonstration Forest (MOTDF; 32.578, -85.423), 2) Kreher Nature Preserve (KNP; 32.662, -85.486), 3) Cherokee Ridge Alpine Trail (CRAT; 32.692, -85.900), 4) Tuskegee National Forest (TUNF; 32.480, -85.606), and 5) Talladega National Forest (TANF; 33.771, -85.571) (Figure 1). Sites were scouted through field reconnaissance in February and March 2022 to focus plot selection in stands where visual estimates of *Pinus* dominance ranged from 30% to 70% basal area (i.e., mixed stands). We also chose a few stands with > 70% *Pinus* basal area (pine dominant) and <

30% *Pinus* basal area (hardwood dominant) to characterize and link stand and fuel conditions to variation in pine dominance based on Helms (1998)'s approximation based on species-specific contribution to basal area. Across sites, we chose plots that captured compositional variation in common southern *Pinus* species (*P. echinata, P. elliottii, P. palustris, P. taeda*) while also including upland oaks (*Q. alba, Q. falcata, Q. rubra, Q. montana*) and other hardwood species (primarily *Acer rubrum, Liquidambar styraciflua, Liriodendron tulipifera*). To minimize variation associated with stand history influence on stand and fuel load characteristics, plots were concentrated in areas with no fire for at least the last three years (common fire return interval in southeastern fire-dependent stands (Wann et al., 2020) and no obvious recent timber management history or natural disturbance.

All sites were classified as humid subtropical (Cfa) climate type within the Köppen Climate Classification system (Kottek et al., 2006). Sites varied in size but ranged from 48 ha (KNP) to 158,886 ha (TANF) and had elevations and slopes ranging from 117 m (TUNF) to 358 m (TANF) and 0.9 ° (TUNF) to 4.4 ° (KNP), respectively. Number of plots sampled at each site varied due to site size and availability of stands that met sampling criteria. Sites were generally similar in annual temperature and precipitation, but dominant species and management history varied (Table 1).

Table 1. Summary characteristics of five sites: Mary Olive Thomas Demonstration Forest (MOTDF), Kreher Nature Preserve (KNP), Cherokee Ridge Alpine Trail (CRAT), Tuskegee National Forest (TUNF), and 5) Talladega National Forest (TANF) and their locations with Alabama, USA. We report the size (ha), number of sample plots (n), average elevation within sample areas (m), average slope within sample areas (°), annual minimum and maximum temperatures (°C), annual precipitation (mm), common names of dominant conifer, upland hardwood, and encroaching species at each site, and a general summary of management history within plot sample areas. Annual temperature and annual precipitation data were extracted from the nearest weather station to the site from Western Regional Climate Center.

Site name	Location	Size (ha)	Plots (n)	Elevation (m)	Slope (°)	Annual temperature (min °C – max °C)	Annual precipitation (mm)	Common conifer and upland hardwood species	Common encroaching species	Management History
MOTDF	Auburn, AL	162	19	192	2.0	11.6 – 24.3	1370	Loblolly pine, white oak, southern red oak	Sweetgum, water oak	None since 1983
KNP	Auburn, AL	48.5	5	198	4.4	11.6-24.3	1370	Loblolly pine, post oak, southern red oak	Sweetgum, water oak	None since 1993
CRAT	Dadeville, AL	150	5	196	3.6	11.0 – 23.7	1350	Longleaf pine, chestnut oak	Tulip poplar, red maple	Unknown
TUNF	Tuskegee, AL	4,553	29	117	0.9	11.6 – 24.3	1370	Longleaf pine, loblolly pine, white oak	Sweetgum, water oak, tulip poplar	At least 3 years without fire
TANF	Heflin, AL	158,886	40	358	3.7	7.9 – 22.5	1455	Longleaf pine, white oak, chestnut oak	Tulip poplar, red maple	At least 3 years without fire

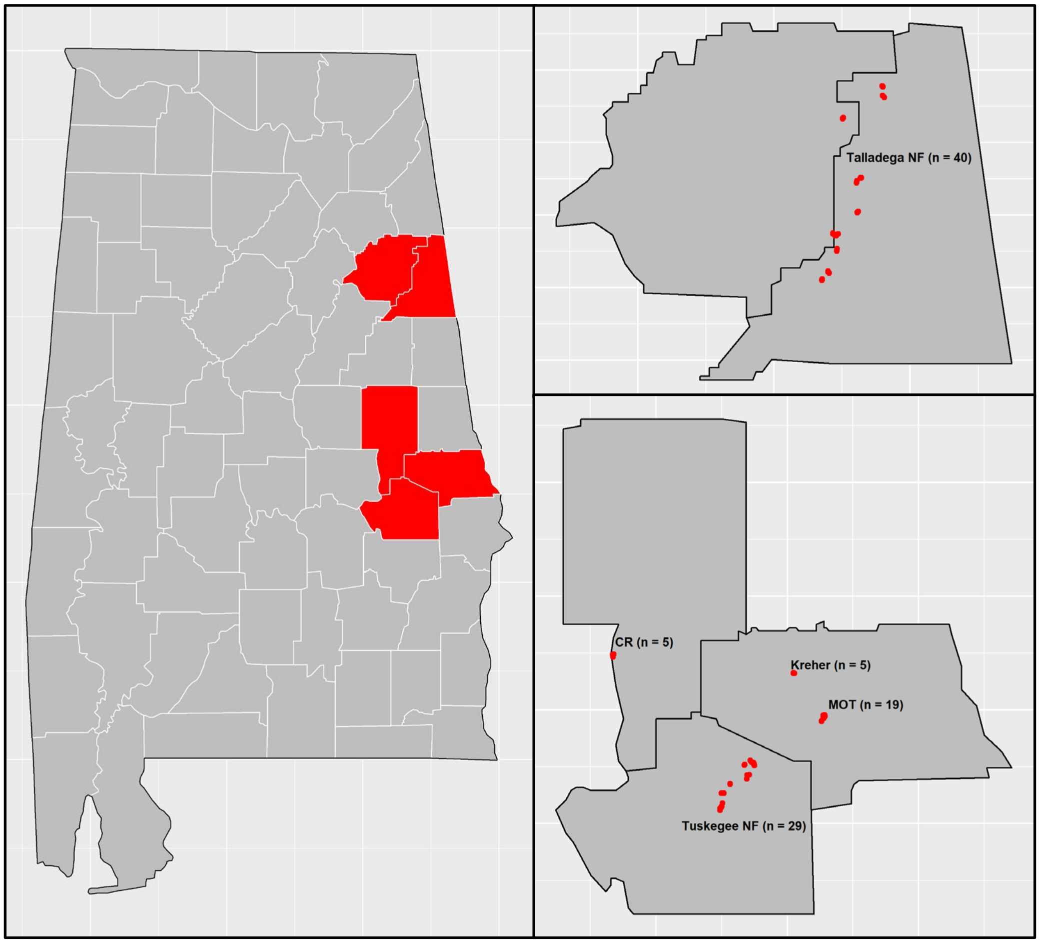

Figure 1. Highlighted counties (Cleburne, Calhoun, Lee, Macon, Tallapoosa) in red within east-central Alabama, USA (left) where stands were established (Mary Olive Thomas Demonstration Forest (MOT), Kreher Nature Preserve (Kreher), Cherokee Ridge Alpine Trail (CR), Tuskegee National Forest (Tuskegee NF), Talladega National Forest (Talladega NF)) with sample size noted. Stands established in Cleburne and Calhoun counties (top, right) and Lee, Macon, and Tallapoosa counties (bottom, right). Maps generated with usmap (https://cran.r-project.org/web/packages/usmap/index.html) package within R-4.2.1 (R Core Team 2018).

Survey of stand and fuel characteristics

All established 0.02-ha (8.01 m radius) plots aimed to characterize stand structure, composition, and fuel conditions across the gradient of pine dominance. To facilitate plot re-location, plots were marked with rebar and latitude/longitude recorded with a GPS when they were scouted. To quantify stand structure and composition, all living overstory (> 20 cm diameter at breast height (1.37 m aboveground); DBH) and midstory (10 – 20 cm DBH) trees were identified to species and DBH recorded. As a proxy for understory light level, we estimated canopy cover at each plot during peak growing season (June – July) by averaging three readings taken 5-m from plot center at 0° N, 135° SE, 225° SW using a convex spherical densiometer (Forestry Suppliers, Inc., Jackson, MS, USA). At the same locations used for canopy cover, we recorded heights and visually estimated percent cover of herbaceous (combined graminoids and forbs) and shrubs understory vegetation using the protocol by (utes and Keane, (2006). Fuel loads of herbaceous and shrub vegetation were calculated using biomass equations as a function of height, cover, and standard bulk densities (Lutes and Keane, 2006). We quantified fine and coarse woody debris by running three 12.6 m Brown's transects (Brown, 1974), one each along 0° N, 135° SE, 225° SW lines from plot center. Fuel loads of fine (FWD; 1-hr, 10-hr, and 100-hr fuels) and coarse (CWD; 1000-hr fuels) woody debris were calculated using standard equations as a function of recorded fuel intersections (FWD) or diameters (CWD), specific gravity based on a visual assessment of decay class (CWD only; Lutes and Keane, 2006), non-horizontal correction and slope factors, and constants from Brown (1974). To quantify leaf litter fuel loads and composition, all fresh leaf litter (i.e., not decomposed) was harvested in early March 2022 within two 30-cm x 30-cm (0.09-m^2) quadrats placed 5 m from plot center at 0° N and 180° S, allowing for some movement if the area to be harvested was obstructed by standing trees or downed logs. Leaf litter samples were sorted in the lab into the following three functional groups: 1) pine species (*P. echinata, P. elliottii, P. palustris, P. taeda*), 2) upland oaks (*Q. alba*, *Q. falcata, Q. rubra, Q. montana, Q. stellata, Q. velutina*), and 3) "encroaching species" (primarily shade-tolerant and fire-sensitive hardwood species such as *Acer rubrum, Liquidambar styraciflua, Liriodendron tulipifera, Q. nigra)*, and dried to constant mass at 60 °C for at least 72 hr and weighed to calculate fuel load contributions for each group. Duff depth was recorded at the center of each quadrat to calculate fuel load based on standard bulk density from Lutes and Keane (2006). Total fuel load (Mg ha^{-1}) was calculated by summing contributions from each fuel load type (herbaceous, woody, fine woody debris, coarse woody debris, leaf litter, duff).

Statistical Analyses

For each plot, we calculated total basal area and the proportion of *Pinus* contribution to total basal area. We then categorized each plot into one of three stands types based on relative basal area of *Pinus* species: 1) < 30%; hardwood stands (n = 8), 2) 30% – 70%; mixed stands (n = 68), and 3) > 70%; pine stands (n = 21). Plot inventory data (overstory, midstory) were used to calculate quadratic mean diameter (QMD; cm) and tree density (trees ha^{-1}) for pine, upland oak, and encroaching species functional groups. Using a linear mixed effects model (Pinheiro and Bates, 2022) with site as a random effect to account for site-level variation, we assessed whether canopy cover, individual fuel loads, and total fuel loads (dependent variables) varied between stand types. Prior to analyses, we tested assumptions of homogeneity (Levene's Test) and normality (Shapiro-Wilk Test) and variables in violation of assumptions were transformed with logarithmic or square-root (for percentages) functions. If variables were transformed, analyses used transformations, but we present means and standard errors using untransformed values. Post-hoc Tukey's HSD tests were used to confirm significant results or interactions at $\alpha = 0.05$.

These initial analyses indicated differences in leaf litter fuel types and loads between the three stand types. Thus, we chose to focus additional analyses on variations in leaf litter composition across the gradient of pine dominance using linear regression. We modeled each sorted leaf litter functional group's contribution to the fuelbed (% by mass) as a function of relative *Pinus* basal area. All statistical analyses were conducted using R-4.2.1 (R Core Team, 2018).

Results

Stand characteristics

Across all 97 plots, mean basal area was 39.5 ± 1.1 m^2 ha^{-1} (Figure 2). There was no difference in mean basal area between hardwood stands (39.3 ± 4.8 m^2 ha^{-1}), mixed stands (38.0 ± 2.4 m^2 ha^{-1}), or pine stands (40.0 ± 1.4 m^2 ha^{-1}) ($p = 0.79$). Across the observed plots, the mean pine basal area was 22.5 ± 1.1 m^2 ha^{-1}, contributing 57.3 ± 1.9% to relative pine basal area. When considering trees across all plots, there were no differences between mean tree QMD ($p = 0.12$) and mean tree density ($p = 0.30$) among stand types, but QMD and density varied among functional groups within stand types ($p < 0.005$) (Figure 3). While upland oak QMD and density decreased as pine dominance increased, pine QMD was similar across the gradient, but pine density increased with higher pine dominance. Across the gradient of pine dominance, encroaching species QMD was lower (20.4 ± 0.6 m^2 ha^{-1}) when compared to pines (39.3 ± 1.2 m^2 ha^{-1}) and oaks (30.6 ± 1.6 m^2 ha^{-1}), but encroaching species were 1.7 and 2.7 times as dense, respectively. This difference was notably more apparent in upland oak stands: encroaching species were 5.9 and 2.7 times as dense as pines and oaks, respectively. Though the midstory is comprised of mostly encroaching species (Figure 3), they are present in overstory positions, and high encroaching species density relative to pines and oaks could be contributing to canopy closure (mean canopy cover 92.3 ± 0.5%) regardless of stand type ($p = 0.13$) (Figure 4).

