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ORIGINAL ARTICLE

Spatiotemporal Changes in Forest Metrics after a Catastrophic Tornado in Planted Loblolly Pine (*Pinus taeda* L.) Stands

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Abstract

Tornadoes drastically impact managed forest landscapes, altering structure, composition, and economic valuation. Tornadoes occur frequently in the US and are projected to increase in the southeastern region, which is a substantial timber-producing region. Quantifying tornado damage in managed forest landscapes is important for guiding management decisions and modeling recovery efforts to recoup economic losses. We assessed the spatiotemporal effects on forest structure, volume, and carbon in 13–17 year old loblolly pine (*Pinus taeda* L.) stands after an EF-3 tornado, with a path length of 35 km long and damage swath of 250 m wide, in Shallotte, North Carolina, US. We established 36 plots along a tornado path and reconstructed pre-storm stand characteristics to compare them to the first and third growing seasons (2021 and 2023) after the storm. To evaluate the spatial distribution of damage, we sampled directly in the tornado's path, along its edge, and in undisturbed, adjacent forest areas within the same stand. We found that damage was localized, reducing trees per hectare, basal area, volume, and aboveground carbon stock by ~ 50% directly inside the tornado track, while plots located on the edge or in undisturbed forest areas were nominally affected. By the third growing season, all metrics from plots inside the tornado track, except for tree density, increased and stand volume returned to the pre-storm levels. This indicates a rapid recovery in even-aged, spatially uniform pine stands with minimal impacts at the edges and forest interior from the tornadic event. By documenting localized losses and metric-specific recovery of forest structure, this study establishes an empirical baseline for understanding short-term tornado effects in even-aged pine stands, which is important for informing targeted post-disturbance management decisions.

Keywords Disturbance · Forest management · North Carolina · Productivity · Tornado · Wind disturbance

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Introduction

Wind disturbances are key drivers in shaping forest ecosystems, influencing successional pathways, species composition, and structural complexity (Peterson 2000a). Among these disturbances, tornadoes are particularly stochastic and intense, resulting in localized damage with sharply defined boundaries (Dyer 1988; Canham et al. 2001). Tornadoes occur more frequently in the US than any other country, with more than six million hectares of total land area affected (i.e., cumulative tornado path area), including ~ 2.2 million hectares of forest land, between 1995 and 2021 (Munro et al. 2024). They are common in the southeastern US where forest land covers ~ 84 million ha (46% of the land area), much of which are loblolly pine (*Pinus taeda* L.) stands (> 22 billion trees throughout its native range; Oswalt et al. 2019) managed for a variety of wood products (Schultz 1999; Barnett and Sheffield 2004; Bettinger et al. 2013). Recent evidence suggests extreme weather events are intensifying in this region, potentially compounding future damage and effects on the forest sector (Stott 2016; Zhang et al. 2020; Fortuin et al. 2022; Munro et al. 2024).

Quantifying tornado effects in managed forest systems is essential for developing targeted management strategies and predicting ecosystem responses. Tornado damage is often measured by reductions in basal area (m^2/ha), stem density (trees/ha), and aboveground biomass (kg/ha), which are not only indicators of ecological change, but also timber yield, carbon storage, and forest resilience (Zhao et al. 2015). Wind disturbances in the US, including tornadoes, cause annual losses exceeding $250 million due to factors such as timber salvage costs, cleanup and replanting efforts, and decreased stumpage prices after storm events (Dale et al. 2001; Cannon et al. 2016; Bradley 2018). Historically, individual tornadic events have reported losses of forest products from $400,000 to over $3 million (GFC 2020). Additionally, water loss in damaged trees can significantly reduce returns for landowners when timber is sold by weight, a common practice in many regions in the US South (Brady 2011; Dickens et al. 2016). Given the localized nature of tornadoes, these economic effects are often geographically concentrated, leading to severe financial consequences for forest landowners (Holmes et al. 2008).

While there is a rich body of literature on the effects of wind disturbance on forest landscapes, most studies focus on hurricanes (Gao and Larjavaara 2024). Tornadoes are less frequently studied, especially in commercially managed forests, and differ from other wind disturbances (e.g., hurricanes and derechos) due to their narrower paths and high-intensity damage over fine spatial scales (Foster 1988; Peterson 2000a). This concentrated damage can create abrupt transitions in forest structure, where heavily damaged areas border relatively undisturbed forest stands. Such spatial heterogeneity drives complex patterns of tree mortality, gap dynamics, and competitive interactions that shape post-disturbance recovery trajectories (Peterson and Rebertus 1997; Xi et al. 2008). Tornado-induced damage, including stem breakage and uprooting (Quine 1995; Peterson 2000a), is influenced by factors such as tornado intensity, tree species and size, stand characteristics (e.g., density, composition, and management history), environmental conditions (e.g., soil and topography), and other exogenous factors (Gardiner 2021; Everham and Brokaw 1996). Loss of dominant canopy trees can trigger competitive release, promoting understory growth and early successional species, potentially altering stand dynamics for decades (Oliver and Larson 1996). Removal of larger trees may also cause a short-term shift in diameter class distributions and reduce aboveground live carbon stocks (Oliver and Larson 1996). Understanding these dynamics in managed forest stands remains critical for maintaining both economic viability and ecosystem health. Further, estimating forest biomass and carbon reductions is becoming increasingly important for voluntary carbon reporting and carbon projects, where disturbance-related fluxes can influence project baselines, credit valuation, and broader climate mitigation goals.

