

Midstory removal of encroaching species has minimal impacts on fuels and fire behavior regardless of burn season in a degraded pine-oak mixture

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ABSTRACT

Anthropogenic 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 often 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 fire's natural role in these forests, management using prescribed fire alone is unlikely to reverse encroachment impacts due to the degree of forest change since fire exclusion. Consequently, additional management techniques (e.g., chemical, mechanical) are often combined with fire to ensure persistence of pine-oak mixtures and their associated ecosystem services. In current-day degraded pine-oak mixtures in the south-eastern U.S., where no one species represents > 75% dominance by stand basal area, encroaching species (e.g., *Liquidambar styraciflua*, *Quercus nigra*) commonly form a dense midstory and occupy overstory positions. To quantify how encroaching species in degraded mixed pine-oak forests impact fuels, canopy cover, and seasonal fire behavior, we thinned the midstory (<20 cm DBH) of all non-pyrophytic species in 12 0.10-ha blocks within a mixed pine-oak stand at the Mary Olive Thomas Demonstration Forest (Auburn, Alabama, USA) in July 2021. Midstory thinning reduced basal area by 6.7 m² ha⁻¹ and canopy cover by 9.1%. In general, midstory thinning reduced shrub and fine woody debris fuel loads while having no impact on herbaceous, leaf litter, and duff fuel loads. When compared to pre-treatment levels, midstory thinning increased the relative proportion of pine leaf litter contribution to the fuelbed by 10.9% while reducing that of encroaching species by 11.4%. Despite changes to residual basal area, canopy cover, and leaf litter contribution, midstory thinning had no statistical impact on fire behavior, regardless of burn season. Early (January) and late dormant season (April) experimental fires had higher fireline intensities, consumed more surface fuels, had faster rates of spread, and higher average maximum temperatures compared to growing season (September) fires. We also noted an increase in these fire parameters with increased pine litter contribution to the fuelbed. In degraded pine-oak mixtures where encroaching species now occupy overstory canopy positions, we recommend investigating the efficacy of more intense thinning treatments that remove overstory individuals with known fire-suppressing traits to have a larger impact on canopy openness, fuels, and fire behavior.

1. 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 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 with comparatively low leaf litter flammability (Hanberry et al., 2020a; Kreye et al.,

2018; McDaniel et al., 2021; Varner et al., 2021) and limited pine and oak recruitment (Abrams, 1992; Shappell and Koontz, 2015). Today, prescribed fire alone is no longer a suitable management tool for forest restoration on most fire-excluded sites that are now degraded beyond midstory densification because encroaching individuals have reached overstory positions and 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

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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 such as thinning to remove encroaching individuals followed by repeated prescribed fire application to stimulate or maintain herbaceous fuels and sustain low levels of encroaching tree species (Dey and Schweitzer, 2018).

Most fire-excluded stands with heavy encroachment of undesirable species will require, at least initially, some degree of thinning to facilitate the eventual restoration of fire. Thinning reduces the density of unwanted and encroaching species that generally have leaf litter and crown characteristics that act to suppress forest flammability. For example, when compared to pyrophytic species (pines, upland oaks), encroaching tree species (e.g., sweetgum (*Liquidambar styraciflua*), water oak (*Quercus nigra*), and red maple (*Acer rubrum*)) 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; McDaniel et al., 2021; Varner et al., 2021). 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). These understory conditions not only limit regeneration potential of shade-intolerant oaks and pines but hinder the development of an herbaceous fuelbed and forest flammability (Alexander et al., 2021). Additionally, leaf litter of encroaching species in pine-oak forests tends to decompose faster than upland oaks (Alexander and Arthur, 2014; Babl-Plauche et al., 2022; Mudrick et al., 1994), and likely pines, potentially altering available leaf litter fuel loads (Dickinson et al., 2016). Reduced leaf litter fuels could be especially important in conditions that limit herbaceous fuels, as leaf litter is the primary carrier of fire in more closed-canopy forests (Arthur et al., 2017). Thus, thinning to alter fuel dynamics is an important first step in restoring fire to pine-oak mixtures.

Following initial thinning, repeated, low-intensity fires are critical for preventing midstory encroachment, thus restoring and maintaining pine and oak landscapes. Thinning with subsequent repeated prescribed fires can increase herbaceous ground cover in previously fire-excluded stands, a common objective in restoring historically open forests (Hanberry et al., 2020b), but usually in areas where canopy cover was substantially reduced to <60% (Bassett et al., 2020; Vander Yacht et al., 2020; Waldrop et al., 2008). Combined thinning and fire treatments can also promote height and diameter growth of upland oak and hickory (*Carya*) species (Holzmueller et al., 2014; Schweitzer et al., 2019), and repeated fires are generally necessary to maintain reduced densities of competing encroaching species to promote advanced regeneration of desirable species (Iverson et al., 2008). Clearly, combining thinning and repeated prescribed fires is essential to perpetuate pine and oak dominance in previously fire-excluded forests.

Although repeated fire application is clearly essential for restoring and perpetuating pine-oak mixtures (Willis et al., 2019), 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 the emergence of live understory fuels, which 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 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 effects, such as top-kill of desirable hardwoods and failure to kill undesirable hardwoods (Knapp et al., 2009). Consequently, there has also been a push to include prescribed fire application during different seasons 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 (Brose and Van Lear, 1998; 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 historically prevalent species, and herbaceous understory remains unknown.