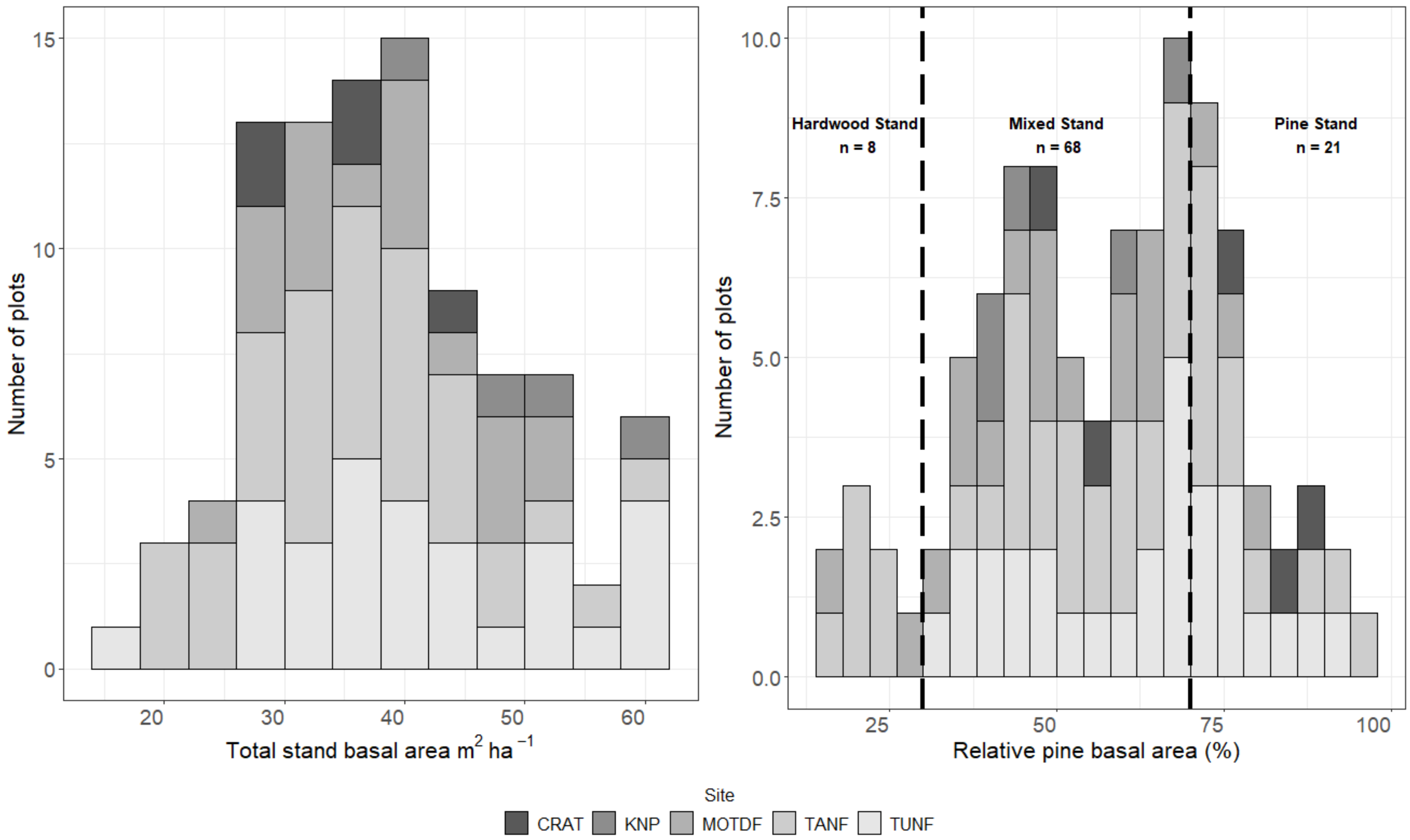

Figure 2**.** Stacked bar charts of number of sample plots (n) at each site (Mary Olive Thomas Demonstration Forest (MOTDF), Kreher Nature Preserve (KNP), Cherokee Ridge Alpine Trail (CRAT), Tuskegee National Forest (TNF), Talladega National Forest (TNF)) across the range of observed stand basal area m^2 ha $^{-1}$ (left). The distribution was broken up into hardwood stand (n = 8), mixed stand (n = 68), and pine stand (n = 21) based on stand relative pine basal area (%) (right).

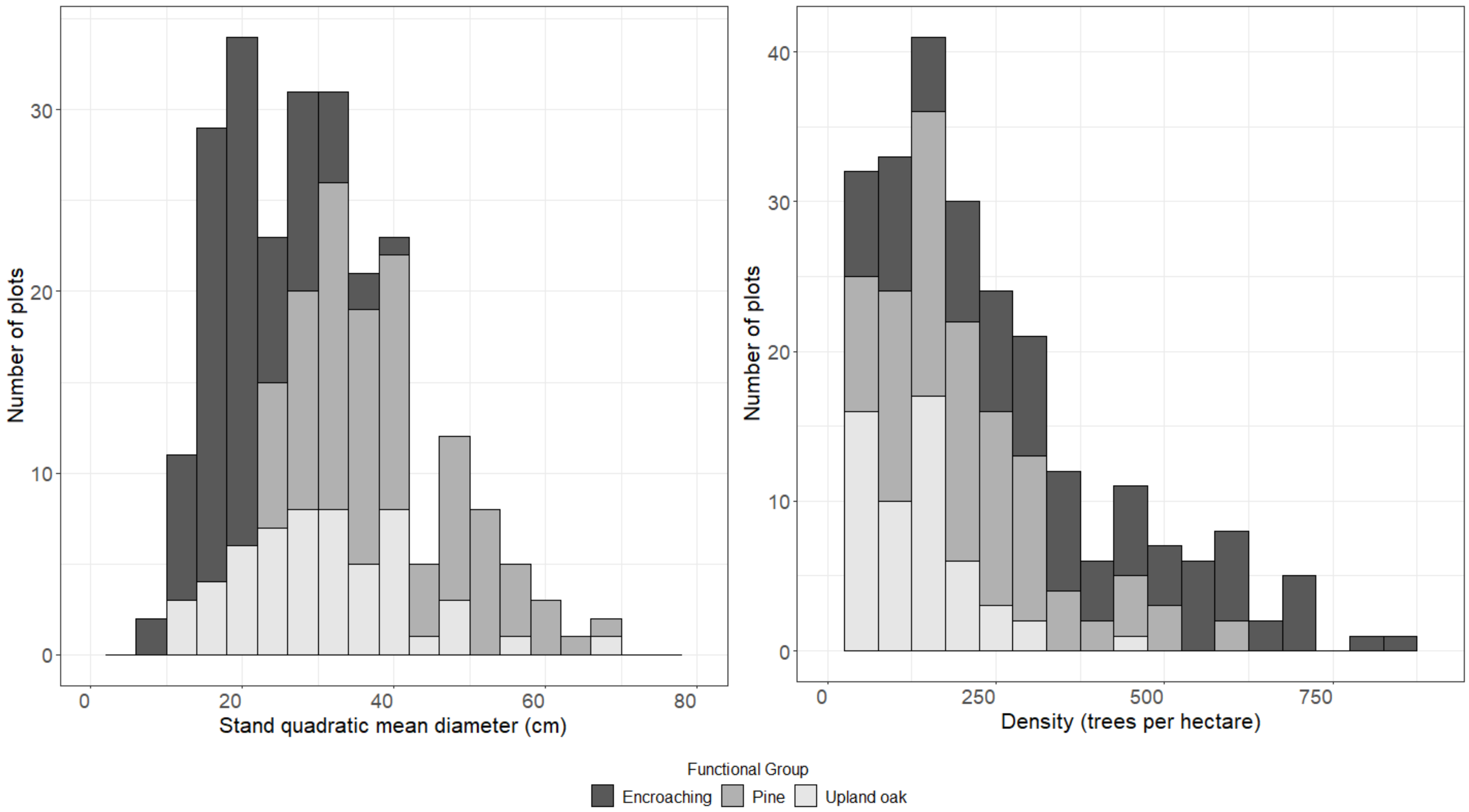

Figure 3. Stacked bar charts displaying the distribution of plots (n) from all sites and relative quadratic mean diameter (cm; left) and tree density (trees ha^{-1}; right) for encroaching, pine, and upland oak overstory (> 20 cm DBH) and midstory (10 – 20 cm DBH) species.

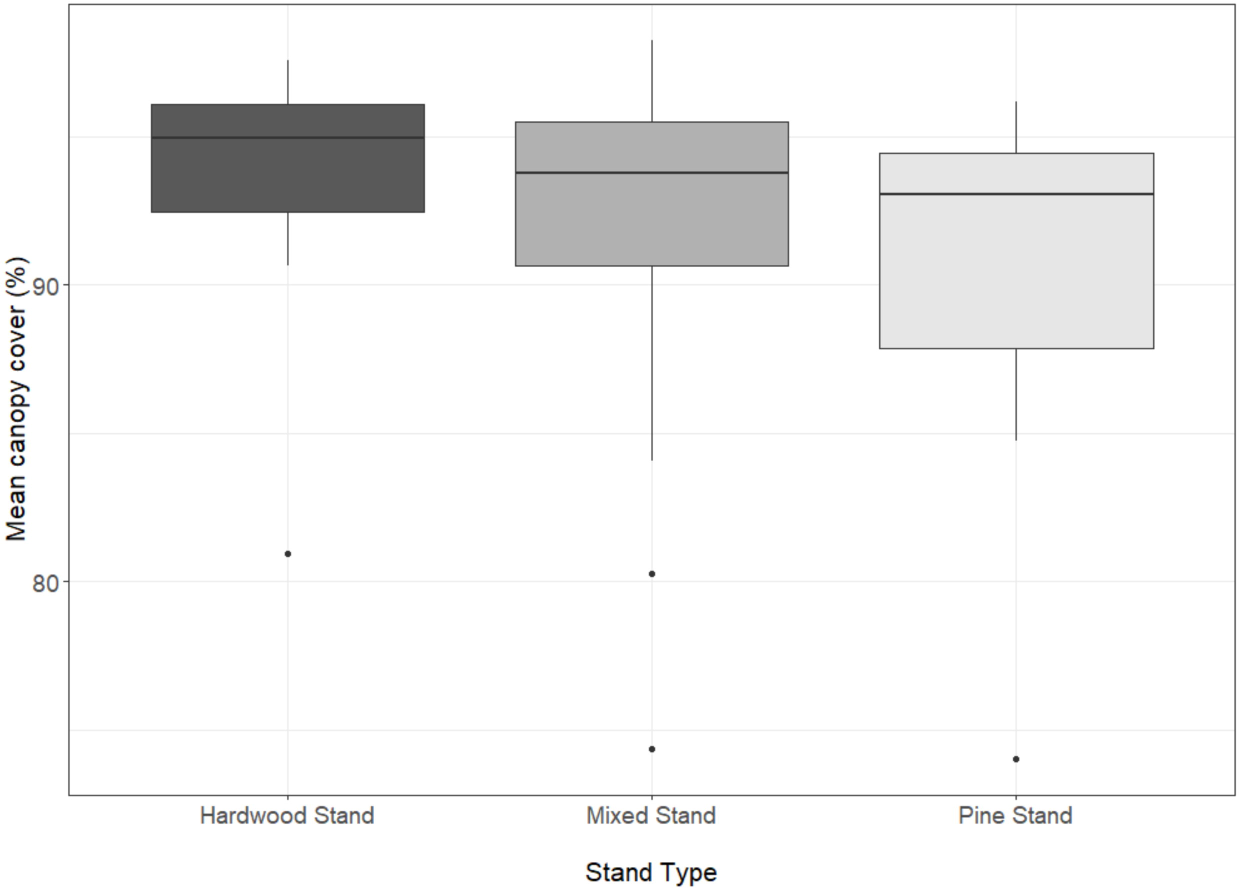

Figure 4. Box and whisker plots of canopy cover (%) across all sample plots at all sites within each stand type (hardwood stand, mixed stand, and pine stand). Individual points are outliers.

Fuel loads

There were no differences among CWD ($p = 0.92$), FWD ($p = 0.34$), herbaceous ($p = 0.84$), shrub ($p = 0.62$), or duff ($p = 0.81$) fuel loads and their relative contribution to total fuel loads between stand types (Table 2). Our estimates of fuel load were not different among stand types ($p = 0.90$). Leaf litter was the only fuel load type that was significantly different among stand types ($p = 0.003$. Pine stands and mixed pine-oak stands had 1.7 ± 0.3 Mg ha^{-1} Mg ha^{-1} ($p = 0.002$) and 1.3 ± 0.2 Mg ha^{-1} ($p = 0.013$) greater leaf litter fuel load when compared to hardwood stands, respectively. While fuelbeds in hardwood stands were comprised of mostly upland oak leaf litter (49.6 ± 6.1%) and fuelbeds in pine stands were comprised of mostly pine leaf litter (63.0 ± 3.4%), encroaching species contributed approximately 22.2 – 30.3% (0.91 – 1.5 Mg ha^{-1}) to the leaf litter fuelbed regardless of stand type.

Pine leaf litter had a positive linear relationship with relative pine basal area. For each 10% increase in pine basal area m^2 ha^{-1}, we observed a 6.9 ± 0.1% increase in pine leaf litter by mass ($p < 0.001$; $r^2 = 0.40$) (Figure 5). Upland oak and encroaching leaf litter contribution had slight negative relationships over the range of relative pine basal area, decreasing by 4.5 ± 0.1% ($p < 0.001$, $r^2 = 0.13$) and 2.3 ± 0.1% ($p = 0.008$, $r^2 = 0.07$) for each 10% increase in relative pine basal area. Encroaching species had greater hardwood leaf litter inputs compared to upland oaks in stands until pine basal area drops below 30%.

