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Research Article

Silviculture

Natural Canopy Disturbance Patterns and Ecological Silviculture in the Alabama Fall Line Hills

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Abstract

As a natural disturbance-based approach to silviculture is increasingly embraced by forest managers, quantitative reference conditions of natural disturbance patterns are paramount. We used LiDAR data to quantify resultant structural patterns from an EF3 tornado on the Oakmulgee Ranger District of Talladega National Forest in the Alabama Fall Line Hills, USA. We found the zone of catastrophic disturbance totaled 123 ha, had a mean width of 360 m, and residual trees were randomly distributed. This zone was buffered by an edge zone of intermediate-severity disturbance where trees were removed individually and in groups. The edge zone averaged 220 m in width. In total, the study area included seventy-nine stands and the percentage of stand area damaged ranged from < 1% to 94%. We suggest that clearcut, seed tree, and shelterwood with reserves regeneration methods may be appropriate analogs to natural canopy disturbance in the Fall Line Hills region. These catastrophic disturbance entries should be buffered from undisturbed neighborhoods by a system that retains mature forest structures and would constitute a zone of intermediate-severity disturbance. Our approach may be used as a template to expand our understanding of natural canopy disturbance patterns in other regions and forest types.

Study Implications: In regions where tornadoes are a natural component of the disturbance regime, including much of the southeastern United States, we suggest that clearcut, seed tree, or shelterwood with reserves regeneration methods may be used to approximate the zone of catastrophic disturbance that corresponds to the tornado track. We observed that reserve tree spatial patterns were random, but residual trees could be selected based on desired species or protection of important biophysical features such as seeps. Surrounding the catastrophic disturbance zone was an edge zone of intermediate-severity disturbance where trees were removed individually and in variably sized groups. We suggest that the structural patterns documented in this edge zone may be created through variable retention harvesting.

Keywords: ecological forestry, natural disturbance, *Pinus palustris*, restoration, tornado, *Quercus*

The ecological forestry approach to forest management is increasingly being embraced to achieve an integrated suite of environmental, economic, and social objectives (D'Amato et al. 2017). This framework is based on an ecological understanding of forest ecosystem processes and prioritizes environmental outcomes (Franklin, Johnson, and Johnson 2018). Ecological silviculture may be considered the application of ecological principles to the manipulation of forest ecosystems (Palik et al. 2021). A basic tenet of this approach is that interventions should be based on natural patterns of disturbance and stand development (Seymour and Hunter 1999). Thus, quantitative and place-based information on natural disturbance patterns is crucial for the development of ecological silvicultural systems (Seymour, White, and deMaynadier, 2002, Franklin, Mitchell, and Palik, 2007, Palik et al. 2021). For example, this approach requires quantification of the size, shape, and frequency of disturbance-created openings and the density and spatial pattern of residual trees to develop silvicultural entries based on the disturbances to which the species within the ecosystems evolved. It is hypothesized that this silvicultural approach will maintain forest diversity and critical ecological functions and promote resilience to future stressors and perturbations (Long 2009).

Natural disturbance processes and patterns vary by geographical region and forest type. As such, quantitative information on natural disturbance regimes is needed for unique regions and forest communities. In the Alabama Fall Line Hills of the southeastern United States, and indeed for much of the broader region, tornadoes are a common canopy disturbance agent. At the landscape scale, these events can be quite frequent. For example, the approximately 65,000 ha that represent the Oakmulgee Ranger District of the Talladega National Forest in Alabama have been affected by twenty-three tornadoes that ranged from EF0 to EF3 in the past 20 years (FEMA 2023). Although the tornado return interval for a single stand may be relatively long when compared with the lifespan of dominant trees, the recurrence interval at the landscape level, or in this case the district level, is less than 1 year. Tornado impacts in forest ecosystems vary depending on storm characteristics, stand conditions, and topography. Along the disturbance severity gradient, tornadoes may be classed as intermediate

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severity to catastrophic disturbance events (Hart and Kleinman 2018). Our goal was to provide quantitative information on the structural patterns resultant from an EF3 tornado in the Alabama Fall Line Hills. This information can be used as a starting point to develop a robust dataset that encompasses the range of natural canopy disturbance patterns in the southeastern United States and we hope will serve as a template for future studies. As an ecological forestry approach is more widely embraced, ecological silvicultural systems will increasingly be implemented, and quantitative information on natural canopy disturbance patterns will be crucial.