This research aims to understand how, or if, midstory thinning of encroaching species in a degraded mixed pine-oak forest influences canopy cover and fuels in ways that impact seasonal fire behavior. Midstory thinning, also called low thinning or thinning from below, removes unwanted species in smaller size classes, typically by chemical injection or felling with hand tools, thereby reducing residual basal area and canopy cover, and may provide an alternative viable approach to overstory thinning, especially in stands where commercial overstory thinning is logistically or economically difficult to implement and understory flammability is essential for restoration. Understanding how midstory thinning treatments combined with seasonal variation in prescribed fire affects fuelbed dynamics is important because: 1) encroaching species are increasingly common in fire-excluded forests, with consequences for forest flammability, 2) thinning treatments reduce residual basal area, increase light to the forest floor, and can alter stand composition, structure, and fuels (Graham, 1999) with relatively unknown impacts on fire behavior in humid, southeastern mixed forests, and 3) growing season fires can reduce hardwood resprouting and promote greater herbaceous species abundance and diversity (common management objectives) than dormant season fires (Knapp et al., 2009). To address this objective, we conducted a manipulative field experiment to quantify how midstory thinning of non-pyrophytic species influences changes in forest structure and composition, fuels, and seasonal fire behavior (early dormant season (January), late dormant season (April), and growing season (September)) in a degraded, mixed pine-oak stand at the Mary Olive Thomas Demonstration Forest in Auburn, Alabama, USA. We hypothesized that removing non-pyrophytic 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 fuel characteristics (i.e., types and loads). This work will inform on the efficacy of midstory removal for managers whose objectives are to reintroduce fire to degraded pine-oak mixtures. Midstory thinning 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 (wild-fire, 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- and drought-resistant pine-oak mixtures.

2. Methods

2.1. Site description and experimental design

Twelve 0.10-ha experimental blocks located > 20-m apart were established within a 3.4-ha management unit at the Mary Olive Thomas Demonstration Forest (MOTDF) in Auburn, Alabama, Lee County, 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). For this area, 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 stand was a naturally regenerated pine-oak mixture that has had no active management since the property was acquired by Alabama Cooperative Extension System and Auburn University College of Forestry, Wildlife, and Environment in 1983 (Hunt et al., 2016). A suite of species (n = 18, see Table 1 for full list) occupied all canopy positions. Dominant trees were 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-split plot design, each 0.10-ha block was randomly divided into one of two treatments: a complete removal of non-pyrophytic species in the midstory (<20 cm DBH) (i.e., thinning treatment), and an unmanipulated control with no thinning (i.e., no thin treatment). Additionally, the thinning and control treatments were further split into four equally spaced (~2-m apart) 4-m × 4-m subplots, which were each randomly assigned to an experimental burn season (early dormant season, late dormant season, growing season, control), creating 24 total burn subplots per season with 12 in each treatment.

2.2. 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. To examine changes in canopy cover pre- and post-thinning treatment, we estimated canopy cover by averaging eight readings (two in each of the four subplots) on a spherical densiometer (Forestry Suppliers, Inc., Jackson, MS, USA) taken at a height of 1.37 m aboveground facing 0° N during peak growing season. To assess compositional changes in the leaf litter fuelbed resulting from thinning, leaf litter fuels were harvested adjacent to each burn subplot at the 315° NW corner within 30-cm × 30-cm quadrats. In the lab, litter was sorted into one of three functional 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 1 for full list). Each collection was dried to a constant mass at 60 °C for 72 h to calculate fuel load of individual groups. Within the burn subplots, we recorded live herbaceous and woody plant heights and visually estimated their cover, and measured litter and duff (organic material) 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 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 fine woody debris (FWD; < 7.6 cm diameter) and coarse woody debris (CWD; > 7.6 cm diameter) 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, CWD, and FWD).

2.3. Thinning implementation

In July 2021, a midstory thinning of non-pyrophytic species was applied to each plot that was randomly assigned to the 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, and summarized in Table 1. 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

