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Effects of catastrophic wind disturbance, salvage logging, and prescribed fire on fuel loading and composition in a *Pinus palustris* woodland

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ABSTRACT

Feedbacks between forest vegetation, forest fuels, and fire are critical to the perpetuation of fire-dependent ecosystems. In *Pinus palustris* (longleaf pine) woodlands, low-intensity fires facilitate a positive feedback in which highly flammable *Pinus* needles produced by canopy trees sustain frequent fires. These frequent fires inhibit recruitment of more fire-sensitive species and facilitate *P. palustris* dominance. Although these relationships are recognized in frequent-fire forests, we do not understand how vegetation-fuels-fire feedbacks may be modified by catastrophic disturbances and subsequent salvage logging in these ecosystems. In this study, we sought to address how the composition of fuelbed components differed between mature, catastrophically wind-disturbed, and salvage-logged sites and how prescribed fire would differentially interact with these fuel complexes. Using a permanent plot network, we quantified total fuel loading and fuel loading by flammability group (seven categories based on flammability characteristics) across the three disturbance treatments before and after operational-scale prescribed fire. For total fuel loading, we found significant interactions between disturbance treatment and time relative to prescribed fire. The fuel complex of mature sites was relatively homogenous, dominated by *Pinus* needles. Fuels on wind-disturbed and salvaged sites had minor contributions from *Pinus* needles, but that was somewhat offset by increased contributions by early successional species that have flammability characteristics similar to *Pinus* needles. The prescribed fire reduced fuel loading across all treatments and homogenized the wind-disturbed and salvage-logged fuel complexes. Although salvage logging resulted in a disparate fuel assemblage, prescribed fire appeared to reduce dissimilarity with the naturally disturbed condition.

1. Introduction

The perpetuation of fire-dependent ecosystems is contingent upon the continuous feedbacks of pyrophytic fuels burning with sufficient intensity to inhibit recruitment of fire-sensitive species. Frequent fires allow fire-adapted tree species to maintain canopy dominance and create understory conditions suitable for the establishment and growth of pyrophytic ground flora (Tepley et al. 2018). The production of pyrophytic litter enforces this positive feedback in fire-dependent ecosystems such as in *Pinus palustris* Mill. forests of the southeastern USA. Changes in fuel conditions, forest structural elements, or fire frequency and severity can alter these interactions (Mitchell et al., 2009; Fill et al., 2015). For example, fire exclusion may allow development of a thick duff layer, which when ignited, may result in high overstory mortality because of increased fire intensity, smoldering duration, and subsequent soil heating (Varner et al., 2005). Forest disturbances, especially catastrophic events, also alter these feedbacks by producing large pulses of woody debris (i.e. fuel) and modifying forest structure (Myers and van Lear, 1998; Busing et al., 2009; Cannon et al., 2014). Kulakowski and Veblen (2007) found that catastrophic wind disturbance was strongly related to fire intensity in subalpine forests in Colorado, USA. Modification of vegetation-fuels-fire feedbacks can in some instances be sufficient to result in an ecosystem state shift (O'Brien et al., 2008; Tepley et al., 2018), and some of these transitions may be nearly impossible to reverse because of operational and financial constraints of management (Suding et al., 2004). Thus, managers of frequent-fire forests must acknowledge the relationships between fuels, forest structures, and fire in forest planning (Loudermilk et al., 2012).

Catastrophic wind disturbances are common in the southeastern USA and are becoming increasingly so (Gensini and Brooks, 2018). Myers and van Lear (1998) hypothesized that prior to European

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settlement catastrophic wind disturbances, specifically hurricanes, interacted with fire to influence composition and structure of forest patterns at the landscape scale across this region. Catastrophic disturbances reduce canopy cover, increase fuel loadings, and create complex microsite conditions near the forest floor. Intra-stand variability ranges from patches that experience direct insolation and higher evapotranspiration rates to shaded, cool microsites that are sheltered by coarse woody debris (CWD, Franklin et al., 2000; Bailey et al., 2012; Logan et al., 2020). As a result, available fuels following catastrophic wind disturbance will no longer be dominated by senesced litter of canopy trees, but rather by diverse, early successional understory vegetation and increased volumes of woody debris (Myers and van Lear, 1998; Holzmueller and Jose, 2012; Cannon et al., 2017; Kleinman et al., 2017). Although there is some indication that early successional plant species (i.e. heliophytes that are dominant after catastrophic disturbance) in fire-dependent ecosystems may burn with similar intensities to pyrophytic tree litter (Emery and Hart, 2020), the legacy of catastrophic wind disturbance on fuelbeds may persist until canopy trees grow well-formed crowns. This may take decades in frequent-fire forests, but foliar production can recover relatively rapidly in some tropical ecosystems dominated by species with high sprouting ability (Whigham et al., 1991).

After catastrophic disturbance, salvage logging is frequently used to remove dead and damaged trees and thereby recover some economic losses and mitigate risks of insect outbreaks or intense fires (Stanturf et al., 2007, Müller et al., 2019). Although salvage logging after catastrophic disturbance is common in forests around the world, the ecological consequences of salvage operations are not fully understood (Leverkus et al., 2018). Among other ecosystem changes, the removal of dead and damaged trees modifies the volume, composition, and spatial continuity of the post-wind disturbance fuelbed. In fact, salvage logging has been specifically criticized for altering forest nutrient recovery via CWD removal (Kishchuk et al., 2015), compacting and exposing mineral soil (Lang et al., 2009), and homogenizing post-fire plant and animal communities (Cobb et al., 2007, Hernández-Hernández et al., 2017; Kleinman et al., 2017). Despite an emerging literature that salvage logging is not ubiquitously negative for ecosystem recovery (Fidej et al., 2016, Taylor et al., 2017; Slyder et al., 2020), salvage logging remains a contentious topic (Stokstad, 2006; Lindenmayer et al., 2017). The impacts of salvage logging on available fuels in fire-dependent ecosystems are poorly understood (Palik and Kastendick, 2009; Kleinman et al., 2020). This information is essential to develop a more comprehensive understanding of salvage logging impacts in particular, and disturbance interactions in general, and is required to make scientifically informed management decisions on the use of salvage operations in frequent-fire forests.