Methods

Study Site

Our study was conducted on the Oakmulgee Ranger District of Talladega National Forest in west-central Alabama. The Oakmulgee Ranger District is situated in the Fall Line Hills ecoregion (level III) and occurs within the *Quercus-Pinus* forest region of the southeastern United States (Braun 1950, Griffith et al. 2001). The Fall Line Hills represent a physiographic transition zone where deeply eroded, marine-deposited sediments of the Coastal Plain meet the steep slopes and higher elevations of the Appalachian Highlands (Fenneman 1938). As such, the region supports plant assemblages characteristic of the Coastal Plain and Appalachian Highlands (Shankman and Hart 2007, Kleinman and Hart, 2018). In the Oakmulgee Ranger District, *P. palustris*-dominated woodlands occur on fire-maintained upper slopes and south-facing lower slopes, and a diversity of *Quercus* spp. and other hardwoods coexist with *P. echinata* and *P. taeda* in the overstories of more mesic sites (Beckett and Golden 1982, Cox and Hart 2015). Hillslopes and ridges in the study area contain deep, moderately well-drained soils derived from the Cretaceous-aged Gordo Formation (Szabo et al. 1988, USDA NRCS 2020). Maubila series soils consist of a sandy loam or loam surface layer up to 10 cm deep and clay-based substrata over 200 cm deep to bedrock (USDA NRCS 2008). The region has a humid mesothermal climate, characterized by long, hot summers and year-round precipitation (Thornthwaite 1948). Mean temperature is 17.2°C, with mean January and July temperatures of 6.6°C and 26.9°C, respectively, and mean annual precipitation is 1376.21 mm (PRISM 2020). The frost-free period is approximately 230 days from March to November (USDA NRCS 2008). The USDA Forest Service has an active prescribed fire program here and manages the compartments in our study area with prescribed fire on a 2–5 year rotation. Low-intensity surface fire is an important component of the disturbance regime in the Alabama Fall Line Hills and we stress that any silvicultural manipulation of canopy trees should be conducted in the context of an active prescribed fire program.

On April 27, 2011, the Oakmulgee Ranger District of Talladega National Forest was affected by an EF3 tornado with estimated maximum wind speeds of 233 km hr^{-1} (National Weather Service 2011). The tornado was one of 362 tornadoes that affected the eastern United States during the April 25–28, 2011, super outbreak and one of three tornadoes to affect the Oakmulgee Ranger District on April 27.

Analytical Methods

To quantify residual stand structure after the EF3 tornado at the landscape scale, we downloaded a canopy height model derived from LiDAR data. The LiDAR data were collected in 2015 in support of the National Ecological Observatory Network (NEON) using an Optech Gemini LiDAR system mounted to a fixed-wing aircraft (NEON 2022). We acknowledge that the 2015 observations may have included wind-induced delayed mortality and mortality not directly related to the 2011 tornado (e.g., insect and disease-induced mortality). The LiDAR data were downloaded from the publicly available NEON database (NEON 2021). The canopy height model (CHM) and digital terrain model (DTM) were mosaicked individually and were downloaded as twelve 1 km^2 tiles. We used the R package "rLiDAR" (Silva et al. 2015) to identify and georeference individual trees within the CHM using a 3 × 3 grid cell window and a minimum height threshold of 5 m. The package "ForestGapR" (Silva et al. 2019) was used to identify the size and count of canopy gaps using a height threshold of 5 m and a minimum area of 25 m^2. These R packages have been used widely in forest disturbance studies (e.g., Mueller et al. 2022).