Table 1

All species (2,334 total individuals, 18 species) surveyed within manipulation blocks are expressed in trees per hectare (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 (unk) 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	Avg TPHA	Shade tolerance ^{1,2}	Fire tolerance ^{1,2}	Removed?	Classification
<i>Acer rubrum</i>	red maple	74	T	I	Yes	Encroaching ^{4,5,7,9,12}
<i>Carya tomentosa</i>	hickory	40	I - T	I (J), T (M)	Yes	Intermediate ^{10,12}
<i>Cornus florida</i>	flowering dogwood	10	VT	I	Yes	Intermediate ⁷
<i>Fagus grandifolia</i>	American beech	40	VT	I	Yes	Intermediate ^{7,8}
<i>Ilex opaca</i>	American holly	2	VT	I	Yes	Intermediate ⁶
<i>Juniperus virginiana</i>	eastern red cedar	27	I	I	Yes	Intermediate/Unk
<i>Liquidambar styraciflua</i>	sweetgum	551	I	I (J), T (J)	Yes	Encroaching ^{6,7,10,12}
<i>Liriodendron tulipifera</i>	tulip poplar	20	T	I	Yes	Intermediate ^{6,7,12}
<i>Nyssa sylvatica</i>	black tupelo	96	T	I	Yes	Encroaching ¹²
<i>Oxydendrum arboreum</i>	sourwood	52	T	?	Yes	Intermediate ¹²
<i>Pinus echinata</i>	shortleaf pine	89	I	I (J), T (M)	No	Pyrophyte ¹²
<i>Pinus taeda</i>	loblolly pine	252	I - T	I (J), T (M)	No	Pyrophyte ¹¹
<i>Prunus serotina</i>	black cherry	64	I - T	I	Yes	Intermediate ¹²
<i>Quercus alba</i>	white oak	89	I - T	I (J), T (M)	No	Pyrophyte ^{9,12}
<i>Quercus falcata</i>	southern red oak	22	I - T	I (J), T (M)	No	Pyrophyte ¹²
<i>Quercus nigra</i>	water oak	232	I - T	I	Yes	Encroaching ³
<i>Ulmus alata</i>	winged elm	7	T	I	Yes	Encroaching ^{7,10}
<i>Vaccinium arboreum</i>	farkleberry	250	T	I	Yes	Intermediate/Unk

Sources referenced above in superscripts: (Burns et al., 1990a¹; Burns et al., 1990b²; Kane et al., 2008³; Alexander and Arthur, 2010⁴; Alexander and Arthur, 2014⁵; Mola et al., 2014⁶; Kreye et al., 2018⁷; Babl et al., 2020⁸; Kane et al., 2021⁹; McDaniel et al., 2021¹⁰; Varner et al., 2015¹¹; Varner et al., 2021¹²).

“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 removed all tree species considered to be non-pyrophytic and <20 cm DBH regardless of height.

All removed stems were mechanically felled by chainsaw. To minimize disturbance of leaf litter fuels and accumulation of treetops and woody debris on our small experimental subplots (only 4-m × 4-m), and because our primary interest was how residual trees impacted fine fuel dynamics and environmental conditions, felled stems and limbs were carefully carried (not dragged) from plots. 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 L of water for cut-stump application to reduce resprouting. The thinning treatment produced a natural gradient of residual basal area by overstory encroaching species (primarily *Q. nigra* and *L. styraciflua*) separated into three groups: 1) low: mean basal area $5.3 \pm 0.3 \text{ m}^2 \text{ ha}^{-1}$, 2) medium: mean basal area $7.4 \pm 0.8 \text{ m}^2 \text{ ha}^{-1}$, 3) high: mean basal area $11.9 \pm 0.3 \text{ m}^2 \text{ ha}^{-1}$. These groups included a natural range of overstory by encroaching species with or without the presence of a midstory of these species, replicated by four blocks each.

2.4. 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 × 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, understory, 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.

2.5. Experimental burns

Within each 4-m × 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 consumed fuels 9–10 months after leaf fall 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 encroaching hardwood control, and minimizing crown scorch/mortality 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). Observed mean weather parameters for each burn are summarized in Table 2. The Keetch-Byram Drought Index (KBDI) was obtained from Fire Weather Intelligence Portal; (<https://products.climate.ncsu.edu/fwip/>), and days since last precipitation and amount were obtained from the NOAA National Centers for Environmental Information for the Auburn, AL, USA station (<https://www.ncei.noaa.gov/cdo-web/datasets/GHCND/locations/ZIP:36832/detail>). To calculate mean maximum temperatures for the nine pyrometers marked with six Tempilaq (Tempil, South Plainfield, NJ, USA) temperature-sensitive paints ranging from 79 °C to 510 °C were attached to pin flags and arranged in a 3 × 3 grid on leaf litter surface in each burn subplot. Though this method only estimates a maximum temperature reached by the

Table 2

Mean weather parameters (air temperature (°C), relative humidity (%), wind speed (m s^{-1}), wind direction, days and amount of the last precipitation event, and Keetch-Byram Drought Index (KBDI); obtained from Fire Weather Intelligence Portal (<https://products.climate.ncsu.edu/fwip/>) 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 subplot.

	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, cm)	6, 0.55	2, 4.1	10, 0.48
KBDI	278	245	740

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 subplot (2 m horizontal distance from ignition), and from the halfway point to the end of the subplot (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 air 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 van Wagner (1978).

2.6. Statistical analyses

We used a mixed effects model using the “nlme” package in R (Pinheiro and Bates, 2022) to test 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 effects of treatment, residual BA of encroaching overstory groups, and their interaction with a random effect using the nested structure of block, thinning treatment, and burn season to account for the split-split plot experimental design. 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 described above to test the differences in each fire parameter (dependent variables) vs. thinning 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. 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 thinning 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).