Pinus palustris woodlands with open midstories and high ground flora diversity are a classic example of fire-dependent ecosystems perpetuated by low intensity surface fires. In *P. palustris* woodlands, prescribed fires facilitate a positive feedback in which highly flammable, canopy-derived *Pinus* litter sustains frequent fires, which inhibit recruitment of more fire-sensitive species thereby maintaining *P. palustris* dominance (Platt et al., 1988, O'Brien et al., 2008, Mitchell et al., 2009). These frequent, low intensity fires result in open canopy and midstory conditions and a species rich ground flora (Outcalt, 2006). Despite recognition of the importance of these relationships in *P. palustris* stands, we lack an understanding of how vegetation-fuels-fire feedbacks may be modified by catastrophic wind disturbances and subsequent salvage logging in these and other frequent-fire ecosystems.

In April 2011, an EF3 tornado impacted a mature *Pinus palustris* woodland in the Fall Line Hills of Alabama, USA. Portions of the catastrophically disturbed woodland were salvage logged. We used this opportunity to explore how vegetation-fuels-fire feedbacks were altered by catastrophic wind disturbance and subsequent salvage logging.

The overarching objective of our study was to understand the interactions of catastrophic wind disturbance, salvage logging, and prescribed fire on fuel loading and composition in *P. palustris* woodlands. Specifically, we questioned how the composition of fuelbed components differed across disturbance treatments before and after operational-scale prescribed fire. We hypothesized that early successional ground flora assemblages would dominate the fuelbed of catastrophically disturbed sites as a legacy of canopy tree mortality and increased insolation near the forest floor. Furthermore, we hypothesized that *Pinus* needles would dominate the fueldbed of mature sites as is typical in fire-maintained *P. palustris* woodland ecosystems. *Pinus* needles, especially the long, resinous needles of *P. palustris*, readily ignite, burn quickly, and are considered critical to maintain positive vegetation-fuels-fire feedbacks in these ecosystems (Platt et al., 1988; Mitchell et al., 2009). However, recent research revealed that some early successional ground flora species common in *P. palustris* woodlands of this region have flammability characteristics similar to *Pinus* needles (Emery and Hart, 2020). Thus, we speculated that ground flora assemblages may fill the role of *Pinus* needles in sustaining fire through the catastrophically disturbed sites.

2. Methods

2.1. Study area

Our study was conducted on the Oakmulgee Ranger District of Talladega National Forest in Alabama, USA (32°55′30″ N, 87°24′00″ W). Elevation of the study area ranges from 110 to 140 m above mean sea level. The Oakmulgee Ranger District occurs in the Fall Line Hills, which is a transition zone between the Appalachian Highlands and the Coastal Plain (Fenneman, 1938; Shankman and Hart, 2007). Regional climate is humid mesothermal, with year-round precipitation and a long, hot growing season (Thornthwaite, 1948). From 1988 to 2019, the average annual temperature was 17 °C with the warmest average monthly temperature of 27 °C occurring in July and the coolest average monthly temperature of 7 °C occurring in January (PRISM, 2020). Across the same thirty-year period, average annual precipitation was 1390 mm, with the wettest month, February, averaging 140 mm, and the driest month, October, averaging 75 mm (PRISM, 2020). The most common soils in the study area are in the Maubila series, where up to the first 10 cm are composed of sandy loam and the next 200 cm are clay-based substrata, underlaid by bedrock (USDA NCRS, 2018).

The Oakmulgee Ranger District occurs within the *Quercus-Pinus* forest region of the United States (Braun, 1950; Dyer, 2006). Beckett and Golden (1982) classified ecological communities on the Oakmulgee Ranger District within the Cahaba River and Black Warrior River watersheds and found that the *Pinus palustris* community type was the most common and occurred most frequently on upper slopes and south-facing lower slopes that experienced cyclic fire (initiated by the USDA Forest Service in the early 1970s; USDA FS, 2005). The US National Vegetation Classification association labels this forest community as Xeric Upper East Gulf Coastal Plain *Pinus palustris* Woodland (Teague et al., 2014). Although *P. palustris* are dominant in the canopy, diverse species of hardwoods may grow in the understory, especially where fire is excluded (Harper, 1943; Cox and Hart, 2015).

In April of 2011, an EF3 tornado with wind speeds estimated up to 233 km h^{-1} and a maximum width of 1609 m tracked through the northwest portion of the Oakmulgee Ranger District (NWS, 2011; Table 1). From July–November 2011, salvage logging occurred at the discretion of operators, generally concentrated near existing road networks. Wheeled skidders were used to compile the most merchantable and accessible logs at a ramp site, where they were loaded by a stationary knuckleboom loader onto trucks for off-site transport. Thus, we had the opportunity to compare fuel loading and composition on mature, wind-disturbed, and wind-disturbed and salvage-logged sites to study interactions between forest fuels, forest structures, and prescribed fire.