We used the dataset to visualize and quantify disturbance-induced structural patterns using methods common in remote sensing studies. We determined the size of disturbance-created openings and used Ripley's K analysis performed in ArcGIS Pro 3.0.3 to quantify the density and spatial patterns of residual trees. Because forest edges can be difficult to delineate when there is a gradual increase in stem density from catastrophically disturbed to undisturbed forest (Goode et al. 2020), we created 210 transects perpendicular to a 4,200 m center line following the southwest to northeast direction of the tornado track. Each transect was 1,000 m in length and contained fifty 20 m × 20 m contiguous quadrats. In total, there were 10,500 quadrats of which 176 were removed because they were outside our delineated study area. The remaining 10,324 quadrats comprised an area of 413 ha. Within each 400 m^2 quadrat, we calculated stem density and grouped the quadrats into bins representing maximum values of 0, 100, 200, 300, 400, 500, and 800 trees ha^{-1}. We also estimated the width of edges surrounding disturbance-created openings by establishing the distance when no discernable canopy impact from the tornado was evident (i.e., the area of intermediate disturbance that surrounded the zone of catastrophic disturbance). To provide quantitative information at the stand scale, we documented the number of stands affected directly by the tornado in our study area as well as the percentage of the stand area with canopy damage. Using this information, we provide examples of silvicultural systems based on the documented disturbance patterns for stands in this region. Stand boundaries, area, forest type, and condition class information were provided by the Forest Service.

Results and Discussion

The main tornado path corresponded to a zone of catastrophic disturbance (i.e., a large contiguous opening) of 123 ha (figure 1). Along the periphery of this large opening was a zone of intermediate-severity disturbance characterized by an abundance of canopy gaps caused by the death of one tree or clusters of trees. The canopy openings in the intermediate-severity zone ranged in size from 26 to 8,351 m^2, and mean

and median opening size were 137 m^2 and 58 m^2, respectively (figure 2).

In the catastrophic disturbance zone, density ranged from zero to four trees per 400 m^2 quadrat and residual tree density varied across the disturbance-created opening (figure 3). Within the large contiguous opening, residual trees exhibited a random distribution, with no significant clustering or dispersion.

The mean width of the catastrophic disturbance zone was 360 m. This zone corresponded to the tornado path and was bordered by the edge zone characterized by intermediate-severity disturbance. The intermediately disturbed edge zone had a mean width of 220 m. Residual density in this zone ranged from five to twelve trees per 400 m^2 quadrat. The edge was characterized by more localized canopy openings rather than a large contiguous opening (figure 4).