3. Results

3.1. 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 abundant at smaller diameters (<20 cm DBH), overall size classes, and 2.7 times as dense (trees ha^{-1}) compared to pine and upland oaks combined (Fig. 1). Before thinning, the mean ($\pm$ SE) standing basal area of all blocks was $32.5 \pm 1.3 \text{ m}^2 \text{ ha}^{-1}$, and all plots had similar canopy cover at $97.9\% \pm 0.5$ ($p = 0.87$). Across all plots assigned to a thinning treatment, we removed a total of 1,294 individuals <20 cm DBH, resulting in an average reduction in block basal area by $6.7 \pm 0.4 \text{ m}^2 \text{ ha}^{-1}$, and canopy cover was significantly reduced by $9.1\% \pm 2.9$ when compared to control plots ($p < 0.001$) (Fig. 2). We found no significant differences in canopy cover across the gradient of encroaching overstory after the thinning treatment ($p = 0.76$).

Initial total fuel loads were similar between control ($38.2 \pm 4.1 \text{ Mg ha}^{-1}$) and thinning ($37.3 \pm 3.0 \text{ Mg ha}^{-1}$) treatments, respectively ($p = 0.86$) (Fig. 3). As felled trees were removed from thinned areas, midstory thinning significantly reduced total fuel loads to $33.7 \pm 2.3 \text{ Mg ha}^{-1}$ ($p = 0.012$) compared to pre-treatment levels. Thinning had significant effects on reducing shrub fuel load by $0.3 \pm 0.1 \text{ Mg ha}^{-1}$ ($p = 0.024$) and

FWD by $0.9 \pm 0.3 \text{ Mg ha}^{-1}$ ($p < 0.01$), marginal effects on decreasing herbaceous fuel load by $1.5 \pm 2.6 \text{ Mg ha}^{-1}$ ($p = 0.062$) and increasing leaf litter fuel load by $1.3 \pm 0.8 \text{ Mg ha}^{-1}$ ($p = 0.12$), and no significant effect on CWD fuel load by $3.2 \pm 4.3 \text{ Mg ha}^{-1}$ ($p = 0.66$), and 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 ($p > 0.05$).

3.2. 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 ($p > 0.05$ for all comparisons). Midstory thinning reduced the leaf litter of encroaching species immediately following leaf off, which continued to decline throughout subsequent leaf litter harvests (Fig. 4). Midstory thinning significantly increased the relative proportion of pine leaf litter contribution to the fuelbed by 10.9% (from ~ 50 to 60.9%) ($p < 0.05$, while significantly reducing the relative proportion of encroaching species leaf litter by 11.4% (from ~ 32.5 to 25.1%) ($p < 0.05$) when comparing pre-treatment harvests in June 2021 to post-treat harvests in June 2022. Though some differences in leaf litter by mass contribution to the fuelbed were not statistically significant, we report observed trends. From leaf litter harvests in 6/2021 (pre-treatment) to 1/2022 (post-treatment), encroaching species relative proportion of leaf litter by mass increased by 6.2% in control plots ($p = 0.058$) but decreased by 5.04% in thinning plots ($p = 0.28$). Relatedly, pine relative contribution to leaf litter by mass decreased by 10.5% ($p < 0.01$) and upland oaks increased by 4.2% ($p = 0.41$) in control plots, while pine relative contribution to leaf litter by mass increased by 2.01% ($p = 0.86$) and upland oaks by 3.03% ($p = 0.54$) in thinned plots. In general, we observed that leaf litter by mass (%) after 1/17/2022 increased for pine contribution, exhibited no change for upland oaks, and decreased for encroaching species regardless of treatment, likely due differences in decomposition rates among species.

3.3. Seasonal experimental burns

Fires in the dormant season had greater fireline intensity, faster rate-of-spread, higher pyrometer-derived average maximum temperature, and consumed more fuel than growing season fires (Fig. 5). Most notably, mean growing season fuel consumption was only 32.4%, and exhibited higher variability among subplots, while early dormant season and late dormant season fuel consumption was 88.0% and 87.7% across all burn subplots, 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 ($p < 0.05$), likely due to the 10°C higher ambient temperature in April compared to late January (observed weather at time of burning reported in Table 2). Though not significant within growing season, fuel consumption in the thinning treatment was 6.4% greater than in the control plots ($p = 0.32$). Despite differences in growing season canopy cover between control and thinned plots, fire behavior for all four fire parameters was similar 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 ($p > 0.05$).

All fire parameters exhibited a positive relationship with increasing pine leaf litter contribution to the fuel bed (Fig. 6). Across all burn seasons and thinning treatment, each 10% increase in pine leaf litter by mass resulted in 10.8 kW m^{-2} greater fireline intensities ($r^2 = 0.39$) (Fig. 6A), 64% greater fuel consumption ($r^2 = 0.54$) (Fig. 6B), 1.2 cm s^{-1} faster fire spread rates ($r^2 = 0.26$) (Fig. 6C), and 30.6°C hotter maximum temperatures ($r^2 = 0.60$) (Fig. 6D) ($p < 0.05$ for all regressions). We observed no statistical differences in any of the four fire parameters between control and thinned burn subplots, and there were