A comprehensive inventory of the *Pinus palustris* woodland studied

Table 1
Timeline of events that influenced conditions in a *Pinus palustris* woodland on the Oakmulgee Ranger District of Talladega National Forest, Alabama, USA.

Event	Date	Description
Prescribed fire	May 2010, April 2014, April 2018	Operational-scale prescribed fire
Tornado	April 2011	EF3 tornado passed through the study site
Salvage logging	July–November 2011	Dead and damaged trees were removed from a portion of the tornado track
Forest inventory	June–July 2016 and 2018	A network of 60 permanent plots were inventoried in mature, wind disturbed, and salvage logged areas
Fuel collection	January–February 2017 and 2019	Fuels were collected on a sample of the permanent study plots

here was reported by Kleinman et al. (2017). Where the woodland was not impacted by the April 2011 tornado, the basal area was 21.69 m^2 ha^{-1} and density of stems ≥ 5 cm diameter at breast height (dbh) was 325 ha^{-1}. *Pinus palustris* represented 75% of the basal area, *Pinus taeda* L. represented 10% of the basal area, and the next most dominant species was *Quercus falcata* Michaux which represented 4% of the basal area. Total tree species richness was 15, but no other species represented more than 3% of the basal area in portions not disturbed by the tornado. Basal area of wind-disturbed portions of the woodland was 1.09 m^2 ha^{-1} and tree density was 31 stems ≥ 5 cm dbh ha^{-1}. Portions of the woodland that were salvage-logged had a basal area of 0.57 m^2 ha^{-1} and 31 stems ≥ 5 cm dbh ha^{-1}.

We took advantage of a network of existing permanent plots established as part of a long-term research project initiated in 2016. The network contains 60 0.04 ha fixed-radius plots established to quantify recovery of differentially disturbed sites using a wide range of response variables. Findings for ground flora, woody plants, macrofungal assemblages, CWD, insolation, and other variables from the network were previously published in Kleinman et al. (2017, 2020) and Ford et al. (2018). The study design ensured all plots were established with similar biophysical conditions (e.g. same watershed, Maubila series soils), land-use, disturbance, and management histories, and prescribed fire rotation. For each treatment type (mature, wind disturbed, and salvage logged), 20 plots were established. For this study, we selected 13 plots from each treatment (n = 39 total study plots). The study site was under a 4-year prescribed fire rotation, which provided the opportunity to compare how fuel composition changed before and after an operational-scale prescribed fire. The most recent burns that occurred on this site were April 2018, April 2014, and May 2010. We acknowledge that our study design did not allow for replicates and that all treatments occurred within the same Forest Service delineated compartment. Experimental replicability was not possible given the disturbance and forest conditions, but we contend that these "natural experiments" are essential to advance our understanding of forest disturbance ecology (Hargrove and Pickering, 1992; Davies and Grey, 2015).

2.2. Field methods

Vegetation and ground surface cover data were collected during the 2016 and 2018 growing seasons (Kleinman et al., 2020). These data were used as explanatory variables for fuel loading and composition in 2017 and 2019, respectively. All dead stems ≥10 cm dbh were measured, including snags (standing dead stems with crowns still intact), snapped stems (standing dead trees that had broken 1.37 m above the root plate), uprooted stems (dead stems with uplifted root networks), and logs (dead stems disconnected from roots). Coarse woody debris (CWD) consisted of downed dead stems (uprooted stems and logs), which was totaled at the plot-scale (m^3 ha^{-1}) and categorized as hardwood CWD and *Pinus* CWD. Additionally, saplings, defined as all live stems > 1 m in height and < 5 cm at 1.37 m above root collar (diameter at breast height, dbh) were enumerated by species. The species composition and diameter of trees (live stems ≥ 5 cm dbh) were also recorded. The composition and foliar cover of ground flora (live woody and herbaceous plants ≤ 1 m in height) were monitored in 10 nested 1 m × 1 m quadrats within each plot. Nested quadrats were also used to tally seedlings (live woody stems < 1 m in height). Tree density and basal area were calculated for the following taxonomic groups: *Pinus* species, *Quercus* species, and non-*Quercus* hardwood species. Sapling and seedling taxonomic categories were Ericaceae (used for *Vaccinium* spp. and *Gaylussacia dumosa* (Andrews) Torr. & A. Gray), *Pinus*, *Quercus*, and non-*Quercus* hardwoods. Ground cover was assessed using Daubenmire cover classes, which included percent ground cover of bare soil, CWD, fine woody debris (FWD, woody material < 10 cm diameter), leaf litter, gravel, rock, and moss (Kleinman et al., 2017). Environmental data in association with these plots such as slope grade, transformed slope aspect (Beers et al., 1966), and percent canopy cover were also measured in 2016. Percent canopy cover was represented by percent cover for each plot reported from five densitometer readings (one at plot center and four at the cardinal directions 5 m from plot center).

In January–February of 2017 (considered pre-prescribed fire conditions) and 2019 (considered post-prescribed fire conditions), we collected fuel from the 39 selected permanent plots. Fuel was collected from each plot within three 1 m × 1 m quadrats placed on the ground 0°, 120°, and 240° 12.29 m from plot center for 2017. To avoid impacting ongoing ground flora surveys, quadrats were placed an additional 1 m beyond plot radius (11.29 m). Also, to prevent the 2017 collection from impacting fuel remaining in 2019, the 1 m × 1 m quadrat locations were modified to 60°, 180°, and 300° 12.29 m from plot center for the 2019 collection. All dead organic material less than 10 cm in diameter fitting within the quadrat was collected (Brown, 1974; Ford et al., 2018). Fuels such as vines or FWD that extended beyond the edges of the quadrat were cut at the edge and the portions that were not inside the quadrat were not included in our samples. Once collected, fuel samples were transported to the laboratory and frozen for 48 h to ensure no pests or diseases were transferred. Fuel was allowed to equilibrate to laboratory temperature and moisture conditions, as oven drying is thought to affect flammability characteristics of fuel (Varner et al., 2015).