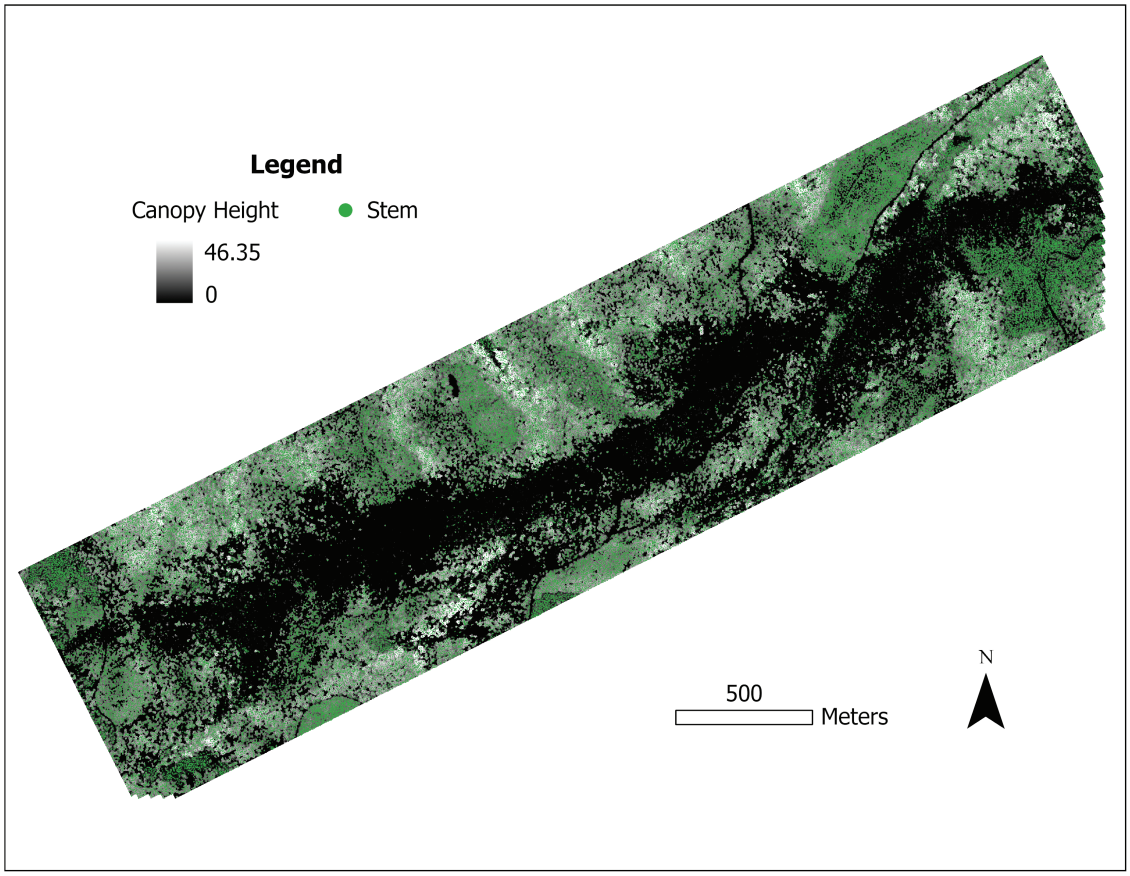

Figure 1 Canopy height model (meters) of residual stems ≥ 5 m height along the path of an EF3 tornado in the Oakmulgee Ranger District, Talladega National Forest, Alabama, USA.

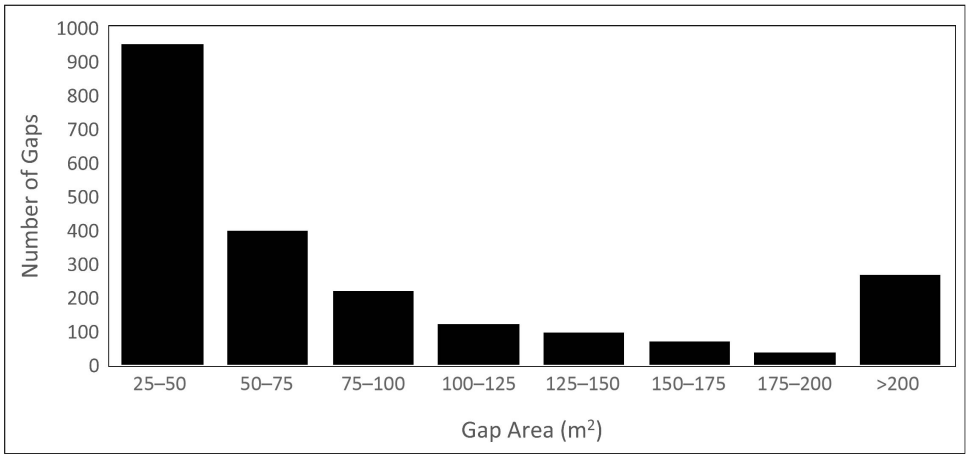

Figure 2 Size-frequency distribution of canopy gaps along the edge zone (i.e., zone of intermediate-severity disturbance) along an EF3 tornado path in the Oakmulgee Ranger District, Talladega National Forest, Alabama, USA.