Assessing tornado damage in managed pine stands has remained a salient gap in forest disturbance research, especially given the unique structural characteristics of single-species planted stands and the potential economic impacts. Prior research has focused on mixed-species or natural stands, where species diversity, varied age classes, and complex structural layers may interact to mediate damage and recovery (Brewer et al. 2012; Cannon and Brewer 2013; Cowden et al. 2014). However, managed pine systems in the southeastern US are typically characterized by even-aged stands, dominated by a single-species, with high stem densities and regular thinning cycles. These stand-level factors may influence both the extent and distribution of damage following a tornado which in turn may influence regeneration and replanting efforts. For example, both mixed and single-species pine stands would likely experience advanced regeneration with recruitment from existing plants in the understory (Szwagrzyk et al. 2018; Peterson 2000b). In mixed stands, they may result in canopy replacement with more shade tolerant species within the stands. Whereas, in single-species pine stands that are managed well to reduce hardwoods by prescribe fire or herbicides, hardwoods may encroach more from the forest edges and thus, interfere with the management's objective.

To better understand how tornadoes may influence dynamics of planted pine forests, we quantified the immediate and post-disturbance state after a catastrophic tornado in the Lower Coastal Plain in North Carolina. Our study is unique because there is little research on tornado damage in even-aged, same-species managed pine stands, and these studies do not measure the direct consequences of the disturbance but instead focus on recovery or mechanistic modeling (e.g., Cremer 1984; Jiao-jun et al. 2003; Fortuin et al. 2022; Ziemblińska et al. 2018). Our research objectives were as follows: 1) to assess the influence of distance from the tornado track on stand metrics (i.e., density, basal area, volume, and aboveground carbon); 2) to determine how these stand metrics change from before the tornado to the first growing season to the third growing season; and 3) to assess the resulting structural damage of individual trees. We reconstructed stands to the pre-disturbance conditions. Field-based inventories of managed pine plantations occur typically every 5–7 years or prior to harvest and are often modeled on low sample intensities that are generalized across the stands. Our estimates are based on intensive field inventories and localized equations with the aim of providing precise measurements of damage. In addition, we continued to monitor conditions over three growing seasons since the storm and provide a case study that spans a longer disturbance-recovery than simply before and after the tornadic event. This spatially stratified sampling design also offers a field-based approach to evaluating fine-scale heterogeneity of tornado impacts within planted forests. To our knowledge, no studies have applied this level of both spatial and temporal resolution in managed pine stands after a wind disturbance. This approach facilitates distinguishing highly localized damage patterns and track zone-specific recovery trajectories. Moreover, it is crucial for understanding both immediate and delayed effects of a tornadic event on stand structure and to inform targeted post-disturbance management decisions to mitigate further economic losses.

Methods

Study Sites

On 15 February 2021, a tornado with wind speeds up to 260 km/h, a damage width of 250 m, and a track the length of 35 km occurred in southwest Brunswick County, North Carolina (National Weather Service 2021). This was considered the strongest tornado to occur in this county and it produced multiple touch-downs with severe damage to structures and forestland along its path (National Weather Service 2021). Six loblolly pine-dominated stands along the tornado path were chosen for the study. The stands were located in the Southern Coastal Plain near Shallotte, North Carolina, US. This area is in the Lower Coastal Plain ecozone with loamy and fine sandy soil types (USDA Web Soil Survey n. d.). During 2021–2023, the average annual minimum and maximum temperatures were 12.52°C and 23.65°C, respectively, and the annual precipitation was about 4200 mm (NOAA 2025). Five stands were established in 2008, and one stand was established in 2004. The average trees per hectare, volume, and basal area (± standard error) pre-storm were 401.99 ± 16.56 trees/ha, 89.97 ± 5.60 m^3/ha, and 14.28 ± 0.73 m^2/ha, respectively.