2.3. Laboratory and analytical methods

All fuels were sorted into one of seven groups: low, moderate-low, moderate, moderate-high, and high flammability groups, *Pinus* needles, and "other" fuels based on the classifications established by Emery and Hart (2020; Table 2). Emery and Hart (2020) quantified burning characteristics of representative fuels in the same *Pinus palustris* woodland studied here. Litter was burned under controlled laboratory conditions and flammability characteristics (i.e. resistance to ignition, maximum flame height, flaming duration, and percent consumption) were measured. The fuels were hierarchically clustered into five groups of similar flammability characteristics. Although *Pinus* litter was statistically placed in the moderate-high flammability group, it was sorted separately because of its abundance and importance in the ecosystem. Fuels were sorted by flammability groups to speed the sorting process and simplify fuel dynamics analysis to these meaningfully grouped fuels. Mass of each fuel group was measured by plot.

Fuel groups were tested for normality and homoscedasticity using Shapiro-Wilkes and Levene's test of homogeneity of variances. Data were not normally distributed so they were transformed using Box-Cox transformations. Total mass and fuel flammability group mass were compared between disturbance treatments (mature, wind, salvage

Table 2
To quantify fuel composition across mature, wind-disturbed, and wind-disturbed then salvage-logged treatments, all fuel was placed into one of seven categories based on similar flammability characteristics (cf. Emery and Hart, 2020).

Flammability Group	Fuel Description
Low	Bark
	Charcoal
Moderate-low	Lower duff (Oa horizon)
	≤9.99 cm diameter hardwood fine woody debris
	≤2.54 cm diameter *Pinus* fine woody debris
	Pinus reproductive structures (cones and strobili)
Moderate	Unidentifiable wood fragments
	Upper duff (Oe horizon)
	2.55–9.99 cm *Pinus* fine woody debris
Moderate-high	*Gelsemium sempervirens* [L.] J.St.-Hil. (vines and leaves)
	Unidentifiable *Quercus* leaf fragments
	Non-fire facilitating *Quercus* leaves (cf. Kane et al., 2008)
	Non-*Quercus* hardwood leaves
	Ericaceae leaves
High	*Pteridium latiusculum* [Desv.] Hier. ex. Fries. = [syn: P. aquilinum]
	Grass (notably *Schizachyrium scoparium* Michx.)
	Fire facilitating *Quercus* leaves (cf. Kane et al., 2008)
Pinus	*Pinus* needles
Other	Various herbaceous plant fragments
	Acer spp. samaras
	Quercus acorns
	Scat
	Insects

logged) and across time (before and after prescribed fire) with 3 × 2 mixed ANOVAs. One-way ANOVAs and Tukey HSD tests were used to assess main effects when disturbance treatment and time did not exhibit significant interactions at $p < 0.05$.

To visualize differences in fuel complexes between treatments and across time, we conducted non-metric multidimensional scaling (NMS) with PC-Ord v. 7 (McCune McCune and Mefford, 2011). An NMS scree plot was used to select the optimal number of axes in the NMS solution, which was run 250 times with real data, applied Euclidean distance, and was compared for consistency with other solutions. We selected Euclidean distance because it has been shown to work well with datasets that have few zeroes, with datasets when zeroes are meaningful, and is most often used with non-species responses such as environmental characteristics (Peck, 2010). Convex hulls were used to group plots by treatment. We used a distance-based multi-response permutation procedure (MRPP) with post-hoc pairwise comparisons to test for significant ($p < 0.05$) differences in fuel complexes by treatment.

3. Results

3.1. Total fuel loading

In 2017, prior to prescribed fire, wind-disturbed sites had the greatest average fuel loading (12,920 kg ha^{-1} ± 1040 SE), followed by mature sites (11,560 kg ha^{-1} ± 720), both greater than salvage-logged sites (7610 kg ha^{-1} ± 420; Fig. 1). After prescribed fire, mature sites contained the highest average fuel loading (6650 kg ha^{-1} ± 610 SE), which was greater than either wind-disturbed (4250 kg ha^{-1} ± 570) or salvage-logged sites (3590 kg ha^{-1} ± 500). A significant interaction occurred between disturbance treatments and time relative to fire on total fuel loading ($p = 0.010$). Prescribed fire reduced total fuel loading by 43% on mature plots, 67% on wind-disturbed plots, and 53% on salvage-logged plots. Overall, post-prescribed fire fuel loading on mature plots was less variable than the disturbed treatments (SE = 194.1 g). Post-fire fuel loading was most variable on wind-disturbed plots (SE = 354.3 g). Whereas all mature and wind-disturbed plots exhibited post-fire fuel reductions, two of 13 salvage-logged plots contained more fuel after prescribed fire.