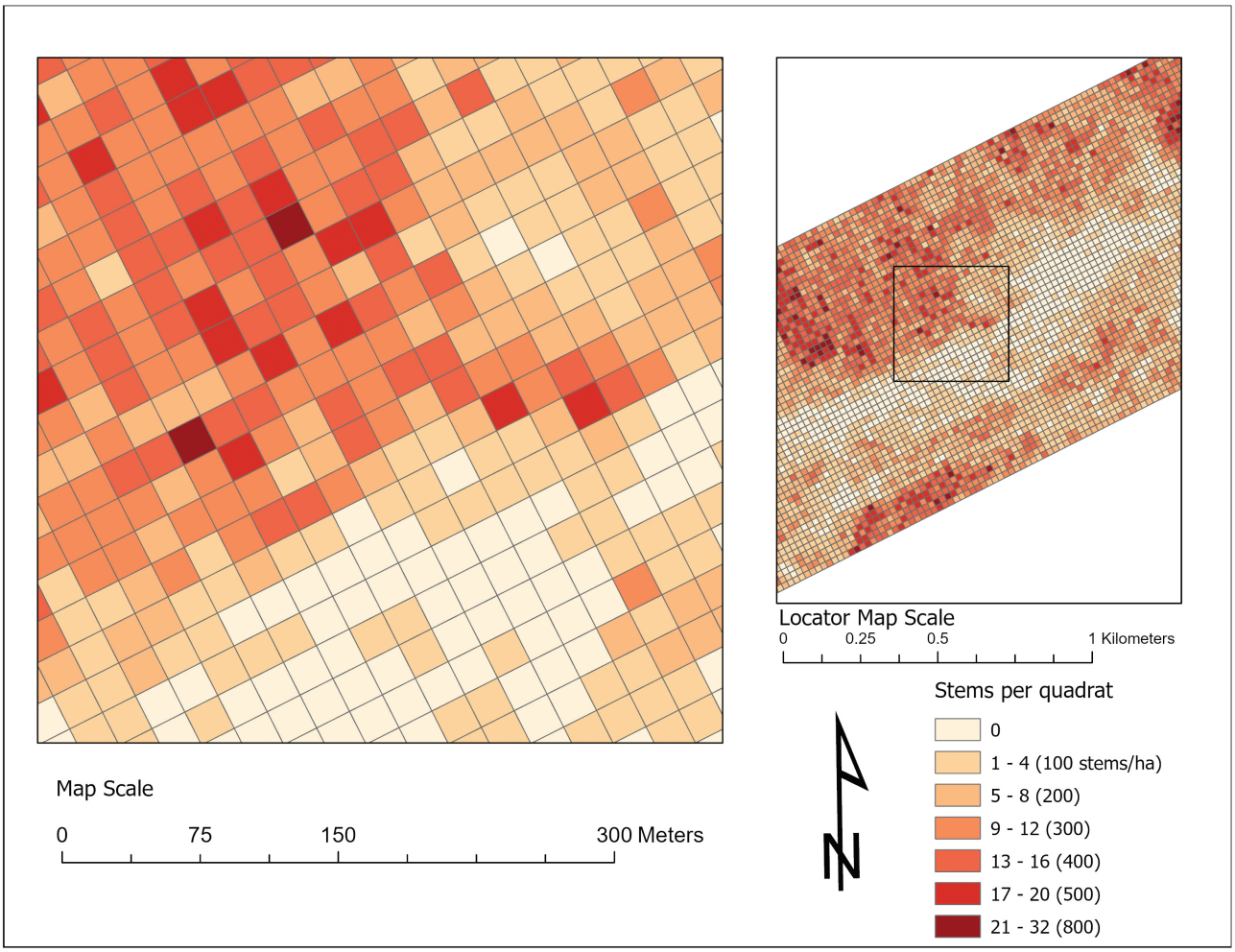

Figure 3 Stem density in 20 m × 20 m quadrats along an EF3 tornado path in the Oakmulgee Ranger District, Talladega National Forest, Alabama, USA. Stems include woody plants ≥ 5 m height.