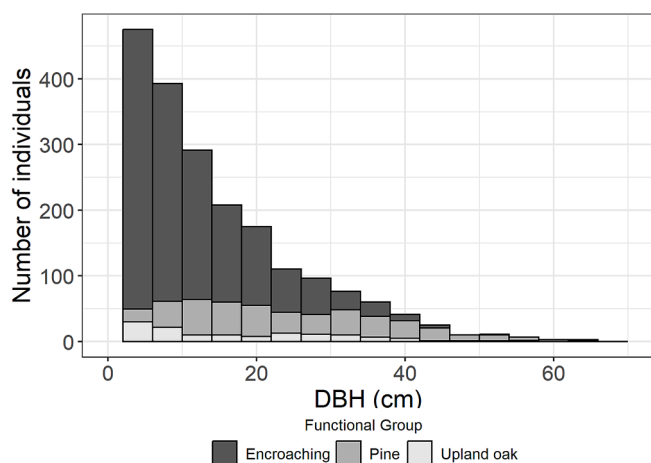


Fig. 1. Stacked bar chart displaying pre-treatment survey of the number of individuals observed in all blocks across the diameter at breast height (DBH; cm) distribution of encroaching, pine, and upland oak species within the management unit.



Fig. 2. Photo taken in June 2021 in one block at the Mary Olive Thomas Demonstration Forest (Auburn, AL, USA) showing (A) unthinned control plot and (B) plot with midstory thinning.

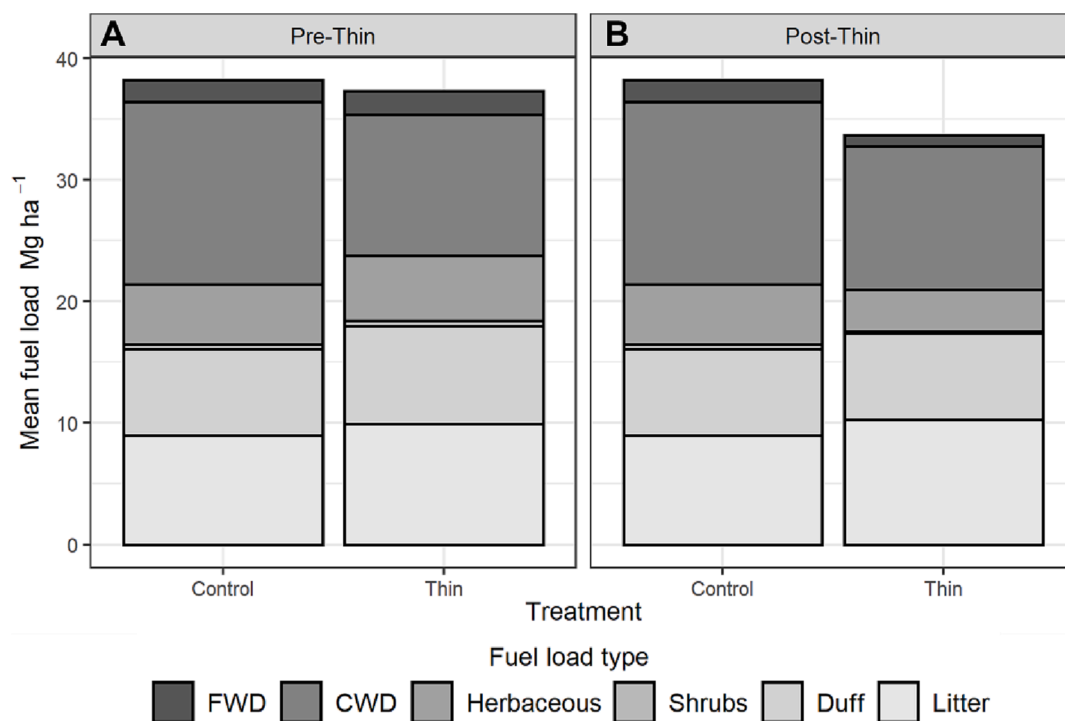


Fig. 3. Stacked bar plots depicting mean fine woody debris (FWD, < 7.6 cm diameter), and coarse woody debris (CWD, > 7.6 cm diameter), herbaceous, shrub, duff, and leaf litter fuel loads (Mg ha^{-1}) at (A) pre-thin and (B) post-thin within control (no thinning) and treatment (thinning) blocks. Pre-thin fuel loads were recorded on 6/24/2021, and post-thin fuel loads were recorded on 6/24/2022.

also no significant differences between early dormant season and late dormant season fires ($p > 0.05$ for all comparisons). However, both early and late dormant season fires had higher fireline intensities, consumed more fuel, had higher fire spread rates, and higher maximum temperatures compared to growing season fires (all $p < 0.05$).

4. Discussion

Despite a reduction in basal area and canopy cover with midstory thinning, we observed no statistical differences in total fuel loads or fire behavior between thinned and unthinned subplots in our degraded

mixed pine-oak stand. This is likely because the strong representation of encroaching species in the smaller overstory size classes (~20–30 cm) maintained a closed canopy and contributed ample senesced leaf litter to the fuelbed, which offset the influence of dominant pine and upland oak individuals in the larger size classes. Many encroaching species are shade-tolerant with relatively high leaf area that is often associated with high crown area and/or volume (e.g. American beech, red maple) (Babl et al., 2020; Canham et al., 1994). These traits increase their competitiveness with largely shade-intolerant pines and upland oaks, often contributing to a recruitment bottleneck (Abrams, 1992; Alexander et al., 2021; Magee et al., 2022) and shifts in forest structure and