3.2. Fuel loading by flammability group

Before the 2018 prescribed fire, fuel from wind-disturbed sites was largely comprised of low through moderate flammability group fuels (ca. 80%). For the low flammability group, a significant interaction occurred between disturbance treatment and time relative to fire (Fig. 2, $p = 0.002$). In the moderate-low flammability group, fuel mass by treatment was not significantly different before prescribed fire. However, moderate-low flammability fuels were significantly reduced after prescribed fire ($p < 0.001$) and exhibited greater mass in mature plots compared to salvage-logged sites ($p = 0.007$). Prior to prescribed fire, moderate fuels were significantly greater in wind-disturbed plots than salvaged-logged plots ($p = 0.043$). Prescribed fire reduced the mass of moderate flammability fuels throughout the treatment area ($p < 0.001$), thereby negating differences between disturbance treatments. Catastrophically disturbed plots had significantly greater moderate-high flammability fuels than mature plots both pre- and post-prescribed fire ($p < 0.009$) and total moderate-high flammability fuels was significantly reduced post-prescribed fire ($p < 0.001$). The high flammability fuels were impacted by the interaction of disturbance treatment and time relative to fire ($p = 0.027$). *Pinus* needles had significantly higher mass in mature plots than wind-disturbed and salvaged plots both pre- and post-fire ($p < 0.001$). *Pinus* needle fuel loading was not significantly different before than after prescribed fire. Although they made only a minor contribution to total fuel loading, fuels in the "other" group significantly increased post-prescribed fire ($p = 0.019$). "Other" fuels did not differ between disturbance treatments before prescribed fire, however, post-fire other fuels were significantly higher on wind-disturbed plots compared to mature plots ($p = 0.020$).

3.3. Influence of disturbance and fire on fuel complexes

A two-dimensional NMS solution (final stress = 12.71) explained 98.4% (non-metric R^2 value) of variation in fuel complexes by disturbance treatment and time relative to prescribed fire (Fig. 3). Axis one explained 62% of the variation in fuel complexes and was negatively correlated with sapling density ($r^2 = 0.37$). Axis two explained 27% of the variation in fuel complexes and was positively correlated with basal area ($r^2 = 0.43$) and negatively correlated with bare ground exposure ($r^2 = 0.29$). Mature plots were associated with the positive range of axis one and positive range of axis two. Pre-prescribed fire wind-disturbed plots showed the most variability in ordination space. Post-prescribed fire wind-disturbed plots were more tightly clustered in ordination space and were associated with the positive range of axis one and the negative range of axis two. Pre-fire salvaged-logged plots were primarily associated with the negative range of axis two. Post-fire salvage-logged plots were less variable in ordination space (homogenized), and primarily associated with the positive range of axis one. After prescribed fire, wind-disturbed plots and salvage-logged plots converged in ordination space on the positive range of axis one and the negative range of axis two (i.e. that exhibited more similar fuel complexes). Results from the MRPP indicated that all fuel complex treatments (combinations of disturbance and time relative to prescribed fire) were significantly different ($p < 0.01$) except for the post-fire wind-disturbed and post-fire salvage-logged treatments ($p = 0.21$).

4. Discussion

4.1. Pre-prescribed fire fuel conditions

Wind-disturbed plots likely had the greatest fuel loading in 2017 collections as a legacy of the 2011 tornado disturbance. This is further

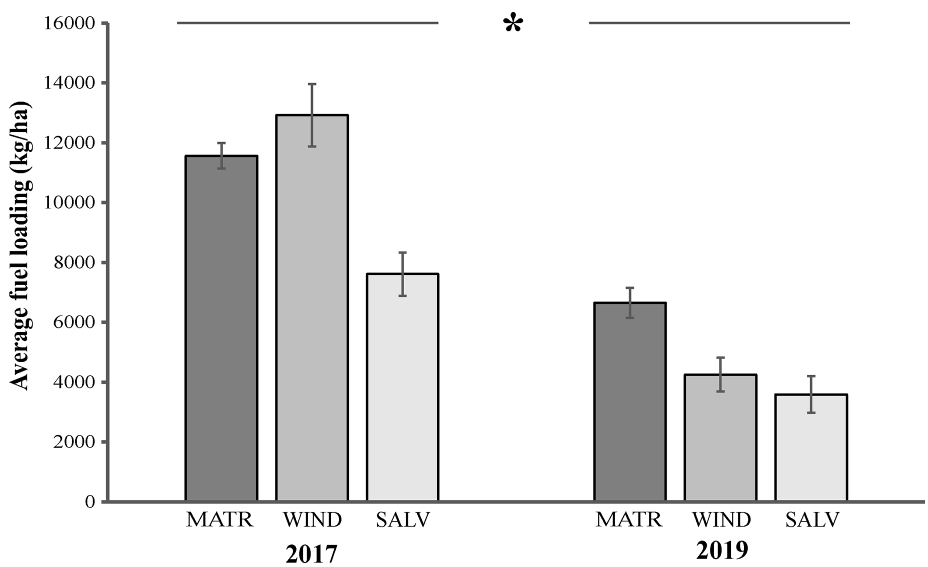

Fig. 1. Mean total fuel loading (kg ha^{-1}) with standard error for mature (MATR), catastrophically wind-disturbed (WIND), and wind-disturbed and salvage-logged (SALV) plots before prescribed fire (2017) and after prescribed fire (2019) in a *Pinus palustris* woodland in the Fall Line Hills of Alabama, USA. A significant ($p < 0.001$) interaction was detected between disturbance treatments and time relative to fire.

supported by the reduced fuel loading on the salvage-logged plots, which, likely because of the salvage operation post-wind disturbance, had similar fuel loadings of woody flammability groups as mature plots (Kleinman et al., 2017; Ford et al., 2018). We report similar *Pinus* litter loadings on mature sites three years after the 2014 prescribed fire (4400 kg ha^{-1}) as a *P. palustris* and wiregrass ecosystem three years post-fire (5000 kg ha^{-1}; Boring et al., 2004), xeric sandhills *P. palustris* ecosystem 4–5 years post-fire (7000 kg ha^{-1}; Wenk et al., 2011), and Coastal Plain *P. palustris* ecosystem 3–4 years post-fire (5700 kg ha^{-1}; Wiggers et al., 2013). Total montane *P. palustris* fuel loadings reported by Bale (2009) were 7200 kg ha^{-1} three years post-fire, much less than total fuel loadings observed for our mature sites (11,560 kg ha^{-1}).