Through the 413 ha study area, seventy-nine individual stands across six Forest Service delineated compartments were directly affected by the EF3 tornado. Predisturbance conditions of these stands ranged in species composition and structure and included those that were *P. palustris* dominated, *Quercus* dominated, and *Pinus-Quercus* mixedwoods. At the time of the wind disturbance, stands ranged from stem exclusion to complex stages of development. For the seventy-nine stands in the study, the percentage of stand area damaged ranged from 1% to 94%. Across all stands, the mean and median stand area damaged by the tornado was 24% and 13%, respectively. Based on our observations, we suggest that the proportion of stand disturbance was related to geographical position along the tornado track more so than species composition or structural condition. The aerial extent of damage exceeded 80% for five of the seventy-nine stands in the study area (figure 5).

Post-disturbance patterns of survivorship can help inform and be integrated into silvicultural methods, which include an active prescribed fire program. We suggest that clearcut with reserves, seed tree with reserves, or shelterwood with reserves regeneration methods may be used to approximate the zone of catastrophic disturbance that corresponded to the tornado track. In this zone, most stems were killed and residual tree density varied from zero to one hundred stems ha^{-1}. We observed that residual tree spatial patterns were random. However, in practice, residual trees could be selected based on desired species or protection of important biophysical features such as seeps. Surrounding the catastrophic disturbance zone was an edge zone of intermediate-severity disturbance. This zone represented a gradient from catastrophically disturbed neighborhoods to those that were undisturbed by the tornado. This zone was heterogenous, as it consisted of an abundance of single and multi-tree gaps. We suggest that the structural patterns documented in this edge zone may be promoted through variable retention harvesting. We note that some stands were almost fully contained within the catastrophic disturbance zone, some stands had only intermediate-severity disturbance impacts, and some stands contained neighborhoods that were catastrophically disturbed, moderately disturbed, and undisturbed by the tornado. Thus, we suggest that silvicultural treatments be implemented in groups that acknowledge intra-stand spatial patterns.

Even if an ecological silvicultural approach is implemented, forest ecosystems will still be influenced by natural intermediate-severity and catastrophic disturbance events, such as tornadoes. Tree vulnerability to wind disturbance is largely a function of tree size (Foster and Boose 1992, Peterson 2007, Cox et al. 2016), so theoretically, smaller trees in recently treated stands should be more windfirm relative to