Table 2. Fuel loads (Mg ha^{-1}) of individual fuel types (herbaceous, shrub, leaf litter, duff, fine woody debris (FWD), and coarse woody debris (CWD)) and fuel loads of leaf litter functional species groups (pine, upland oak, encroaching) and their relative proportion (%) in hardwood, mixed, and pine stands. Fuel load values are means ± SE.

	Hardwood Stand		Mixed Stand		Pine Stand	
	Fuel load (Mg ha^{-1})	Relative proportion (%)	Fuel load (Mg ha^{-1})	Relative proportion (%)	Fuel load (Mg ha^{-1})	Relative proportion (%)
Individual fuel types						
Herbaceous	0.3 ± 0.2	1.40	0.3 ± 0.1	1.31	0.4 ± 0.1	1.47
Shrub	2.9 ± 1.4	12.5	1.9 ± 0.3	8.1	2.0 ± 0.5	8.1
Leaf litter	3.8 ± 0.2	16.0	5.0 ± 0.1	21.5	5.4 ± 0.3	22.3
Duff	5.2 ± 1.0	22.0	4.9 ± 0.6	21.2	5.6 ± 1.1	22.7
FWD	4.3 ± 1.0	18.5	3.7 ± 0.3	32.0	3.0 ± 0.2	12.2
CWD	6.9 ± 3.7	29.6	7.5 ± 1.2	15.7	8.1 ± 3.0	33.4
Total	23 ± 2.7	100	23 ± 1.6	100	25 ± 2.3	100
Leaf litter contribution						
Pine	0.98 ± 0.27	24.8 ± 6.1	2.50 ± 0.02	48.2 ± 2.3	3.52 ± 0.34	63.0 ± 3.4
Upland oak	1.90 ± 0.25	49.6 ± 6.1	1.01 ± 0.13	21.5 ± 2.8	0.78 ± 0.22	14.7 ± 4.1
Encroaching	0.91 ± 0.22	25.6 ± 6.2	1.50 ± 0.10	30.3 ± 1.9	1.15 ± 0.20	22.2 ± 3.9

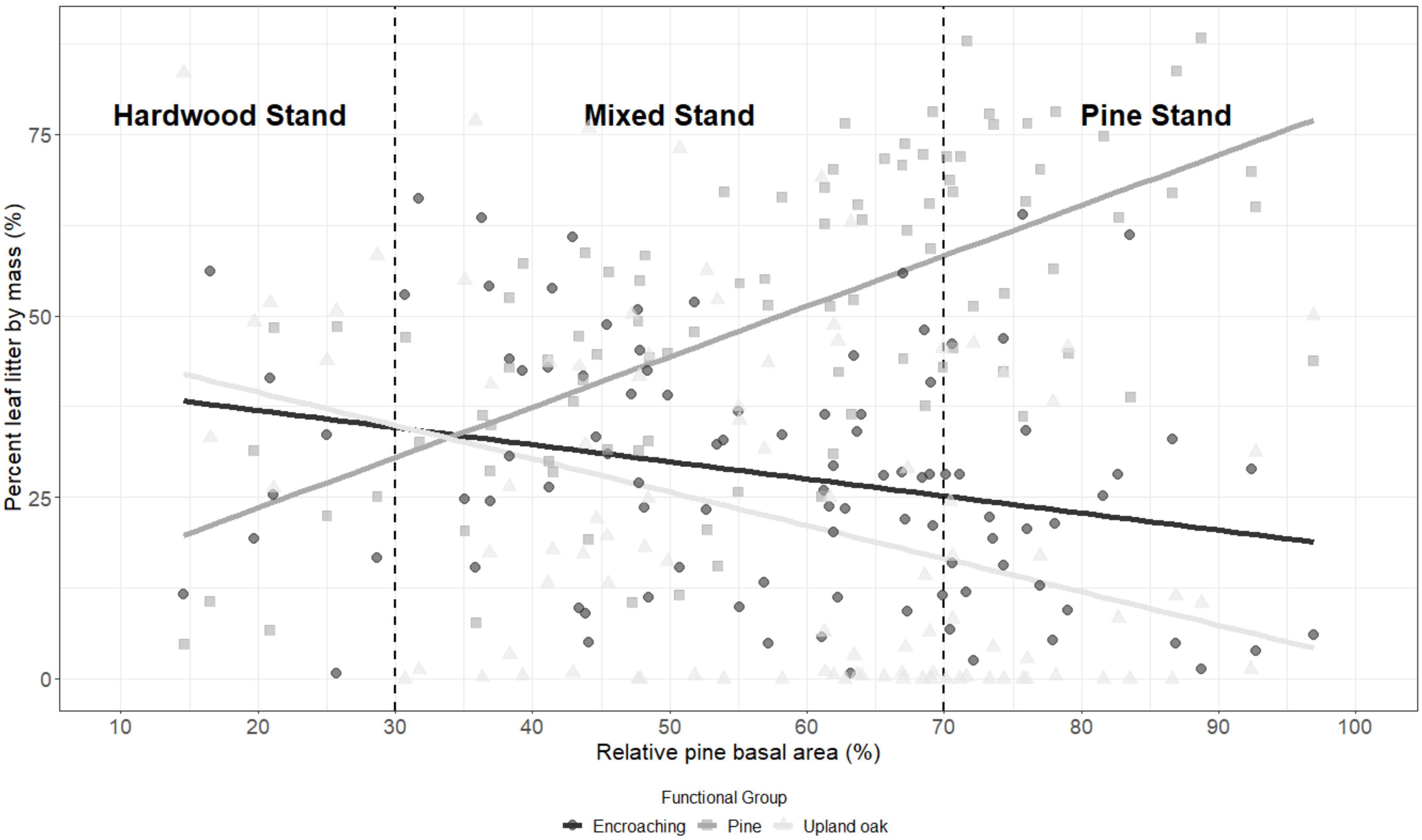

Figure 5. Linear regression model of the relationship between the leaf litter proportion by mass (%) of three species functional groups (encroaching species (circles), upland oaks (triangles), and pines (squares)) across the range of observed relative pine basal area (%). Dashed vertical lines at 30% (left) and 70% (right) show transition from hardwood stands to mixed stands and from mixed stands to pine stands, respectively.

Discussion

This work demonstrates that in the absence of recent (< 3 year) prescribed fire, increasing midstory and overstory density of encroaching species could increase canopy closure regardless of stand type, potentially contributing to a recruitment bottleneck in relatively shade-intolerant pines (Magee et al., 2022) and oaks (Abrams, 1992) through impacts on both light and fuel contribution. The size and density of encroaching species is also concerning because these species tend to have dense crowns with smooth bark, traits that influence water cycling and increase fuel moisture surrounding a tree's bole through changes in throughfall and stemflow, with potential to dampen local flammability and fire continuity (Alexander and Arthur, 2010; Babl et al., 2020; Siegert et al., 2020). Recruitment of generally shade-tolerant encroaching species has been positively associated with dense midstories developing beneath oak canopies, while also being better suited to take advantage of canopy openings (Allen et al., 2018) contributing to their survival, growth, and likely eventual loss of overstory oaks. Though pine and upland oak species dominate the largest trees in these stands (> 30 cm DBH), age-related mortality of these species will result in their eventual replacement due to lack of advanced regeneration, raising increased concern for the legacy of fire-exclusion on fire-dependent species across stand types.

Contrary to our hypothesis, we observed similar total and individual fuel loads (except leaf litter) among stands in all three stand types. In general, our total fuel loads of 23 to 24 Mg ha^{-1} are similar to a study in western Arkansas (McDaniel et al., 2016) quantifying pre-treatment fuel loads in pine-oak and mixed-oak stands in their study area using similar methods. McDaniel et al. (2016) reported pre-burn total fuel loads of 22.0 ± 4.8 Mg ha^{-1} in hardwood stands, 28.8 ± 4.8 Mg ha^{-1} in pine-oak stands, and 22.9 ± 4.8 Mg ha^{-1} in pine woodlands, roughly equivalent to our observed total and individual fuel loads in each stand type. McDaniel et al. (2016) also noted that outside of pine woodlands, forest cover types were closed-canopy (> 70% canopy cover) with little herbaceous cover (< 25%), consistent with our observations. When focused on leaf litter specifically, our estimates of fuel loads in mixed pine-oak stands (5.0 ± 0.1 Mg ha^{-1}) were slightly higher, but within the observed range, when compared to two unburned, closed-canopy mixed mesophytic-oak stands in northern Mississippi (4.05 Mg ha^{-1}; Nation et al. 2021) and southeastern Ohio (3.82 Mg ha^{-1}; Graham et al. 2006). Our results show that fuels in modern-day hardwood, mixed, and pine stands are becoming similar in the absence of frequent fire disturbances, with potential differences in flammability compared to historical pine-oak mixtures.

Across our observed plots, encroaching species contributed roughly a quarter of total fuelbed leaf litter regardless of stand type. Our assessment of leaf litter contribution in mixed fuelbeds among stand types experiencing encroachment from shade-tolerant and fire-sensitive species is essential to understanding and predicting flammability, as densification of forests have shifted the dominant fuel source driving surface fires from herbaceous understory fuels transition to senesced leaf litter (Nowacki and Abrams, 2008). In general, many of the encroaching species found at our sites (sweetgum, water oak, red maple, tulip poplar) have similar leaf litter (Babl-Plauche et al., 2022; Kane et al., 2021; Kreye et al., 2018, 2013; McDaniel et al., 2021; Varner et al., 2021) or crown (Alexander and Arthur, 2010; Babl et al., 2020; Ray et al., 2005; Siegert et al., 2020) traits known to suppress forest flammability. This is concerning because the lack of frequent fire management (> 3 years since fire) in these stands has likely contributed to encroaching species growth and survival, which could contribute to a positive-feedback of high abundance and density of species with fire-suppressing traits (Nowacki and Abrams, 2008). In

South Carolina, repeated prescribed fire alone decreased leaf litter and duff fuel loads in managed slash pine and pine-hardwood stands with low basal area (5 to 15 $m^2 ha^{-1}$), while increasing forb groundcover fuel loads, but these effects of fire were subdued at higher basal areas (> 20 $m^2 ha^{-1}$) (Parresol et al., 2012). Encroaching species in our stands with relatively large diameters and high density contributed approximately 22 – 30% of the leaf litter fuelbed by mass, while laboratory and field experiments demonstrated that when fuelbed contribution of encroaching non-oak leaf litter (sweetgum, winged elm, hickory) ranges from 33% to 66%, fuel moisture content increases and flammability decreases when compared to 100% oak leaf litter contribution (Kreye et al., 2018; McDaniel et al., 2021). Mixed species fuelbeds are complex and could result in a synergistic, dampening, or no impact on fire response variables (Varner et al., 2015), but encroaching species spread could threaten fire re-introduction through changes in flammability. Though we did not measure flammability, our results indicate that encroaching species spread across stand types in the southeastern U.S. has the potential to alter stand and fuel characteristics, leaving the efficacy of fire management in fire-excluded mixed species stands unknown.

Conclusion

Encroachment from shade-tolerant and fire-sensitive species in unmanaged or infrequently fire-managed stands could be contributing to canopy closure and the homogenization of understory fuels. Though our observed plots capture a range of species composition, our results indicate that these stands are becoming structurally similar due to high densities of midstory and overstory encroaching species relative to pines and oaks. We acknowledge that while our plots could vary in factors such as stand age, previous land use, and other attributes not measured here, our sampling generally characterizes stand and fuel characteristics across a range of pine dominance. Our estimates of stand characteristics and total and individual fuel loads could aid applicability of fuel load and fuel consumption models such as the First Order Fire Effects Model that largely lack estimates of fuel loads and consumption in southeastern forests (McDaniel et al., 2016). Such models are widely used by managers and are important for predicting and assessing wildland and prescribed fire effects and air pollutant emissions (Ottmar, 2014; Urbanski, 2014), and could be critical in mixed stands that are undergoing compositional and structural shifts due to encroachment of shade-tolerant and fire-sensitive species.

A major challenge to successful restoration of fire-excluded stands is the necessity of herbaceous groundcover fuels with flammable surface fuels, which will require additional mechanical or chemical treatments plus repeated prescribed fire that remove encroaching species, eliminating their leaf litter inputs and promoting surface fuel drying via losses in shade (Kreye et al., 2020). It is unlikely that fire re-introduction would cause mortality to encroaching species due to a developed fire tolerance with increased size, and local changes in flammability due to moister microclimate conditions under individuals leading to less flammable fuels that generally dampen fire intensity. Further work investigating how the quantity and identity of encroaching species influences the flammability and fire behavior in mixed fuelbeds could be essential to understanding the appropriate use of fire treatments. In fire-excluded and closed-canopy stands, we recommend restoration treatments (e.g., combination of mechanical and/or chemical with repeated prescribed fire) to focus efforts on targeting encroaching species, increasing understory light that alleviates moist microclimate conditions and promotes herbaceous communities with leaf litter of higher flammability species.