Pinus needles were a dominant fuel on mature plots, however, we also noted a stronger presence of fuel types not commonly observed in frequently burned *Pinus* stands (Bale, 2009; Stokes et al., 2010). Specifically, wind-disturbed plots and salvage-logged plots had much lower fuel loadings of *Pinus* needles (300 kg ha^{-1} and 60 kg ha^{-1}, respectively) because they lacked overstory *Pinus* individuals. However, the lack of *Pinus* needles on these sites was somewhat offset by increased contributions of fuels such as vines, shrubs, and non-*Quercus* broadleaf species that have similar flammability characteristics to *Pinus* needles. This finding is inconsistent with O'Brien et al. (2008) and Cannon et al. (2014), but patterns are likely site-specific and related to climatic conditions or severity of disturbance events (Cannon et al. 2017). We documented loadings of moderate-high and high flammability fuels (2400 kg ha^{-1} on wind-disturbed and 1900 kg ha^{-1} on salvage-logged sites) on disturbed sites that were comparable to the fuel loadings documented by Wenk et al. (2011). Although the increased contributions of moderate-high and high flammability fuels on wind-disturbed and salvage-logged sites may help sustain prescribed fire and offset the loss of *Pinus* needles, fire behavior may be different (Wiggers et al., 2013; Robertson et al., 2019). For example, Emery and Hart (2020) observed that the high flammability group fuels had taller flame heights, but shorter flaming durations than *Pinus* needles. However, the fuel loading will be important to consider as well.

Pre-prescribed fire fuel complexes in wind-disturbed plots exhibited the greatest variability in ordination space, followed by salvage-logged plots. Natural catastrophic disturbances often result in relatively complex, heterogeneous intrastand patterns of biological legacies, and an important legacy is dead wood. We speculate that the high variability of fuels in the wind-disturbed treatment prior to the 2018 prescribed fire is a result of patches of high woody debris loading that varied through space. We suspect that salvaged-logged sites exhibited less fuel variability as a result of the mechanical removal and redistribution of fuels. In contrast, the relatively homogenous fuel complexes observed on mature sites, which exhibited little overlap with disturbed plots, were attributed to the presence of abundant *Pinus* needles derived from live overstory *P. palustris* trees. Fuel complexes on the catastrophically disturbed plots were associated primarily with sapling density, which was a direct result of canopy removal by the catastrophic wind disturbance event.

4.2. Post-prescribed fire fuel conditions

After the 2018 prescribed fire, mature plots had the highest average total fuel loading because of *Pinus* needles, which continued to be a dominant fuel on mature sites after prescribed fire (2700 kg ha^{-1}). Robertson et al. (2019) noted that the abundance of ground-layer plants is often limited by competition with canopy *P. palustris* trees, *Pinus* needle mulching, and fire severity associated with *Pinus* needles, branches, and cones. Although our fuel collections occurred in the dormant season, we observed an increase in the relative abundance of early successional species in the fuel complex after the prescribed fire. Spencer and Baxter (2006) discussed how *Pteridium* spp. rapidly regenerate after disturbances, such as a prescribed fire, from belowground rhizomes. Some grasses (e.g. *Schizachyrium scoparium* Michx. Nash) have a similar post-fire response. Gagnon et al. (2015), Parresol et al. (2012) and Stokes et al. (2010) noted a similar response of grass to fire, suspecting low basal area and moderate fuel loading resulted in a stronger grass response, while high basal area and greater than normal fuel loading limited grass response. Holzmueller and Jose (2012) observed that the invasive grass *Imperata cylindrica* (L.) Beauv. was more abundant on sites in Florida, USA that had low basal area and had been burned repeatedly.

Based on our collections, fuel loading decreased 43% for mature plots, 67% for wind-disturbed plots, and 53% for salvage-logged plots. These reductions were more moderate than the 75–80% fuel reduction proposed by Wade and Lunsford (1989) as targets for operational prescribed fires in the southeastern USA. For comparison, complete or near complete consumption was reported for *Q. laevis*, wiregrass, and *P. palustris* fuelbeds (93–97%; Wenk et al., 2011) and litter (90–95%; Ferguson et al., 2002) by prior researchers. We note that our post-fire fuel collection occurred nine months after the 2018 prescribed fire and this period certainly allowed for post-fire fuel accumulation.

The treatment that experienced the greatest total decrease in fuel loading was the wind-disturbed treatment, and mature sites experienced the lowest total fuel loading decrease. Fuel reduction patterns may in part be a result of the higher accumulation rates on mature plots