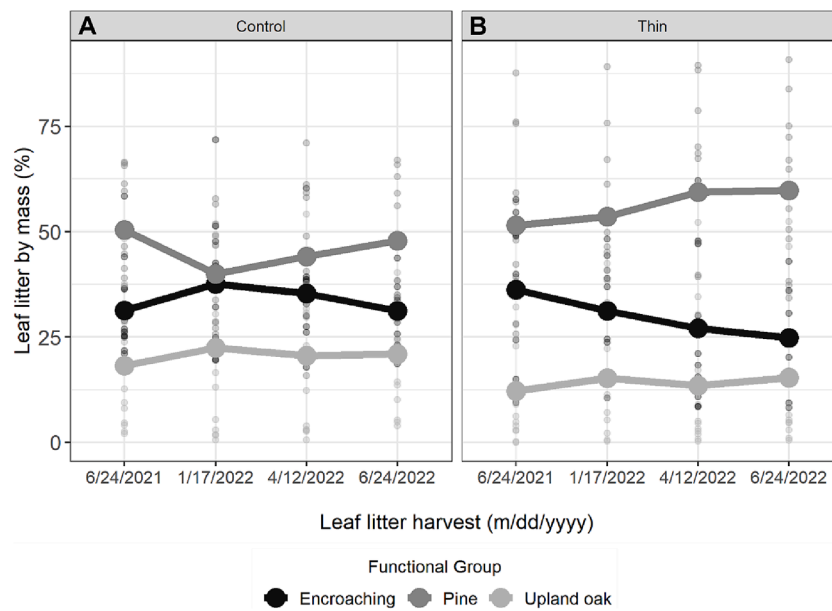


Fig. 4. A time series line chart depicting the change in leaf litter by mass (%) in encroaching, pine, or upland oak species groups based on sorted leaf litter harvests from 6/24/2021, 1/17/2022, 4/12/2022, and 6/24/2022 in (A) control (unthinned) and (B) thinned treatment subplots. The thinning treatment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

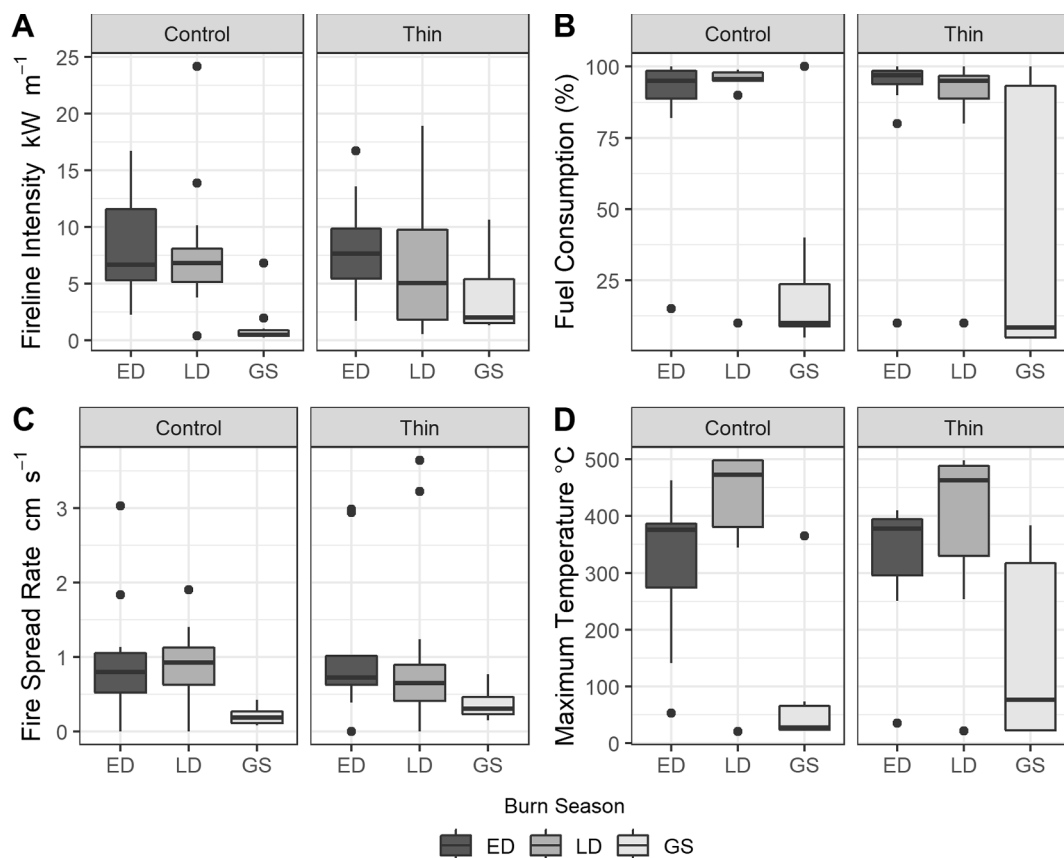


Fig. 5. Box and whisker plots showing differences between control and thin plots in three burn seasons (early dormant season (ED; 1/27/2022), late dormant season (LD; 4/02/2022), growing season (GS; 9/29/2022)) for four fire behavior parameters, (A) fireline intensity (kW m^{-1}), (B) fuel consumption (%), (C) fire spread rate (cm s^{-1}), and (D) average pyrometer-derived maximum temperature ($^{\circ}\text{C}$). Points are outliers.