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Chapter 2: Midstory removal of encroaching species has minimal impacts on fuels and fire behavior in a mixed-pine stand

Abstract

Intentional fire exclusion has contributed to forest structural and compositional shifts, resulting in the encroachment of shade-tolerant, often fire-sensitive and/or opportunistic species throughout forest ecosystems. In the central and eastern U.S., encroaching species generally exhibit fire-suppressing leaf litter and crown traits, reducing prescribed fire efficacy to restore and maintain fire-dependent mixed pine (*Pinus* spp.) and oak (*Quercus* spp.) forests. Despite the natural role of fire in these forests, fire alone is unlikely to reverse encroachment impacts due to the degree of forest change since fire exclusion. Consequently, other management techniques (e.g., chemical, mechanical) in addition to fire may be needed, at least initially, to ensure persistence of these forests and their associated ecosystem services. In current-day mixed forests, where no one species represents > 75% dominance by stand basal area, encroaching species (e.g., *Liquidambar styraciflua* and *Quercus nigra*) commonly form a dense midstory, restricting advanced regeneration of relatively shade-intolerant pine and oak species. Once overstory pine and oak begin to senesce, encroaching species are likely to advance into dominant positions, further restricting pine and oak development. To quantify how encroaching species in mixed pine-oak forests in the southeastern U.S. impact fuels and canopy cover, and fire behavior, we experimentally thinned encroaching species from the midstory (< 20 cm DBH) at the Mary Olive Thomas Demonstration Forest (Auburn, Alabama, USA) in July 2021. Midstory thinning of encroaching species reduced basal area by 6.7 m^2 ha^{-1} and canopy cover by 9.1%. In general, thinning reduced shrub and fine woody debris fuel loads while having no impact on herbaceous, coarse woody debris, leaf litter, and duff fuel loads. When compared to pre-treatment levels,

thinning increased pine leaf litter contribution to the fuelbed by 10.9% while reducing leaf litter of encroaching species by 11.4%. Experimental fires in the early dormant season (January) and late dormant season (April) had higher fireline intensities, consumed more surface fuels, had faster rates of spread, and higher average maximum temperatures compared to growing season (September) fires. Despite changes to residual basal area, canopy cover, and leaf litter contribution, we detected no differences in fire behavior between thinned and unthinned plots. In degraded pine-oak mixtures where encroaching species now occupy prominent canopy positions, we recommend more intense thinning treatments in size or scale targeting overstory individuals with known fire-suppressing traits to have a larger impact on canopy openness, fuels, and fire behavior.

Introduction

Open, fire-dependent pine (*Pinus*) and oak (*Quercus*) forests, characterized by frequent, low-intensity fires driven by highly-flammable herbaceous fuels, once dominated the central and eastern U.S. (Hanberry et al., 2020b). Decades of successful fire exclusion, however, contributed to their transition to closed-canopy forests with a dense midstory of shade-tolerant, often fire-sensitive and/or opportunistic species, limited pine and oak recruitment (Abrams, 1992; Shappell and Koontz, 2015), and leaf litter fuels of low flammability (Hanberry et al., 2020a; Kreye et al., 2018; Varner et al., 2021). Today, fire alone is no longer a suitable management tool for open forest restoration on most fire-excluded sites because encroaching individuals are large enough to resist fire damage or capable of prolific resprouting after top-kill by fire (Abrams, 2005; Arthur et al., 2015; Ryan et al., 2013; Signell et al., 2005) and because canopy and fuel conditions associated with encroachment often act to suppress forest flammability through a positive feedback termed “mesophication” (Nowacki and Abrams 2008; Alexander et al. 2021). Consequently, returning desired structure and composition will likely require active management using targeted approaches such as thinning to remove encroaching midstory individuals followed by repeated prescribed fire application to stimulate or maintain herbaceous fuels and sustain low levels of competing hardwood species (Dey and Schweitzer, 2018) .

Most fire-excluded stands with heavy encroachment of off-site species will require, at least initially, thinning to remove undesired species and increase understory light. Thinning is a common stand-tending practice to reduce competition and promote residual tree growth (Nyland, 2016). Midstory thinning, also called low thinning or thinning from below, removes unwanted species, typically by chemical injection or felling with hand tools, thereby reducing residual basal area and canopy cover to increase light and promote growth and recruitment of previously suppressed trees (Bailey et al., 2011; Lhotka and Loewenstein, 2009; Parrott et al., 2012). Thinning from below, including fuel reduction treatments in general, has been heavily studied in mixed-conifer forests in the western U.S. with contradictory results on wildfire intensity (Johnston et al., 2021; Prichard et al., 2010; Raymond and Peterson, 2005; Stephens and Moghaddas, 2005), but this approach has been understudied in eastern mixed forests where no one species represents > 75% dominance by stand basal area (Helms, 1998). Midstory thinning can alter stand composition and structure by removing specific species common at a specific canopy layer (Graham, 1999), but it is currently not known if there is an effect of midstory thinning treatments on the relationship between residual stand composition and fuel, and consequently, the influence of fire behavior in pine-oak forests due to changes in canopy cover and available fuels.

Following initial thinning, frequent, low-intensity fires will be critical for restoring and maintaining pine and oak landscapes, but there remains much debate as to the appropriate timing of prescribed fires. Historically, in the southeastern U.S., fires ignited by lightning were most common in the growing season (May – September), while fires ignited by indigenous peoples typically occurred in the dormant season (October – early April) (Komarek, 1964; Wann et al., 2020). In general, differences among fire intensity across season in the southeastern forests are highly confounded due to variable weather and annual climate, forest type, fuelbed composition, and ignition patterns (Knapp et al. 2009). Notably, seasonal variation influences canopy openness (e.g., decreased in the growing season due to green up) and fuel characteristics (e.g., leaf litter is increasingly decomposed with time since leaf drop, and live understory fuels have high moisture in the growing season), two key predictors of flammability (Sparks et al., 2002). Though modern fire practitioners concentrate prescribed fire use in the dormant season to due to operational issues, safety concerns, and to avoid impacts on nesting birds (Ryan et al., 2013), there is concern that repeated dormant season fire may result in undesirable ecological changes (Knapp et al. 2009). Consequently, there has also been a push to include variable fire season applications to maximize biodiversity, however, a review on the ecological effects of prescribed fire season (Knapp et al. 2009) showed that whether or not a forest burned (i.e., fire frequency) proved more important in species response (growth, biodiversity) than the relatively minor effect caused by burning in different seasons. Nonetheless, dormant season fires are typically less effective at killing encroaching hardwood species (a common objective) than growing season fires (Stanturf et al., 2002; Streng et al., 1993), but growing season fires generally are more difficult to implement due to higher moisture conditions and the spatial variation of green up (Slocum et al., 2003; Wade et al., 2000). Thus, seasonality is an important driver of fire behavior, but which season provides the best fire conditions through differences in weather, canopy conditions, and fuel type and availability that hinder encroaching species while promoting desired pines, oaks, and herbaceous understory remains unknown.

Midstory removal can also impact fuels, and consequently fire behavior, primarily by reducing the density of unwanted and encroaching species that generally have leaf litter and crown characteristics that are hypothesized to suppress forest flammability. When compared to pyrophytic species (pines, upland oaks), encroaching tree species generally have leaf litter that is flat and thin with high surface area to volume ratios (SA:V) that are associated with lower maximum burn temperatures, lower flame lengths, and slower rate of fire spread due to their influences of fuel structure and arrangement (Babl et al., 2020). This is exacerbated by crowns with typically high volume and leaf area that decrease light intensity and create shadier, cooler microclimate conditions at the forest floor (Babl et al., 2020; Ray et al., 2005). Additionally, leaf litter of encroaching species in pine-oak forests tend to decompose faster than upland oaks (Alexander and Arthur, 2014; Babl-Plauche et al., 2022), potentially altering available leaf litter fuel loads (Dickinson et al., 2016). Thinning treatments targeting undesirable species paired with subsequent repeated prescribed fire are generally successful in increasing herbaceous ground cover in fire-excluded stands, a common objective in restoring historically open forests (Hanberry et al., 2020b), and can dramatically increase coarse and fine woody fuels (Vander Yacht et al., 2018). Combined thinning and fire treatments promote greater height and diameter growth to oak and hickory species in the central hardwood region (Holzmueller et al., 2014; Schweitzer et al., 2019), but repeated fires are necessary to reduce high densities of competing encroaching species (commonly *Acer rubrum* (red maple), *Liquidambar styraciflua* (sweetgum), *Liriodendron tulipifera* (tulip poplar)) to promote advanced regeneration of desirable species (Iverson et al., 2008). For these reasons, thinning and repeated prescribed fire treatments are likely essential to perpetuate pine and oak dominance in previously fire-excluded forests, but little is known about the efficacy of targeted midstory thinnings in maintaining or restoring closed-canopy mixed pine-oak forests.

This research aims to understand how, or if, the removal of encroaching species in the midstory of a mixed pine-oak forest can influence fire behavior through changes in canopy cover and fuels. Understanding how targeted thinning treatments combined with prescribed fire seasonality is important because 1) thinning treatments reduce residual basal area, increase light, and can alter stand composition, structure, and fuels (Graham, 1999) with unknown impacts on fire behavior in southeastern mixed forests, 2) growing season fires can reduce hardwood resprouting and promote greater grass and herbaceous species abundance and diversity (common management objectives) than dormant season fires (Knapp et al. 2009), and 3) encroaching species are increasingly common in fire-excluded forests, with consequences for forest flammability. To address this objective, we conducted a manipulative field experiment to quantify how a targeted midstory removal of encroaching species influences changes in forest structure and composition, fuels, and seasonal fire behavior through early dormant season (January), late dormant season (March), and growing season (September) experimental fires at the Mary Olive Thomas Demonstration Forest in Auburn, Alabama, USA. We hypothesized that removing encroaching species from the midstory would alter fire behavior (e.g., increased fireline intensity, fuel consumption, fire spread rate, maximum temperature) through changes in residual canopy openness and fuels. This work could inform the efficacy of targeted midstory treatments for managers whose objectives are to reintroduce fire in previously fire-excluded forests. Application of growing season prescribed fire (May - September) is often difficult in mixed pine-oak forests due to understory shading and higher relative humidity, but targeted midstory treatments could create more favorable understory conditions by directly removing a canopy layer and potentially altering microclimate and/or fuel conditions that could extend burn windows into the growing season. Evidence suggests passive disturbances (wildfire, drought) and climate change may cause a loss of forest resources due to conversion to other forest types (Agee, 2002; Vose and Elliott, 2016) – thus active management using a combination of thinning and prescribed fire could be instrumental in restoring fire-dependent pine-hardwood mixtures.

Methods

Site description and experimental design

Twelve 0.10-ha experimental blocks were established within a 3.4-ha management unit at the Mary Olive Thomas Demonstration Forest (MOTDF) in Auburn, Alabama, USA (32.578 N, 85.423 W) in April 2021. All blocks were considered within a mixed pine-oak stand as the proportion of *Pinus* basal area ranged from 30.6% to 59.1% (Helms, 1998). The mean annual low temperature is 11.7 °C and annual high temperature is 23.3 °C and receives on average 1340 mm precipitation annually (US Climate Data, weather station location 32.609, -85.480; data from 1981 to 2010). Site elevation is approximately 210 m (Google Earth Pro Version 7.3) and classified within the humid subtropical (Cfa) climate type of the Köppen Climate Classification system (Kottek et al., 2006). Soil types are primarily Pacolet sandy loam (49.3% at 1-6% slope; 47.5% at 6-10% slope) and Pacolet and Toccoa sandy loam (3.2%; 0-2% slope) (Natural Resources Conservation Service, Web Soil Survey).

The management unit is a naturally regenerated mixed pine-oak stand that has had no active management since the property was acquired by Alabama Cooperative Extension System and Auburn University School of Forestry and Wildlife Sciences in 1983 (Hunt et al., 2016). A suite of species (n = 18, see Table 3 for full list) occupy all canopy positions, while dominant trees are primarily large diameter pines (*P. taeda, P. echinata*), upland oaks (*Q. alba, Q. falcata*), and other encroaching hardwoods (*Q. nigra, Liquidambar styraciflua*). In a split-plot design (Figure 6), each 0.10-hectare block was randomly divided into one of two treatments: a complete removal of encroaching species in the midstory (< 20 cm DBH) and below (i.e., thinning treatment), and an unmanipulated control with no thinning (i.e, no thin treatment). Additionally, each split-plot treatment included four 4 m x 4 m subplots randomly assigned to an experimental burn season (early dormant season, late dormant season, growing season, control; 24 total burn subplots per season – 12 in each treatment).