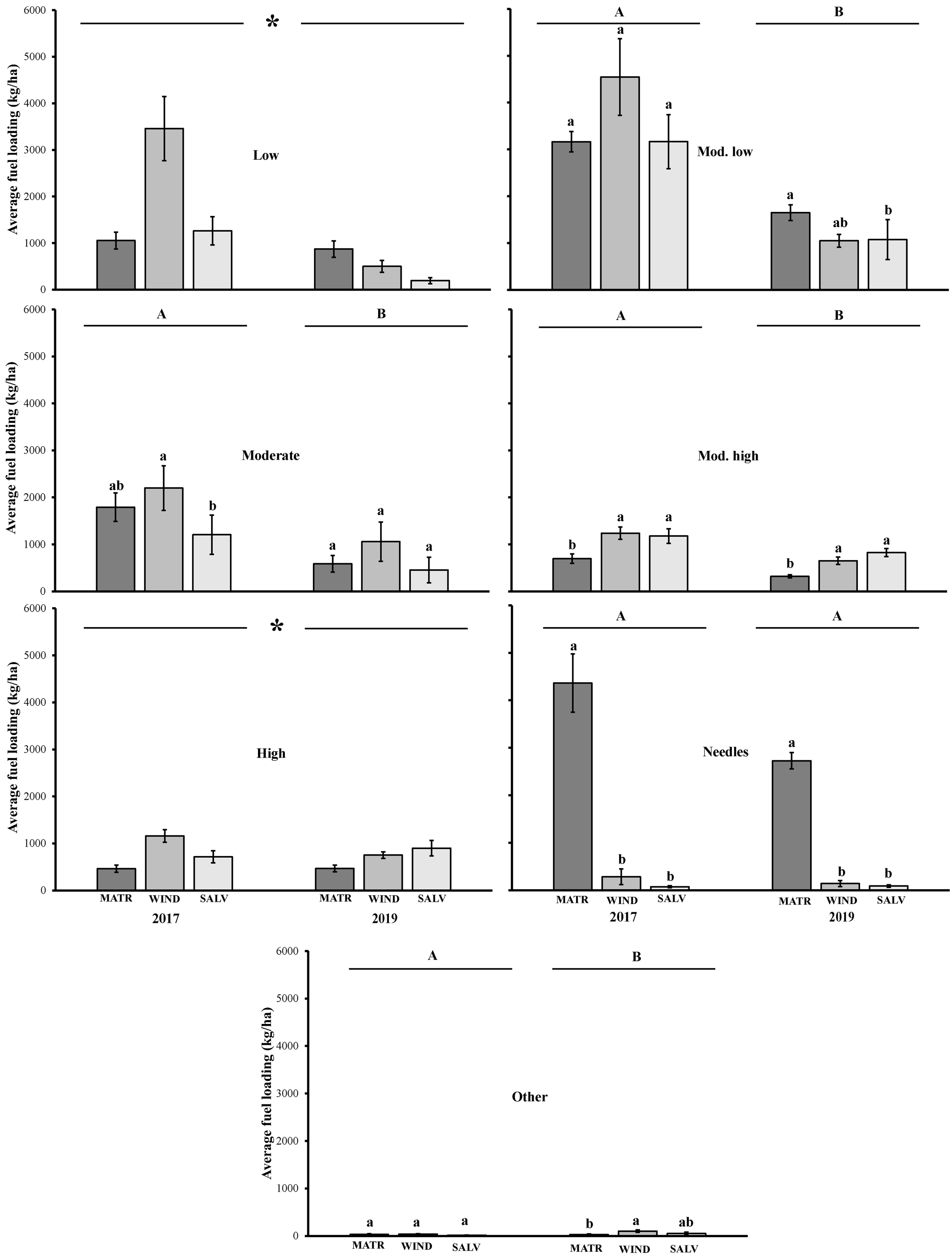

Fig. 2. Mean total fuel loading (kg ha-1) by flammability group with standard error for mature (MATR), catastrophically wind-disturbed (WIND), and wind-disturbed and salvage-logged (SALV) plots before prescribed fire (2017) and after prescribed fire (2019) in a *Pinus palustris* woodland in the Fall Line Hills of Alabama, USA. An * indicates a significant ($p < 0.05$) interaction was detected between disturbance treatment and time relative to fire. When a significant interaction was not detected, different lower-case letters indicate significant differences by disturbance treatment and different upper-case letters indicate significant differences by time relative to fire.