We established six circular plots with a 10 m radius in each stand, for a total of 36 plots, that were either: 1) directly inside the tornado path; 2) at the edge, ~ 35 m from the tornado path; or 3) outside the tornado path ~ 150 m away in an adjacent undisturbed portion of the same forest stand (Fig. 1). Edges appeared to be distinct with damaged and undamaged trees on either side, and hence we visually estimated approximate edge locations. Within a 10 m radius of each plot center, we measured all loblolly pine trees with a stem diameter > 10 cm for diameter at breast height (cm; DBH; 1.3 m above the ground) using a logger's tape and total stem height (m) using a Nikon Forestry Pro II Laser Rangefinder (Burkhart et al. 2019). We also assigned each tree a mortality code (dead = 0; live = 1). Additionally, we assigned a tree damage classification for each tree as follows: 1 = standing and intact; 0.75 = crown was broken off; 0.5 = tree broke mid-bole; 0.25 = tree broke at lower bole; 0 = tree was uprooted.

Fig. 1 Photos taken from 10 m radius plots that were sampled immediately after the tornado (year one) and three growing seasons after the tornado (year three) in North Carolina, US. Measurements were performed in plots directly inside the path of the tornado, on the edge of the tornado path, and outside the tornado path in undisturbed adjacent forest. Photos taken by Holly Munro and Simone Lim-Hing

Stand Metric Calculations

We collected field data in July 2021 (hereafter year one) and three growing seasons later in September 2023 (hereafter year three). To reconstruct stand metrics prior to the tornado, field crews re-created the pre-tornado stand structure from careful site evaluation of the location of all stems, regardless of tree damage category (e.g., standing dead, downed dead, and leaning dead). For downed or broken trees, we used a simple DBH to height relationship to impute missing tree heights (Burkhart et al. 2019) based on existing measured heights in the stand. We used height and DBH to determine trees per hectare, basal area, and volume. Conversely, we only used live and standing trees for year one and year three estimates.

Plot-level values were converted to per ha values using an expansion factor. The expansion factor, calculated as the inverse of the sampled area (plot size, in ha), scaled plot-level estimates to a per-hectare basis. Volume per tree was estimated using loblolly pine specific volume equations from Sherrill et al. (2011), and volume per hectare was calculated by summing per-tree volumes within each plot and then applying the expansion factor. Basal area per tree was calculated using standard forest mensuration equations (Burkhart et al. 2019), then summed and expanded to a per-hectare basis. We estimated live carbon using biomass equations developed for planted loblolly pine trees (Zhao et al. 2015, 2017). We individually calculated stem wood, stem bark, dead and live branches, and foliage biomass and multiplied these by the carbon content of the relevant component (45.8%, 48.4%, 46.7%, and 47.9%, respectively; Zhao et al. 2019). We then converted the live carbon content values to a per unit area similar to trees per hectare, volume, and basal area.

Statistical Analyses

We assessed stand characteristics (i.e., trees per hectare, volume, basal area, and aboveground carbon) by proximity to the tornado (inside, on the edge, and outside of the tornado path) and time (pre-storm, year one, and year three). We used a one-way ANOVA model to determine if there were differences in stand characteristics among the three sampling locations. We used a linear mixed-effect model to determine if there were differences in stand characteristics over time, which accounted for repeated measures sampling. To account for the differences in stand age (the older stand established in 2004 had slightly higher basal area and volume; data not shown), we included stand replicate as a random effect. We performed *post-hoc* Tukey test analyses of models indicating significant differences ($\alpha = 0.05$) and the reported *P*-values are adjusted using the Bonferroni method to prevent inflated false positives. We used a general linear model (GLM) with a Poisson distribution to compare the frequency of trees in different tree damage categories including intact, uprooted, broken at lower or mid-bole, and broken at crown. All analyses confirmed the normal distribution of residuals and were performed at an alpha-level of 0.05. The null hypothesis posited that no significant differences exist in these stand characteristics across the three sampling locations and the three different time points relative to the tornado event. All analyses were performed in RStudio (R Core Team 2022). Figures were created using the R package 'ggplot2' (Wickham 2016) and Illustrator (Adobe 2019). Summary statistics for all analyses are provided in Supplementary Tables 1–2.

Results

Proximity to Tornado Path

In the reconstruction of pre-storm stand conditions, tree density ($F_{2,30} = 1.973$, $p = 0.157$), volume ($F_{2,30} = 3.13$, $p = 0.058$), and aboveground carbon ($F_{2,30} = 3.256$, $p = 0.053$) did not differ by sampling location including inside the tornado track, at the edge, and outside the tornado track (Table 1; Figs. 2a, b, d). There was a marginally significant difference between locations for basal area ($F_{2,30} = 3.575$, $p = 0.041$) with pairwise comparisons indicating the edge plots had higher levels of basal area than the inside plots ($p = 0.041$; Fig. 2c).