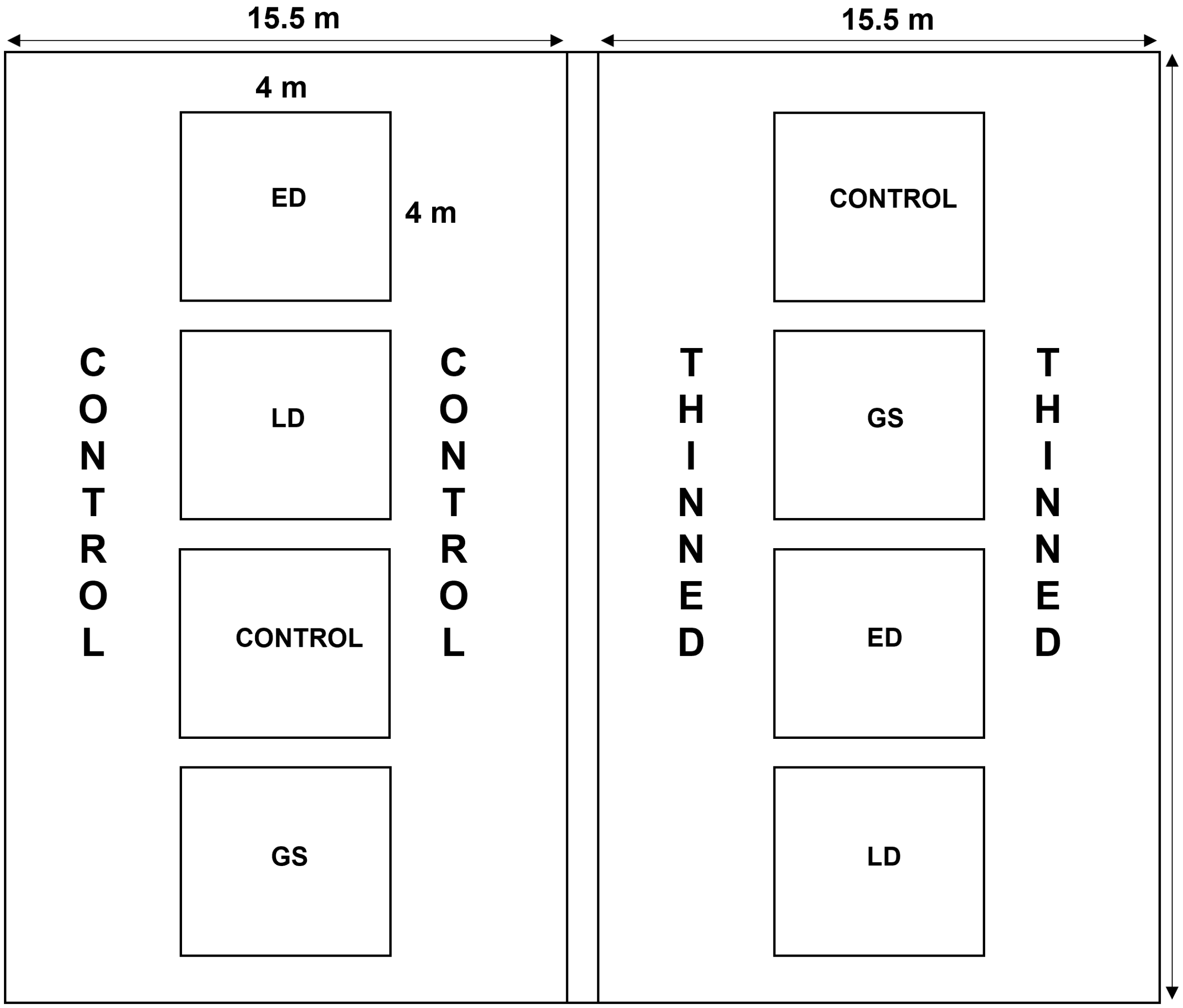

Figure 6. A sample schematic of one of twelve 0.1-ha experimental blocks. Each 0.1-ha block was randomly split between a control treatment (left) and targeted midstory thinning treatment (right). Each split-plot also included four randomly assigned 4 m by 4 m subplots that were experimentally burned in different seasons: early dormant season (ED; January 27), late dormant season (LD; April 2), growing season (GS; September 29), and a control.

Table 3. All species (2,334 total individuals, 18 species) surveyed within manipulation blocks are expressed in trees per hectacre (TPHA). Shade and fire tolerances are classified as intolerant (I), tolerant (T), and very tolerant (VT). Juvenile (J) and mature (M) life stages are noted if they are different. Species marked "yes" were removed in thinning treatments if DBH < 20 cm. Each species is classified along a gradient of fire-promoting or fire-suppressing (pyrophyte species, intermediate/unknown species, encroaching species) given their tolerances and leaf litter and/or crown traits from published data, or lack thereof (sources referenced below table).

Scientific name	Common name	Average TPHA	Shade tolerance[1,2]	Fire tolerance[1,2]	Removed?	Classification
Acer rubrum	red maple	74	T	I	Yes	Encroaching[4,5,7,9,12]
Carya tomentosa	hickory	40	I - T	I (J), T (M)	Yes	Intermediate[10,12]
Cornus florida	flowering dogwood	10	VT	I	Yes	Intermediate[7]
Fagus grandifolia	American beech	40	VT	I	Yes	Intermediate [7,8]
Ilex opaca	American holly	2	VT	I	Yes	Intermediate[6]
Juniperus virginiana	eastern red cedar	27	I	I	Yes	Intermediate/Unknown
Liquidambar styraciflua	sweetgum	551	I	I (J), T (J)	Yes	Encroaching [6,7,10,12]
Liriodendron tulipifera	tulip poplar	20	T	I	Yes	Intermediate[6,7,12]
Nyssa sylvatica	black tupelo	96	T	I	Yes	Encroaching[12]
Oxydendrum arboreum	sourwood	52	T	?	Yes	Intermediate[12]
Pinus echinata	shortleaf pine	89	I	I (J), T (M)	No	Pyrophyte[12]
Pinus taeda	loblolly pine	252	I - T	I (J), T (M)	No	Pyrophyte[11]
Prunus serotina	black cherry	64	I – T	I	Yes	Intermediate[12]
Quercus alba	white oak	89	I – T	I (J), T (M)	No	Pyrophyte[9,12]
Quercus falcata	southern red oak	22	I - T	I (J), T (M)	No	Pyrophyte[12]
Quercus nigra	water oak	232	I - T	I	Yes	Encroaching[3]
Ulmus alata	winged elm	7	T	I	Yes	Encroaching [7,10]
Vaccinium arboreum	farkleberry	250	T	I	Yes	Intermediate/Unknown

Sources referenced above in superscripts: (Burns et al. 1990a[1]; Burns et al. 1990b[2]; Kane et al. 2008[3]; Alexander and Arthur 2010[4]; Alexander and Arthur 2014[5]; Mola et al. 2014[6]; Kreye et al. 2018[7]; Babl et al. 2020[8]; Kane et al. 2021[9]; McDaniel et al. 2021[10]; Varner et al. 2015[11]; Varner et al. 2021[12])

Pre-thinning measurements

Each block was sampled to assess initial stand conditions prior to manipulation in May 2021. All living trees within each block were identified to species and their DBH recorded to calculate basal area. Overstory trees (> 20 cm DBH) on the edge were considered within a block if their crowns extended into the block. Canopy cover was estimated by averaging eight readings on a spherical densiometer (Forestry Suppliers, Inc., Jackson, MS, USA), two taken within each burn subplot facing 0° N during peak growing season to examine changes in canopy cover pre- and post-thinning treatment. To assess compositional changes in the leaf litter fuelbed resulting from thinning, leaf litter fuels were harvested adjacent to each burn plot at the 315° NW corner within 30-cm x 30-cm quadrats. In the lab, litter was sorted into one of three species groups: 1) pines (*P. taeda, P. echinata*), 2) upland oaks (*Q. alba*, *Q. falcata, Q. rubra*), and 3) "other" (primarily encroaching species such as *Liquidambar styraciflua*, *Q. nigra*, see Table 3 for full list). Each collection was dried to a constant mass at 60 ˚C for 72 hours to calculate fuel load of individual groups. Within the burn subplots, we recorded live herbaceous and woody plant heights and visually estimated their percent cover, and measured litter and duff depths at the center of each burn subplot. Fuel loads of herbaceous, shrub, litter, and duff were calculated using biomass equations and standard bulk densities (Lutes and Keane, 2006) to compare to post-treatment fuel loads. Woody debris was quantified by running two 10.6-m standard planar transects in each split-plot, recording intersections of fine (1-hr, 10-hr, and 100-hr fuels) and diameters and decay class of coarse (1000-hr fuels) woody debris to calculate fuel loads using equations and constants from (Brown, 1974). Total fuel load (Mg ha^{-1}) was calculated by summing all sources of fuel (herbaceous, shrub, litter, duff, coarse woody debris, and fine woody debris).

Thinning manipulations

In July 2021, a targeted removal of midstory encroaching species was applied at each split-plot randomly assigned to a thinning treatment. All species recorded (n = 18) were classified into one of three categories: “pyrophyte”, “intermediate/unknown”, or “encroaching” based on published literature, or lack thereof, that describes structural and/or functional traits that influence flammability (Table 3). Species in the “pyrophyte” classification are upland oak and pine species known to be historical keystone drivers of forest flammability due to their fire-promoting characteristics. Species in the “intermediate/unknown” classification lack definitive published research characterizing their species traits as either fire-promoting (i.e., pyrophytic) or fire-suppressing (i.e., mesophytic). Lastly, species in the “encroaching” classification are either known or hypothesized to suppress flammability due to their specific leaf litter and/or crown traits based on published data. The thinning treatment targeted all tree species considered to be non-pyrophytic and < 20 cm DBH.

All removed stems were mechanically felled by chainsaw, and debris discarded from the block. Felled stems and limbs were carefully carried (not dragged) to minimize disturbance of surface fuels. Stumps were chemically treated with imazapyr (Arsensal Applicators Concentrate, BASF Corporation, Research Triangle Park, NC, USA) at suggested label rates of 177 ml per 3.8 liters of water for cut-stump application to reduce resprouting. The thinning treatment resulted in a natural gradient of residual basal area by overstory encroaching species (primarily water oak and sweetgum) separated into three groups: 1) low: mean basal area 5.3 m^2 ha^{-1}, 2) medium: mean basal area 7.4 m^2 ha^{-1}, 3) high: mean basal area 11.9 m^2 ha^{-1}). These groups examined a natural range of overstory by encroaching species with or without the presence of a midstory of these species, replicated by four blocks each.

Post-thinning monitoring

Upon completion of thinning treatments, each block was monitored until September 2022 to observe the effects of thin and no thin treatments on fuels and canopy cover. Leaf litter fuel composition was assessed by harvesting leaf litter fuels in 30-cm x 30-cm quadrats and sorted as described above. Four harvests (June 24, 2021, January 17, 2022, April 12, 2022, and June 24, 2022) were planned around experimental fires to directly associate the fuel composition at the time to fire behavior, as well as changes in fuel load overtime. Canopy cover, herbaceous and woody plant communities, litter, duff, and woody fuels were surveyed in thin treatments as described above in the growing season of 2022 to compare to pre-treatment data.

Experimental burns

Within each 4-m x 4-m subplot, we conducted experimental burns at three times: 1) early dormant season burns (January 27, 2022) that consumed relatively newly dropped fine fuels, 2) late dormant season burns (April 2, 2022) that consumed fine fuels that had sat on the forest floor for 3-4 months after abscission and begun decomposition, and 3) growing season burns (September 29, 2022) that captured any remaining fuels along with the effect of canopy closure. Each experimental burn was conducted under conditions that coincide with fire practitioners' most common objectives in this forest type and region: reducing fuel loads, maximizing hardwood control, and minimizing crown scorch/morality of valuable or desirable species (Dey and Schweitzer, 2018).

Prior to the burning of each experimental subplot, fire weather (ambient temperature (°C), relative humidity (%), wind speed (m/s), wind direction was recorded with a Kestrel 5500 Fire Weather Meter Pro (Kestrel Instruments, Neilsen-Kellerman Company, Boothwyn, PA, USA) (Table 4). Nine pyrometers marked with six Tempilaq (Tempil, South Plainfield, NJ, USA) temperature-sensitive paints ranging from 79 °C to 510° C were arranged in a 3 x 3 grid in each burn subplot to calculate mean maximum temperatures. Though this method only estimates a maximum temperature reached by the pyrometer rather than the actual fire temperature, they are reliable for estimating mean maximum temperatures when compared to thermocouples (Iverson et al., 2004), and are appropriate for making relative comparisons among treatments when more precise methods are unavailable or prohibitively expensive (Nation et al., 2021; Wally et al., 2006).

When ready for ignition, a stopwatch was started, and each fire was ignited with a strip head fire using a drip torch with a fuel mix of 3:2 diesel to gasoline. The fire progressed until the flame self-extinguished or until all available fuel was consumed. If the flame self-extinguished upon consuming the drip torch fuel, fires were not relit. During each burn, we visually estimated flame height (cm) using a nearby marked meter stick for reference. Rate of spread was calculated by noting distinct time points: from ignition point to burning half of the plot (2 m horizontal distance from ignition), and from the halfway point to the end of the plot (4 m horizontal distance from ignition). Upon flame expiration, total duration (from ignition to complete flame expiration) was recorded, and we visually estimated the percentage of fuel consumption by noting the area of consumed fine fuels exposing mineral soil or leaving only ash. Pyrometers in each burn subplot were collected, read in the lab, and averaged to determine mean pyrometer-derived maximum temperature (°C). If the flaming front did not reach a pyrometer, or the lowest threshold of paint (79 °C) was not triggered, the ambient temperature at the time of burning that subplot was used. As in Varner et al. (2021), fireline intensity (kW m^{-2}) was calculated as a function of flame height using a manipulation of Byram's (1959) equation for fire intensity; metric unit conversions by Wagner (1978).

Table 4. Mean weather parameters (air temperature ((°C), relative humidity (%), wind speed (m s^{-1}), wind direction, and days and amount of the last precipitation event) for early dormant season, late dormant season, and growing season fires at the Mary Olive Thomas Demonstration Forest (Auburn, AL, USA) in 2022. All parameters were recorded with a Kestrel 5500 Fire Weather Meter Pro (Kestrel Instruments, Neilsen-Kellerman Company, Boothwyn, PA, USA) prior to ignition of each burn plot.