composition with negative consequences for forest flammability (Hanberry, 2019; Kane et al., 2021; McDaniel et al., 2021; Varner et al., 2021). These consequences of encroachment were notable in our

degraded stand, and although still a mixed pine-oak stand by definition, the stand no longer functions like a historical pine-oak mixture due to changes in structure and composition, leading to relatively low pine

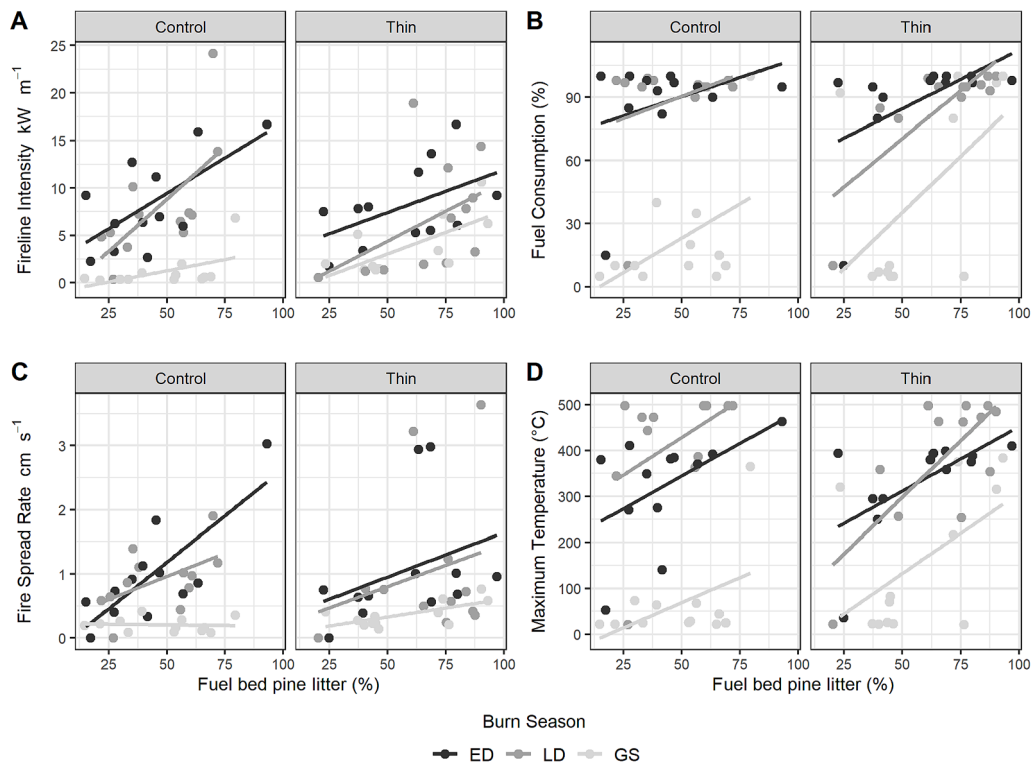


Fig. 6. Linear regressions showing the relationship between pine leaf litter relative contribution to leaf litter fuel mass (%) and four fire behavior parameters – (A) fireline intensity (kW m^{-1}), (B) fuel consumption (%), (C) fire spread rate (cm s^{-1}), and (D) average pyrometer-derived maximum temperature ($^{\circ}\text{C}$) in both control and thinned plots in three burn seasons (early dormant season (ED; 1/27/2022), late dormant season (LD; 4/02/2022), growing season (GS; 9/29/2022)).

contribution to the fuelbed across most plots. 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 the combination of midstory-only thinning and seasonal prescribed burning.

The lack of midstory thinning effect on total fuel loads is likely due to the relatively low contribution of the midstory to fuel loads, especially fine fuels. Pre-thinning, total fuel loads were generally higher when compared to a burned mixed pine-oak forest in Arkansas ($28.76 \pm 4.84 \text{ Mg ha}^{-1}$) (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 midstory thinning 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. The lack of midstory thinning on live herbaceous fuels may reflect the minimal changes in understory light levels (i.e., plots remained closed canopy even after thinning) or a depauperate seed bed. However, our results may not be representative of the long-term effects of midstory thinning due to potential legacy effects of fuelbed properties before treatment (e.g., duff development) or insufficient time for thinning-induced compositional shifts to manifest in the fuelbed. In addition, CWD and some FWD were removed from thinned plots (this would not occur in an operational thinning), which clearly influenced CWD loads. 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).

Though midstory thinning increased pine and upland oak leaf litter percent contribution to the fuelbed and decreased the percent contribution from leaf litter of encroaching species, we detected no differences in any fire behavior parameter among thinning treatments in both dormant and growing season fires. This is likely because of the relatively high basal area of encroaching species in the smaller (20–30 cm DBH) overstory size classes, which were unaffected by midstory thinning and

are still contributing to shady, moist understory conditions and the production of leaf litter fuels of low flammability and high decomposition rates, which likely mitigated any potential effects of midstory thinning on fire behavior. As encroaching species become more abundant with range expansion in the absence of management (Hanberry, 2013), and fuelbeds become increasingly mixed, decomposition rates may further increase due to greater abundance and diversity of microbial communities adapted to these fuel mixtures (Chapman et al., 2013; Kaneko and Salamanca, 1999; Li et al., 2009) along with increased leaf litter moisture (Li et al., 2009; Mudrick et al., 1994). Ultimately, predictions of fuelbed dynamics in eastern forests experiencing encroachment will ultimately require a better understanding of the balance between increased leaf area due to encroachment of shade-tolerant species, and consequently increased leaf litter fuels, and the loss of leaf litter fuels through increased leaf litter decomposition rates.