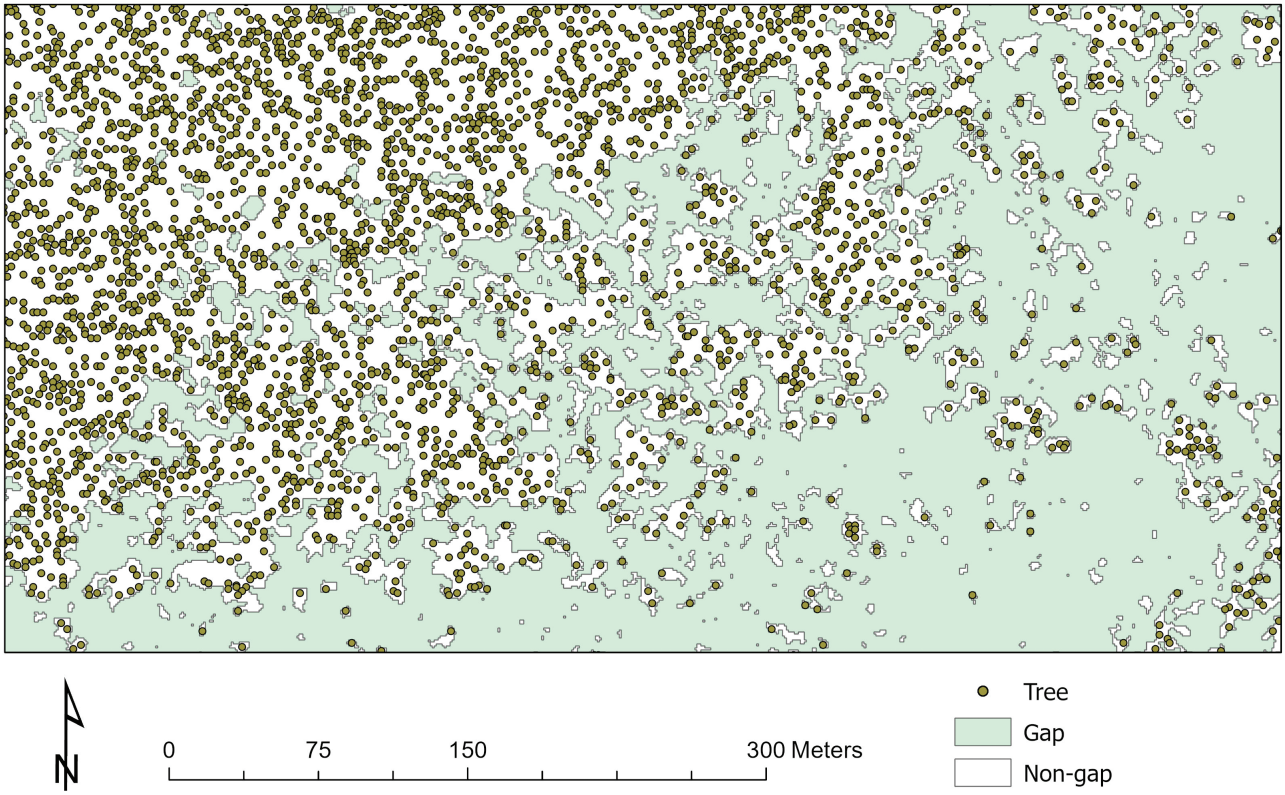

Figure 4 Residual trees (stems ≥ 5 m height) and canopy gaps along an EF3 tornado path in the Oakmulgee Ranger District, Talladega National Forest, Alabama, USA.