	Early Dormant Season	Late Dormant Season	Growing Season
Date	January 27	April 2	September 29
Air temperature (°C)	14.7	24.7	24.1
Relative humidity (%)	32.9	35.4	33.7
Wind speed (m s^{-1})	0.55	0.65	0.42
Wind direction	NW	N	N
Last precipitation event (days since, mm)	25, 18.8	11, 8.1	17, 6.6

Statistical Analyses

Using a mixed effects model, we tested for differences in stand characteristics (basal area, canopy cover) and fuel loads (herbaceous, shrub, litter, duff, coarse woody debris, fine woody debris, and total) between the fixed factors of treatment and residual encroaching overstory groups, and any interactions using the “nlme” package in R (Pinheiro and Bates, 2022). We used a hierarchical structure including block, encroaching residual overstory, thinning treatment, and burn season in a nested random effect to account for variation within and among blocks. Leaf litter harvests from June 2021 and June 2022 were directly compared using an analysis of variance (ANOVA) to test for differences in sorted litter groups due to the treatment, while all leaf litter harvests were compared to assess changes in fuel load over time. To assess fire behavior and intensity, we report on four parameters based on our data collection at the time of experimental burns: fireline intensity (kW m^{-2}), average maximum temperature (C), fuel consumption (%), and fire rate of spread (m s^{-1}). We also used a mixed effects model with the same random effect nesting structure to test the differences in each fire parameter (dependent variables) vs. treatment, residual encroaching overstory, and burn season (fixed factors) and their interactions. All variables were tested for homogeneity (Levene’s Test) and normality (Shapiro-Wilk Test) prior to analyses. Variables in violations of assumptions were transformed with logarithmic functions. Post-hoc Tukey’s HSD tests were used to confirm any significant results or interactions at $\alpha = 0.05$. If no interactions were significant ($p < 0.05$), we presented differences between treatment only. Using linear regression, we also modeled each fire behavior parameter as a function of percent pine leaf litter by mass in the fuelbed across treatments and burn seasons. Each leaf litter harvest (January 17, April 12, June 24) was directly associated with each respective burn timing (January 27, April 2, September 29) to best approximate fuelbed composition at the time of burn (a burn was planned for mid-July, but was cancelled due to poor weather conditions). All statistical analyses were conducted using R-4.2.1 (R Core Team, 2018).

Results

Initial stand survey and thinning treatment results

Within all blocks, we recorded 2,334 individuals across 18 observed species (Table 3). The most common pyrophytes were loblolly pine, shortleaf pine, and white oak, while the most common encroaching species were sweetgum and water oak. Pine and upland oaks were dominant at larger diameters (> 30 cm DBH), but encroaching species were 4.8 times as common at low diameters (< 20 cm DBH) and 2.7 times as dense (trees ha^{-1}) compared to pine and upland oaks (Figure 7). Before thinning, the mean (± SE) standing basal area of all blocks was 32.5 ± 1.3 m^2 ha^{-1}, and all split-plots had similar canopy cover at 97.9% ± 0.5 ($p = 0.87$). Across all split-plots assigned to a thinning treatment, we removed a total of 1,294 encroaching individuals < 20 cm DBH, resulting in an average reduction in block basal area by 6.74 ± 0.37 m^2 ha^{-1}, and canopy cover was significantly reduced by 9.1% ± 2.9 when compared to the control ($p < 0.001$). Thinning also resulted in a residual basal area gradient of overstory encroaching species at three levels: low encroaching overstory = 5.3 m^2 ha^{-1}, medium encroaching overstory = 7.4 m^2 ha^{-1}, and high encroaching overstory = 11.9 m^2 ha^{-1}. We found no significant differences in canopy cover across the gradient of encroaching overstory after the thinning treatment ($p = 0.76$).

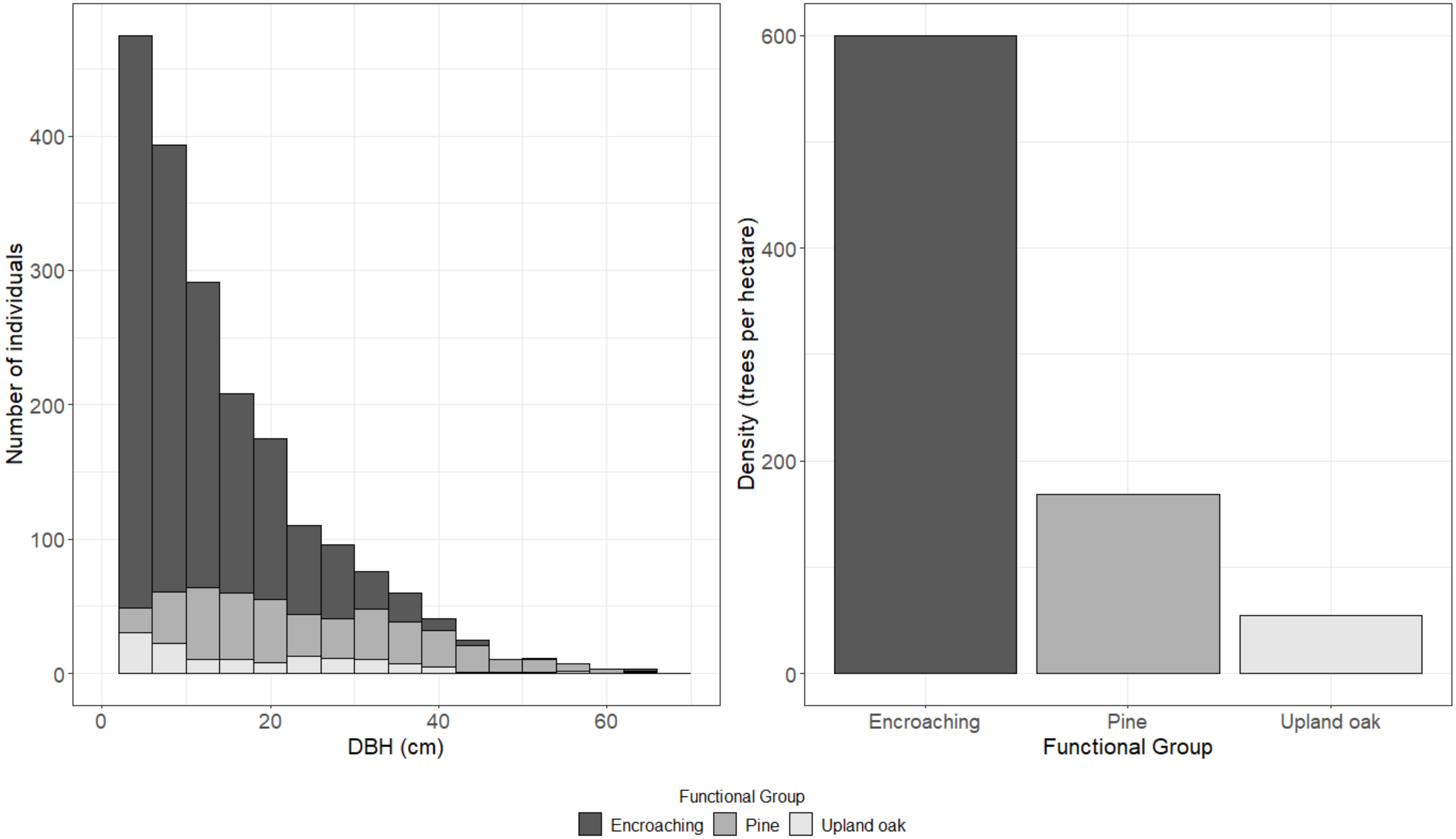

Figure 7. Stacked bar chart displaying the cumulative number of individuals (n) observed in all blocks across the distribution encroaching, pine, and upland oak quadratic mean diameter (cm; left), and bar graph of mean tree density (trees ha^{-1}; right) for encroaching, pine, and upland oak species within the management unit.

Thinning impacts on fuel loads

Initial total fuel loads were similar between control (38.2 ± 4.1 Mg ha^{-1}) and thinning (37.3 ± 3.0 Mg ha^{-1}) treatments, respectively ($p = 0.86$) (Figure 8). Compared to pre-thinning, thinning in treatment split-plots significantly reduced total fuel loads to 33.7 ± 2.3 Mg ha^{-1} ($p = 0.012$). Thinning reduced herbaceous fuel load by 1.5 ± 2.6 Mg ha^{-1} ($p = 0.062$), reduced shrub fuel load by 0.27 ± 0.1 Mg ha^{-1} ($p = 0.024$), reduced CWD by 3.2 ± 4.3 Mg ha^{-1} ($p = 0.66$), reduced FWD by 0.9 ± 0.3 Mg ha^{-1} ($p < 0.01$), increased leaf litter fuel load by 1.3 ± 0.8 Mg ha^{-1} ($p = 0.12$), and had no change on duff fuel load ($p = 0.99$) when compared to the control. We detected no significant differences in fuel loads among encroaching species overstory categories, nor its interaction with thinning ($p > 0.05$).

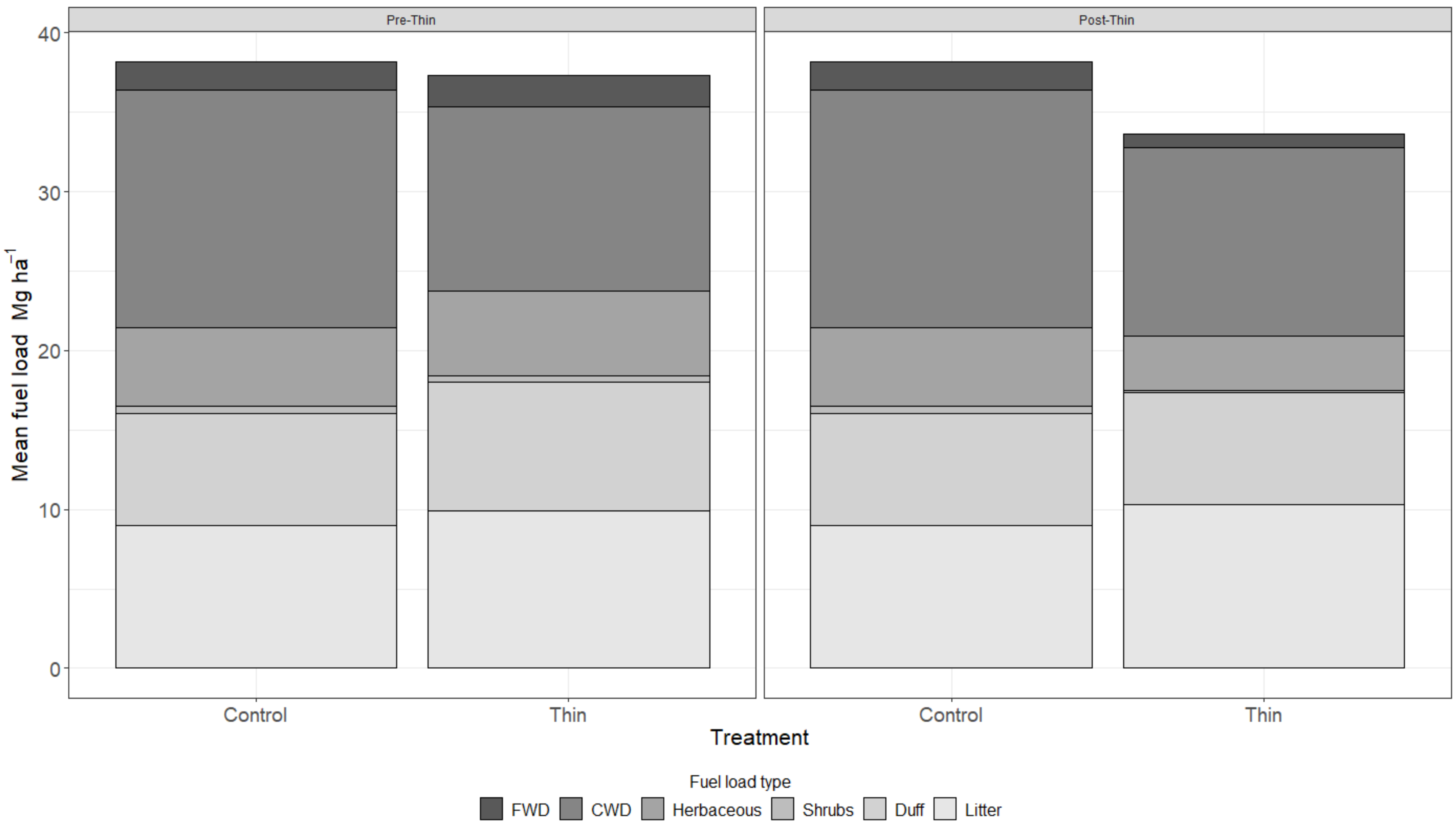

Figure 8. Stacked bar plots depicting mean fine woody debris (FWD), and coarse woody debris (CWD), herbaceous, shrub, duff, and leaf litter fuel loads (Mg ha^{-1}) at pre-thin (left) and post-thin (right) within control (no thinning) and treatment (thinning) blocks. Pre-thin fuel loads were recorded on 6/24/2021, and post-thin fuel loads were recorded on 6/24/2022.

Thinning impacts on leaf litter composition

Before treatments were applied, leaf litter by mass (%) of pine, upland oak, and encroaching species leaf litter groups were similar between control and treatment plots ($p > 0.05$) (Figure 9). Among encroaching species overstory groups, upland oak leaf litter by mass in the low group was 26.9% ($p = 0.03$) and 31.8% ($p = 0.01$) greater when compared to medium and high categories, respectively. Thinning significantly increased pine leaf litter group by 10.9% ($p = 0.019$), while significantly reducing the encroaching species leaf litter group by 11.4% ($p = 0.004$) when comparing pre-treatment harvests in June 2021 to post-treat harvests in June 2022. We observed no significant interaction between thinning treatment and the residual encroaching overstory groups ($p > 0.05$).