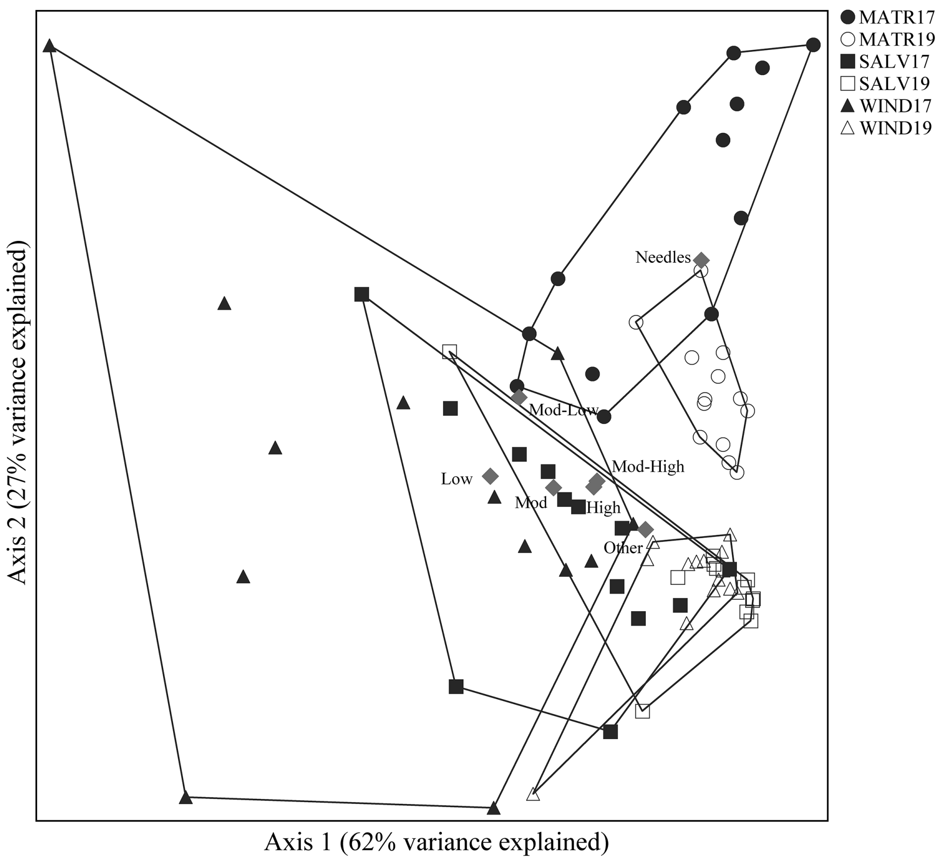

Fig. 3. Non-metric multidimensional scaling ordination summarizing variation in fuel complexes by treatment combinations (disturbance treatments by time relative to fire) for a *Pinus palustris* woodland in the Fall Line Hills of Alabama, USA. MATR: mature sites not impacted by the 2011 tornado, WIND: sites catastrophically disturbed by an EF3 tornado, SALV: sites catastrophically disturbed and subsequently salvage logged, 17: 2017 collection year and pre-fire condition, 19: 2019 collection year and post-fire condition. Gray diamonds illustrate position of fuel flammability groups in ordination space.

because they had dominant canopy trees (Loudermilk et al., 2011). Additionally, wind-disturbed plots showed a large decrease in fuel loadings for woody fuels. We actually noted increase fuel loading on two salvage-logged plots after the 2018 prescribed fire (fuel mass increased by 0.2% and 9.0% on those plots). Interestingly, we also noted a decrease of fuel mass of 82% for a plot in the salvage-logged treatment. In general, wind-disturbed plots and salvaged plots contained more fuelbed compositional diversity, with grasses, *Pteridium latiusculum*, and other herbaceous species as the dominant fuels. With more variability in fuel loading and with a more complex fuelbed composition, prescribed fire on disturbed sites may have been more discontinuous (i.e. patchy) relative to fire on mature sites that had relatively homogenous, contiguous fuelbed of *Pinus* needles. However, patchy fires may be desirable as Robertson et al. (2019) and Loudermilk et al. (2011) found that patchy fires may aid *P. palustris* regeneration by providing spatially distinct areas where *P. palustris* seeds could germinate and survive to the relatively fire-tolerant grass stage. However, it is possible that these patchy fires may only aid *P. palustris* regeneration when associated with canopy gaps that meet certain size thresholds (McGuire et al., 2001).

The 2018 prescribed fire resulted in a homogenization of fuel complexes, as evidenced by post-fire treatment constriction in ordination space (smaller perimeters of convex hulls). The post-prescribed fire mature treatment was positively related to basal area and negatively related to exposed mineral soil. With greater overstory basal area, needle deposition is ubiquitous and the fuelbed complex contains little variability in mass and composition. We speculate that convergence of the fuelbed complexes of wind-disturbed and salvaged treatments was likely a function of ground flora responses to prescribed fire on sites without a canopy. Although the wind-disturbed and salvage-logged sites had different ground flora assemblages (Kleinman et al. 2017), the different species were distributed similarly across our flammability groups (i.e. contribution across flammability groups was similar).

Our study was focused on the second prescribed fire since the 2011 tornado and salvage-logging operation. Prescribed fire appeared to homogenize the fuelbeds of wind-disturbed and salvage-logged sites, but we do not know if fuel loading and composition will remain similar or if they will diverge with time since fire. Our 2017 fuels collection represented conditions three growing seasons after prior prescribed fire. Thus, it is possible the sites will again diverge along different pathways with time since fire.

5. Management implications

Overall, our results indicated that prescribed fires reduced fuelbed variability across mature, wind-disturbed, and salvage-logged treatments in a *P. palustris* woodland. Furthermore, prescribed fire facilitated the convergence of the fuelbed complexes of wind-disturbed sites and salvaged-logged sites. Mature site with a nearly monospecific canopy of *P. palustris* had fuelbeds predominately composed of *Pinus* needles, with low variability of fuelbed composition and loading within the treatment. Catastrophically disturbed sites largely lacked *Pinus* needles in the fuelbed, but the dearth of *Pinus* needles was somewhat offset by increases in moderate-high and high flammability fuels in these treatments. Thus, the catastrophic disturbance removed *P. palustris* trees from the canopy and in so doing, increased insolation near the forest floor which resulted in more ground cover, some of which burns comparable to *Pinus* needles. Vegetation-fuels-fire feedbacks on mature sites also appeared to be stable with a fuel loading and basal area similar to those reported in other *P. palustris* ecosystems (Varner et al., 2005; Teague et al., 2014; Kirkman et al., 2017). Our results provide quantitative information on the effects of catastrophic disturbance and subsequent salvage logging on fuel complexes in frequently burned woodlands. This information may help managers decide if salvage logging is situationally appropriate after catastrophic wind disturbance in other fire-dependent ecosystems. Salvage logging resulted in dissimilar fuel assemblages compared to wind-disturbed sites but, continued use of prescribed fire ultimately homogenized fuelbed composition and loading. Thus, if salvage logging is utilized, we recommend the continued use of prescribed fire to minimize the impact of salvage logging on fuelbed composition and loading. This information also improves our ability to predict and guide the ecological effects of prescribed fire in frequently burned forests.

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.

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Declarations

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Consent for publication: Not applicable.

Availability of data and material: The datasets used and analyzed during the current study are available from the corresponding author upon reasonable request.

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