Most differences in fire behavior were due to fire season. Similar to Sparks et al. (2002), growing season fires were significantly less intense across all parameters and consumed less fuel than dormant season fires. 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 reduce sunlight to the forest floor, leading to increased relative humidity (Knapp et al., 2009) and fine fuel moisture (Babl et al., 2020; Ray et al., 2005). Moreover, encroaching species 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) inputs during the growing season, potentially increasing fuel moisture surrounding a tree's bole and acting as a natural wet line that protects trees from fire (Alexander and Arthur, 2010; Babl et al., 2020; Babl-Plauche et al., 2022; Siegert et al., 2020). The greater spatial variation of live versus dead fuels during the growing season may also reduce fire intensity. Early and late dormant season fires performed similarly, likely due to the leaf-off condition leading to a lower relative humidity and drier fine fuels, conditions favorable for

flammability and fire behavior (Kreye et al., 2020). A lack of an interaction between thinning and fire season likely reflects the minimal impacts of thinning on canopy cover and the short-term nature of our project. The experimental burns occurred within one year of thinning treatment, leaving little time for any compositional changes to impact the fuelbed, especially if there were legacy effects from the pre-thinned stand on fuels (e.g., duff development). Although not statistically significant, we did observe increased variability in fuel consumption and fire temperature in thinned plots during the growing season burns. We do not fully understand the mechanisms driving this pattern, but thinning effects like these may become more pronounced in the long-term following repeated prescribed fires and increased time since thinning.

Though we did not control for spatial variation of individual trees, we noted that subplots with more pine leaf litter contribution to the fuelbed burned more readily, while those with relatively more encroaching species leaf litter appeared to limit fire behavior. Notably, in 17 experimental burn subplots that burned poorly (<15% fuel consumption) regardless of thinning treatment, encroaching overstory group, or season, encroaching species (primarily water oak) contributed $38.8\% \pm 5.0$ (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). Patches of encroaching species' leaf litter that burn poorly could contribute to the survival of small diameter (<10 cm DBH) fire-sensitive species that typically would have been top-killed (Dey and Schweitzer, 2018). As encroaching tree species replace mature pyrophytic pines and oaks due to age or passive disturbance related mortality, ecosystem-level consequences including decreases in forest flammability, altered biogeochemical cycles, and loss of wildlife species are predicted (Alexander et al., 2021).

Because we were trying to test specific hypotheses about the effects of removing midstory individuals of encroaching species on fuels and seasonal fire behavior using a replicated experimental design and limited forest area, our study has several limitations. First, we removed woody debris from our subplots, which likely would not have happened in operational conditions, and prior studies show that logging debris increases fire behavior (Waldrop et al., 2008). Doing so, however, allowed us to consider how changes in species composition and stand densification impact leaf litter fuels, which are the primary carriers of fire in closed-canopy forests (Arthur et al., 2017). In addition, we investigated fire behavior in small plots that likely do not reflect actual fire behavior over much larger scales where fire builds and develops over space and time. Even so, fires in these plots still showed common variations in fire behavior due to leaf-on versus leaf-off canopy conditions, confirmed the importance of pine leaf litter for carrying fire, and demonstrated that patches with high density of encroaching species burn poorly. We also only burned in the first-year post-thinning, and compositional and structural effects on fuels from midstory thinning may take more time to manifest if there are legacy effects of pre-thinning stand conditions.

5. Conclusion

Our results from a degraded, mixed pine-oak stand demonstrate that midstory removal had relatively little influence on canopy cover and fuel characteristics, and no effect on 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, as their removal has little impact on the main canopy. It is likely that the high abundance of encroaching species already in the mid- and small overstory size classes has structurally and functionally transformed this stand from a fire promoting pine-oak woodland into a fire-resistant, multi-layered closed-canopy mixture. Future studies should 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 (e.g., sweetgum, red maple) due to their excellent capabilities to resprout (Stanturf et al., 2002). We suspect that a more comprehensive thinning that removes encroaching species in the overstory size class, in addition to a mechanical or chemical treatment of the midstory, will be needed to 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. This combination of treatments will be particularly important in improving the efficacy of growing season fire in mixed pine-oak stands because of canopy shading. 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.

CRediT authorship contribution statement

Steven Cabrera: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Writing - original draft, Writing - review & editing. **Heather D. Alexander:** Conceptualization, Methodology, Validation, Resources, Visualization, Supervision, Project administration, Funding acquisition, Writing - original draft, Writing - review & editing. **John L. Willis:** Conceptualization, Methodology, Validation, Resources, Writing - review & editing. **Christopher J. Anderson:** Methodology, Writing - review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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