Thinning reduced the leaf litter of encroaching species immediately following leaf off and continued to decline throughout subsequent leaf litter harvests (Figure 10). From leaf litter harvests in 6/2021 (pre-treatment) to 1/2022 (post-treatment), encroaching species leaf litter by mass increased by 6.2% in control subplots ($p = 0.058$) but decreased by 5.04% in thinning subplots ($p = 0.28$). Consequently, leaf litter by mass of pines decreased by 10.5% ($p = 0.0001$) and upland oaks increased by 4.2% ($p = 0.41$) in control subplots, while leaf litter by mass of pines increased by 2.01% ($p = 0.86$) and upland oaks by 3.03% ($p = 0.54$) in thinning subplots. In general, we observed that leaf litter by mass in harvests after 1/17/2022 increased in pines, had no change in upland oaks, and decreased in encroaching species regardless of treatment – likely due differences in decomposition rates among species.

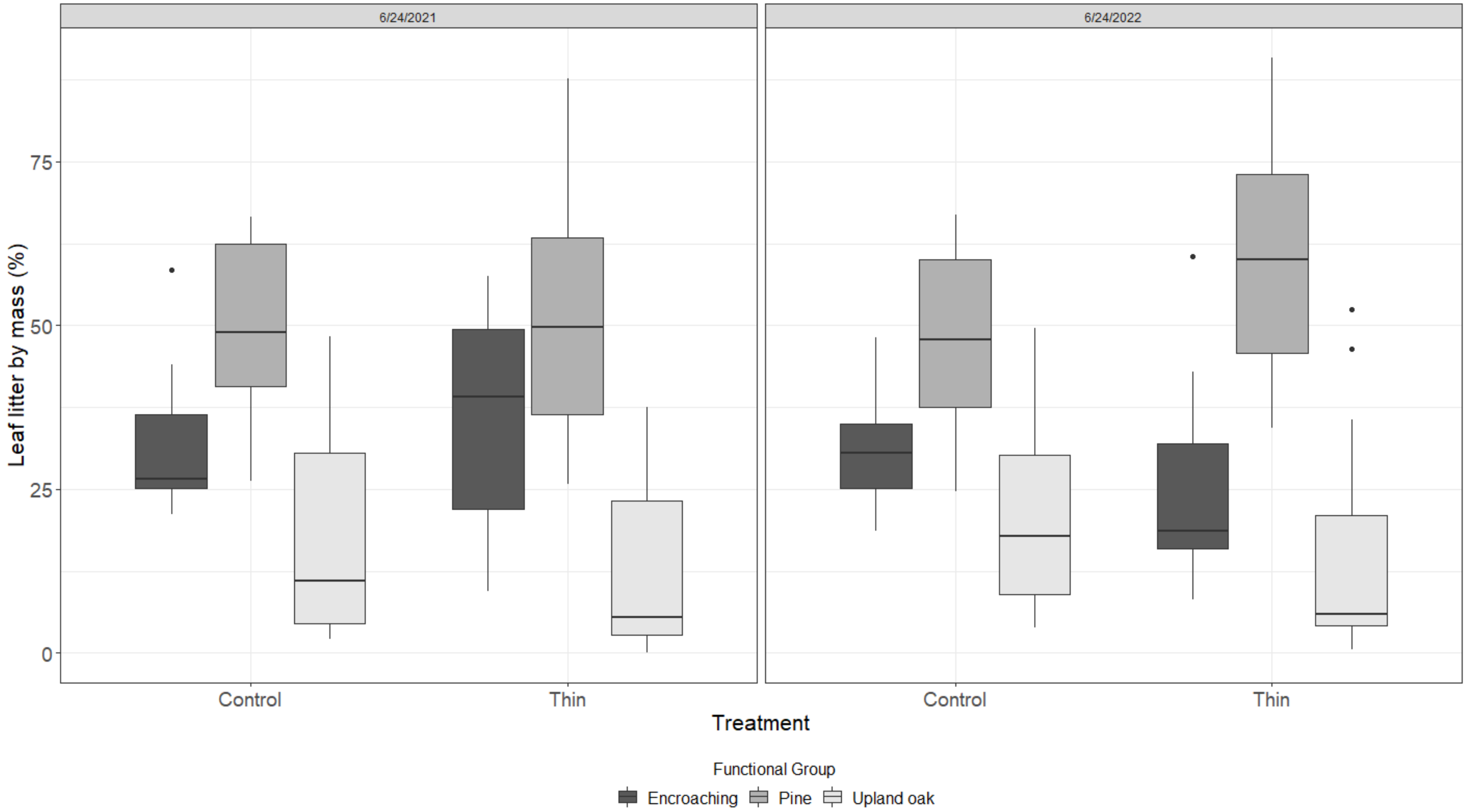

Figure 9. Box and whisker plots showing change in leaf litter by mass (%) among species groups (encroaching, pine, and upland oak) between control (unthinned) and thin treatments. Leaf litter was harvested on 6/24/2021 before thinning (left) and on 6/24/2022 after thinning (right) and later sorted in the lab. Points are outliers.

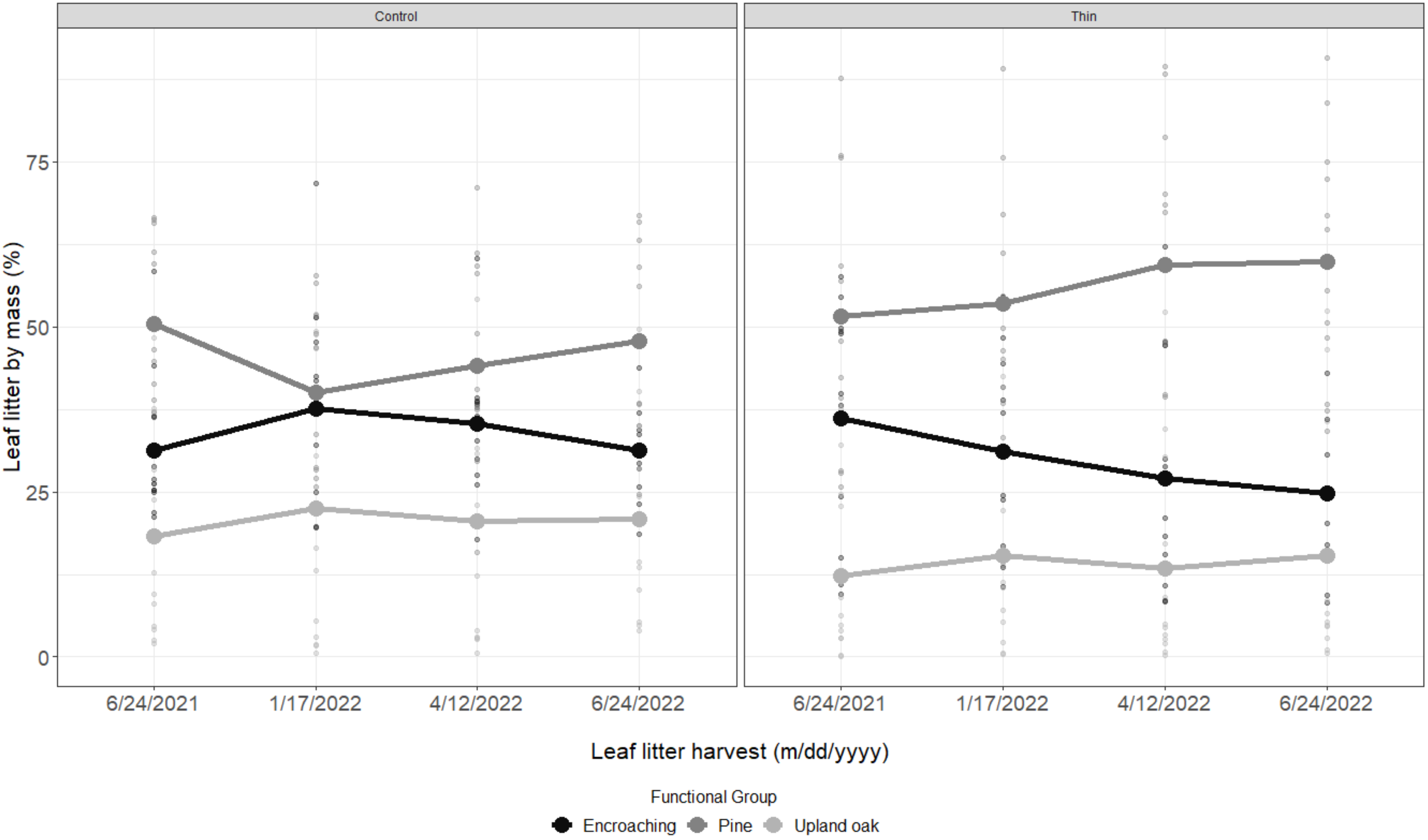

Figure 10. A time series line chart depicting the change in leaf litter by mass (%) in encroaching, pine, or upland oak species groups based on sorted leaf litter harvests from 6/24/2021, 1/17/2022, 4/12/2022, and 6/24/2022 in control (left) and thin (right) treatment subplots. The thinning treatment was applied in July 2021. Larger points depict the mean while smaller background points are individual values.

Seasonal experimental burns

Fires in the dormant season had greater fireline intensities, faster fire spread rates, higher pyrometer-derived average maximum temperatures, and consumed more fuel than fires in the growing season (Figure 11). Most notably, mean growing season fuel consumption was 32.4%, while early dormant season and late dormant season fuel consumption was 88.0% and 87.7%, respectively. Early dormant and late dormant season fires were similar in all fire parameters ($p > 0.05$) except for average maximum temperature. Recorded temperatures in late dormant season fires were 73.4 °C hotter than in the early dormant season ($p = 0.02$) – likely due to the 10 °C higher ambient temperature in April compared to late January. Though not significant within the growing season, fuel consumption in the thinning treatment was 6.4% greater than control plots ($p = 0.32$). Despite differences in growing season canopy cover between control and treatment plots, fires performed similarly regardless of thinning. Additionally, thinning, residual encroaching overstory, and their interaction were not significant factors in any of the fire parameters in any season of burn ($p > 0.05$).

In general, pine leaf litter had a slight positive relationship ($r^2 = 0.15$), upland oak had no relationship ($r^2 = 0.01$), and "other" leaf litter had a slight negative relationship ($r^2 = 0.10$) with fire parameters across all seasons (Figure 12). Across all seasons, each 10% increase in pine leaf litter by mass resulted in 9.6 kW m^{-2} greater fireline intensities, 1.1 m s^{-1} faster fire spread rates, 62% greater fuel consumption, and 30.9 °C hotter maximum temperatures (all $p < 0.05$). In general, plots with less than 26% pine leaf litter by mass burned poorly (< 15% fuel consumption) regardless of thinning treatment, residual overstory, or burn season.

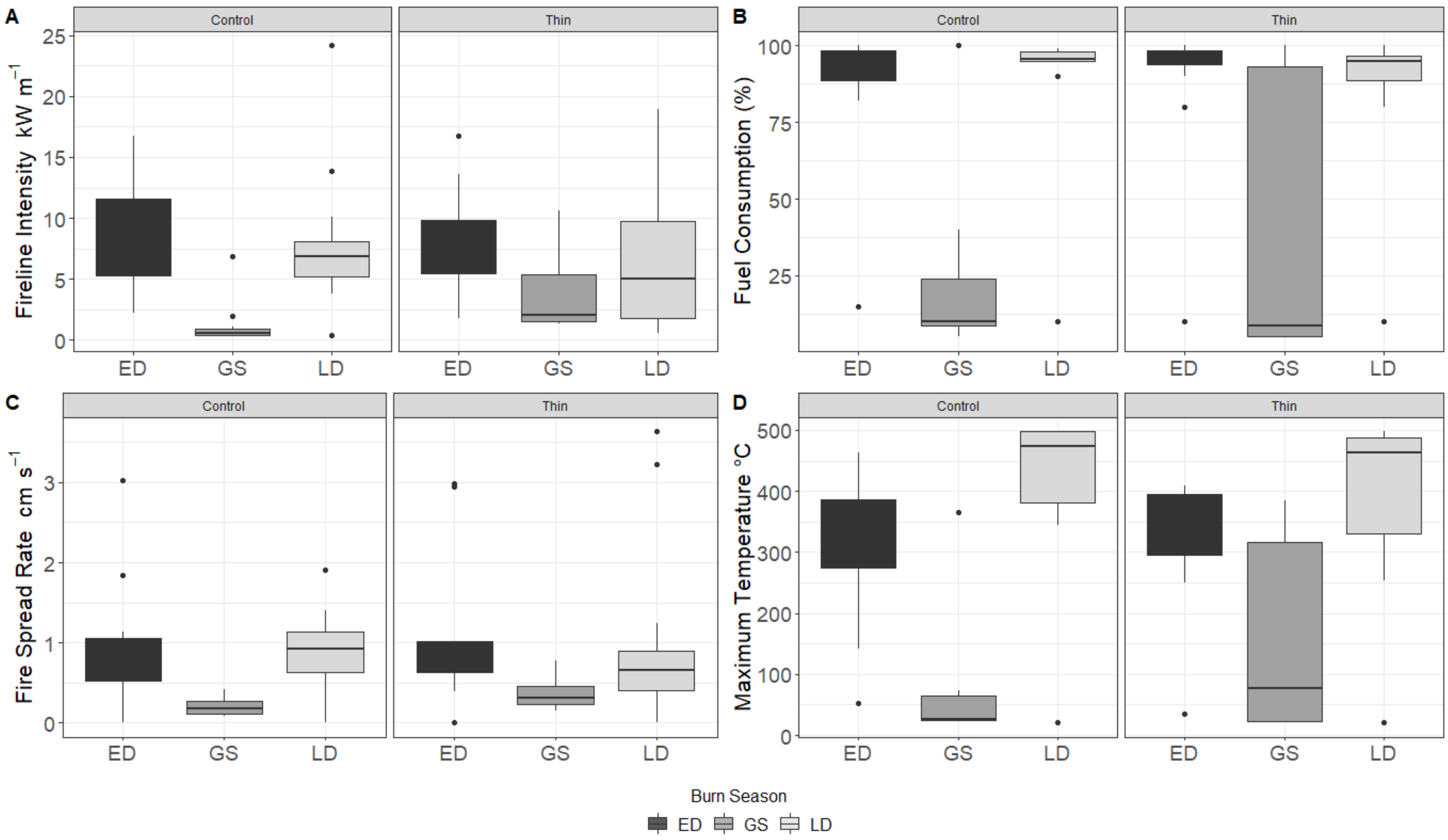

Figure 11. Box and whisker plots showing differences between control and thin plots in four fire parameters, (A) fireline intensity (kW m^{-1}), (B) fuel consumption (%), (C) fire spread rate (cm s^{-1}), and (D) average pyrometer-derived maximum temperature (°C) in three burn seasons: early dormant season (ED; 1/27/2022), late dormant season (LD; 4/02/2022), and growing season (GS; 9/29/2022) and between control and thin subplots. Points are outliers.