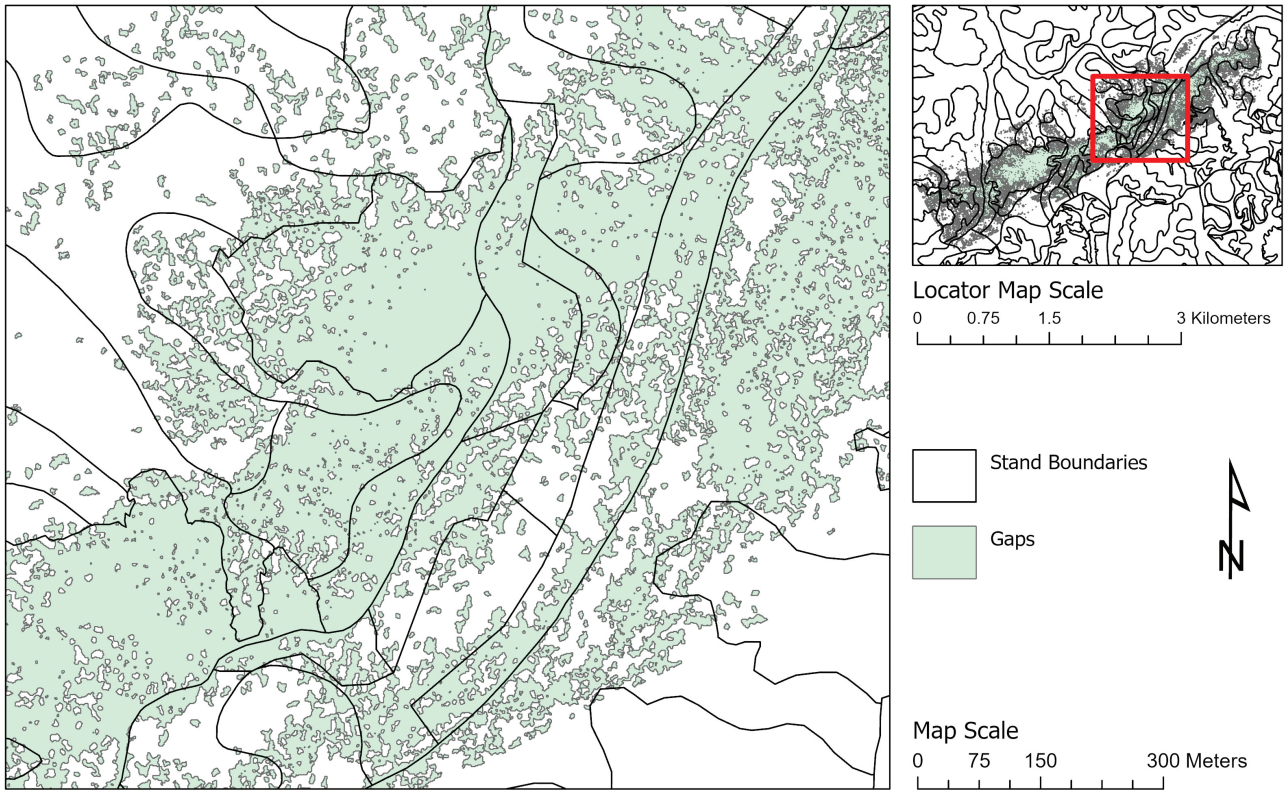

Figure 5 Delineated canopy gaps (no stems ≥ 5 m height) and stand boundaries along an EF3 tornado path in the Oakmulgee Ranger District, Talladega National Forest, Alabama, USA.

larger trees that are more abundant in older stands. Thus, at the landscape scale, tornado-damaged forest land area may decrease, as recently treated stands would contain smaller stems that are less vulnerable.

We stress that intermediate-severity and catastrophic disturbance events are not the only disturbances that affect stands in the Alabama Fall Line Hills. Without question, low-intensity surface fire is a critical part of the disturbance regime (Emery et al. 2020, Kleinman et al. 2021). Any ecological silvicultural system developed and implemented on upland sites in this region should include an active prescribed fire program, such as the one at the Oakmulgee Ranger District of Talladega National Forest. In fact, implementing thinning and regeneration treatments in the absence of a prescribed fire program would likely serve to accelerate succession to more shade-tolerant taxa (Abrams and Nowacki 1992; Holzmueller et al. 2012). We do note that canopy treatments, as described here, and prescribed fire are complimentary. Specifically, retention of canopy trees through the cut block allows for a more contiguous fuel bed, which may help achieve desired fire effects. In addition to surface fire and intermediate-severity and catastrophic disturbances, localized canopy disturbances are also an important part of the disturbance regime in this region (Ford et al. 2017, Mueller et al. 2022). Certainly, localized canopy gap formation is much more common here than intermediate-severity and catastrophic canopy disturbances, and these events could also be incorporated into silvicultural systems such as those described by Brockway and Outcalt (1998), Brockway et al. (2015), or others. We stress that an ecological silvicultural system should consider and incorporate the entire natural disturbance regime (Palik et al. 2021). We call for additional studies such as this to expand our understanding of residual stand structures that result from natural canopy disturbances, and we hope our approach can be used as a template for future investigations.

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None declared.

Conflict of Interest

None declared.

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