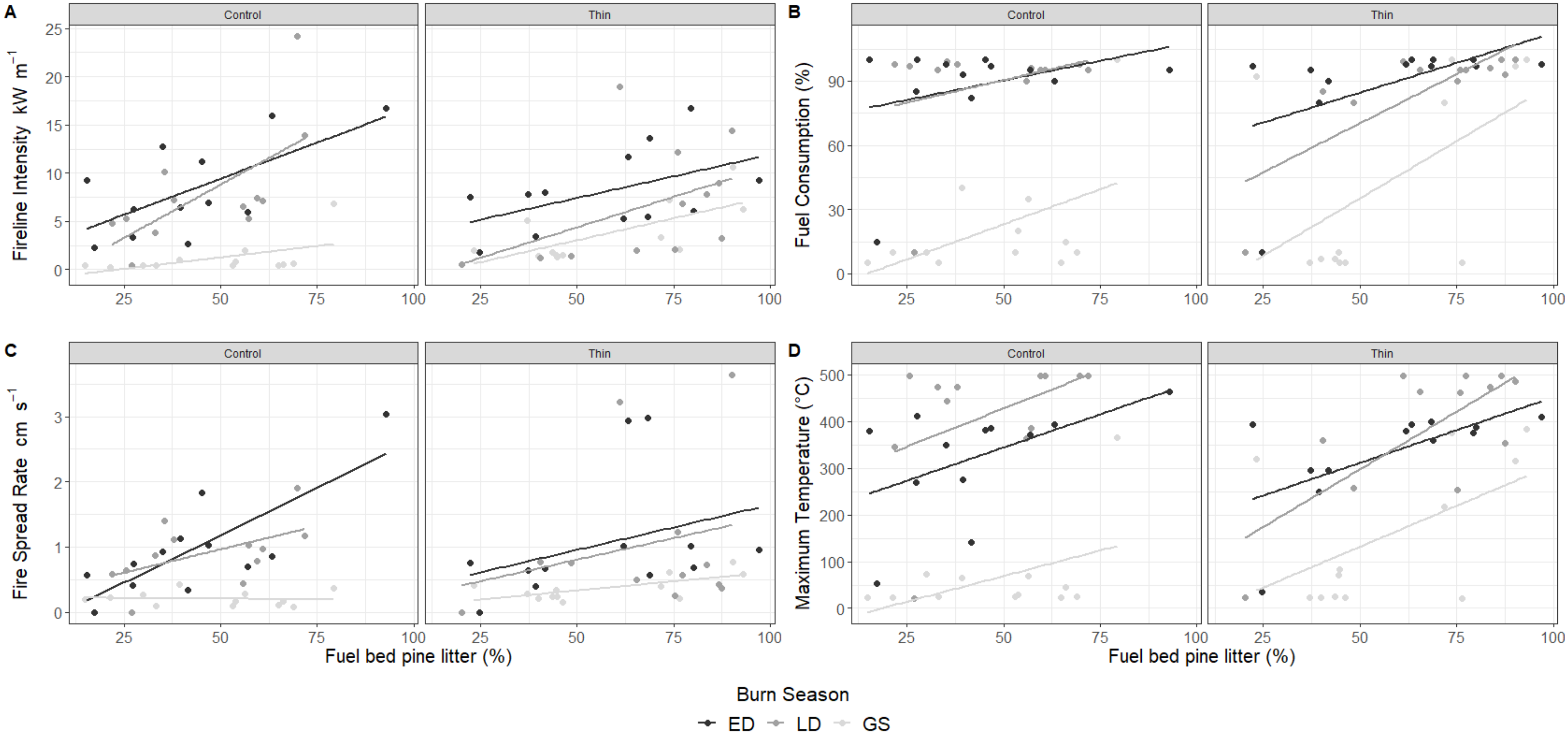

Figure 12. Linear regressions showing the relationship between four fire parameters – (A) fireline intensity (kW m^{-1}), (B) fuel consumption (%), (C) fire spread rate (cm s^{-1}), and (D) average pyrometer-derived maximum temperature (°C) as a function of pine leaf litter fuel by mass (%) at three burn seasons: early dormant season (ED; 1/27/2022), late dormant season (LD; 4/02/2022), and growing season (GS; 9/29/2022) and between control and thin subplots.

Discussion

Despite a reduction in residual basal area and canopy cover with midstory thinning, we observed no differences in total fuel loads or fire behavior between thinned and unthinned plots in our unmanaged, mixed forest. This is likely because encroaching species occupied dominant overstory positions in addition to creating a dense midstory such that their influence on stand and fuel characteristics persisted even in thinned stands. Encroaching species are typically shade-tolerant species with high crown volume (Canham et al., 1994) that increases their competitiveness with largely shade-intolerant pines and upland oaks, consequently contributing to a recruitment bottleneck (Abrams, 1992; Magee et al., 2022) and shifts in forest structure and composition with negative consequences for forest flammability (Hanberry, 2019; Kane et al., 2021). While still a mixed stand by definition, our mixed pine-oak stand in this study no longer functions like a historical pine-oak mixture due to changes in structure and composition. Thus, allowing encroaching species to reach the overstory through lack of management has the potential to create long-term ecosystem-level consequences that cannot be easily remedied through midstory thinning.

The lack of midstory thinning effect on total fuel loads may be because midstory individuals do not significantly contribute to total fuel loads. Pre-thinning, total fuel loads were generally higher when compared to a burned mixed pine-oak forest in Arkansas (28.76 ± 4.84 Mg ha^{-1}) (McDaniel et al., 2016), likely due to the lack of management within our stand, but fuel loads were similar to an unmanaged, mixed-mesophytic forest in Ohio (Graham et al., 2006). Graham et al. (2006), who also performed a manipulative thinning from below and prescribed fire treatment to assess fuel loads, concluded that silvicultural treatments of this intensity have minor impact on fine-fuel loading, consistent with our results here. However, our results may not be representative of the long-term effects of a midstory thinning due to potential legacy effects of the natural fuelbed before treatment, CWD and FWD were removed from thinned plots (this would not occur in an operational thinning) which could have influenced fire behavior, and the experimental burns occurred within one year of thinning treatment. It is possible that trends between treatments may be more pronounced in the long-term following repeated prescribed fire, especially if performed at the stand level. Nonetheless, the removal of larger diameter trees is likely needed to increase understory light and promote changes in fuel loads and types (e.g., more herbaceous fuels).

Midstory thinning increased pine and upland oak leaf litter contribution to the fuelbed and decreased contribution from leaf litter of encroaching species relative to total contributions, with potential impacts on fuelbed dynamics through species-specific differences in decomposition rates. Notably, plots with low levels of residual overstory basal area of encroaching species had significantly more upland oak leaf litter than plots with medium and high levels. Leaf litter of encroaching species generally decomposes more rapidly than pine and upland oak leaf litter (Alexander and Arthur, 2014; Babl-Plauche et al., 2022), and as relatively high basal area of encroaching species will likely not only contribute more leaf litter fuels, but also create shadier and moister microclimate conditions that influence decomposition rates. Though we not did directly measure decomposition rates here, our results indicate that thinning decreased the initial amount of leaf litter contributed by encroaching species during leaf fall (1/17/2022 harvest), and leaf litter contribution of encroaching species declined steadily in subsequent harvests in both treatments. Because the abundance of encroaching species is predicted to expand (Hanberry, 2013b) as fuelbeds become increasingly mixed, increased decomposition rates due to greater abundance and diversity of microbial communities within fuel mixtures (Chapman et al., 2013; Kaneko and Salamanca, 1999; Li et al., 2009) could ultimately lead to a reduction in leaf litter fuel loads and increase fuelbed bulk density with consequences for flammability (Dickinson et al., 2016). Furthermore, thinning could impact decomposition rates through background changes in microclimate (Brosofske et al., 1997; Li et al., 2009), and because thinning typically increases residual tree growth, the balance between productivity and decomposition is an essential component to fuelbed flammability in eastern forests (Graham et al., 2006).

Though midstory thinning increased the leaf litter contribution of pyrophytic species relative to encroaching species, we detected no differences in any fire behavior parameter among thinning treatments across the residual overstory gradient in both dormant season fires. Both dormant season fires performed similarly likely due to the reduced canopy cover after leaf-off, increasing light incidence that led to warmer microclimate conditions and drier fuels at the forest floor – conditions that are favorable for flammability and fire behavior (Kreye et al., 2020), as well as ease of operations (Knapp et al. 2009). Growing season fires were significantly less intense across all parameters and consumed less fuel, and midstory thinning had no effect on stand structure or leaf litter contributions to the fuelbed that significantly increased fire behavior. Conversely to the dormant season, the dense, full crowns of overstory trees during the growing season act as a physical barrier to wind, a significant predictor of fire spread and intensity (Hollingsworth et al., 2012), and likely decreased understory light, creating more moist microclimate conditions with high moisture fuels (Babl et al., 2020; Ray et al., 2005). Additionally, leaf litter of encroaching species pool under their own crowns with faster decomposition rates (Babl-Plauche et al., 2022), and generally have crown and bark traits that influence throughfall (precipitation that reaches the forest floor by falling through canopy gaps or leaf drip) and stemflow (precipitation that funnels down along a tree's limbs and bole), contributing to potentially creating zones of influence that control fuel moisture surrounding a tree's bole and act as a natural wet line to protect trees from fire (Alexander and Arthur, 2010; Babl et al., 2020; Babl-Plauche et al., 2022; Siegert et al., 2020). Though we did not control for spatial variation of individual trees, stands with high concentrations of encroaching species could severely influence local fire continuity, contributing to the survival of fire-sensitive species that typically would have been top-killed by fire at small diameters (< 10 cm DBH; (Dey and Schweitzer, 2018)). In 17 experimental plots that burned less than 15% regardless of thinning treatment, encroaching overstory group, or season, encroaching species (primarily water oak) contributed 38.8% ± 5.0 (range 5.5 – 70.3) to the leaf litter fuelbed, consistent with other results predicting dampening of fire behavior when encroaching species contribution ranges from 33% to 66% (Kreye et al., 2018; McDaniel et al., 2021). As encroaching tree species replace mature pyrophytic pines and oaks due to age or passive disturbance related mortality, drastic ecosystem level consequences including decreases in forest flammability, altered biogeochemical cycles, and loss of wildlife species are predicted (Alexander et al., 2021).

Conclusion

This unmanaged, mixed pine-oak stand demonstrates that the efficacy of midstory treatments was marginal at best in influencing canopy cover, fuels, and seasonal fire behavior. In general, forest stand improvement treatments can be beneficial to stimulate understory vegetation by creating canopy gaps (Turner et al., 2020), but midstory treatments are unlikely to create such conditions. It is likely that the high abundance of encroaching species in mid- and overstory size classes due to altered disturbance regimes contribute to canopy closure (> 90% canopy cover) and changes in available fuels, making this stand functionally beyond a traditional pine-oak mixture through due to changes in stand structure and composition. Future studies could explore larger scale (size) or more intense (method) thinning approaches that could potentially “reverse” the mesophication process by eliminating species with fire-suppressing leaf litter and crown traits. Repeated dormant season fires are the norm for prescribed fire application in the southeastern U.S., but generally only reduce the size, not the number, of hardwood stems (i.e, sweetgum, red maple) due to their excellent capabilities to resprout from root-suckering (Stanturf et al., 2002). Growing season fire in mixed pine-oak stands underdoing severe encroachment (as in this stand) will require more intensive thinning and/or herbicide approaches plus repeated prescribed fire to remove larger diameter overstory trees that change fuel loads and composition, alleviate surface fuel moisture and microclimate conditions created by understory shading, promoting herbaceous fuels, and top-killing encroaching species resprouts. Though heterogeneity in fire-prone ecosystems at the landscape level is important for burn patch complexity (Kerby et al., 2007) and wildlife habitat (Bowman and Harris, 1980; Chia et al., 2015), increasing dominance of encroaching species hinders restoration objectives in unmanaged and fire-suppressed southeastern mixed forests.

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