Table 1 Summary of trees per hectare, volume, basal area, and aboveground carbon biomass separated by timing and proximity to the tornado track in North Carolina, US

Proximity	Timing*	Trees per ha	Volume (m^3/ha)	Basal area (m^2/ha)	Carbon (mg/ha)
Inside	Pre-storm	366.58 ± 23.05	81.48 ± 6.51	12.95 ± 0.85	20.45 ± 4.76
Edge	Pre-storm	443.62 ± 33.63	103.48 ± 11.79	16.27 ± 1.60	26.05 ± 2.97
Outside	Pre-storm	395.80 ± 25.87	84.98 ± 9.60	13.60 ± 1.09	21.26 ± 2.39
Inside	Year one	183.29 ± 22.24	43.11 ± 6.69	6.73 ± 0.97	13.61 ± 3.33
Edge	Year one	374.55 ± 40.04	88.32 ± 12.24	13.71 ± 1.70	27.70 ± 3.68
Outside	Year one	387.83 ± 25.68	84.50 ± 9.56	13.47 ± 1.09	26.52 ± 2.83
Inside	Year three	151.41 ± 21.18	70.35 ± 13.10	8.97 ± 1.49	17.74 ± 4.75
Edge	Year three	318.77 ± 32.12	130.11 ± 18.91	16.80 ± 2.06	32.60 ± 4.76
Outside	Year three	342.67 ± 18.03	133.54 ± 19.00	17.29 ± 1.78	33.23 ± 4.75

*Pre-storm = Reconstructed stand conditions from measurements taken at post-storm sampling time, Year one = June 2021; Year three = September 2023

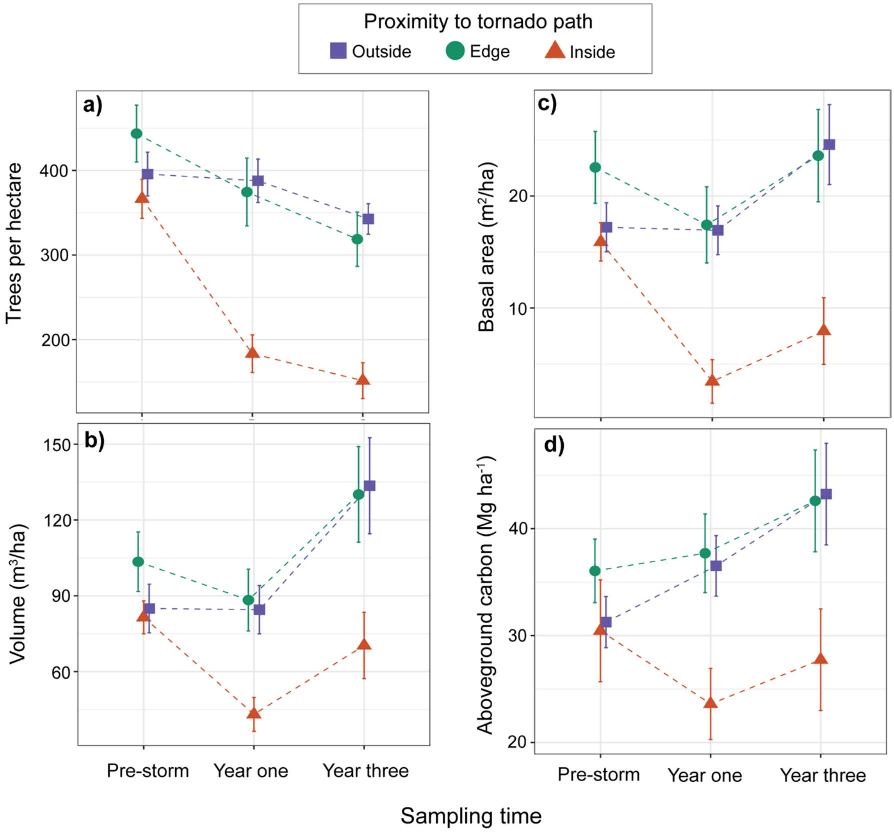

Fig. 2 Mean and standard error of **a**) trees per hectare, **b**) volume, **c**) basal area, and **d**) aboveground carbon estimated from the height and diameter at breast height following an EF-3 tornado in North Carolina, US. Summary metrics are separated by sampling time and proximity to the tornado track. Note the different y-axes values

Following the tornado (i.e., year one), the stand structure diverged based on proximity to the tornado track, with an approximately 50% reduction in all metrics compared to those taken in the edge and outside plots (Table 1; Fig. 3). Plots on the inside of the tornado track were 48.10% lower in tree density ($F_{2,30} = 15.294$, $p < 0.001$) compared to the outside ($p < 0.001$) and the edge ($p < 0.001$). Similarly, the volume of plots inside the tornado track was 49.90% lower ($F_{2,30} = 14.800$, $p < 0.001$) than the volume in the plots outside ($p < 0.001$) and edge ($p < 0.001$) of the tornado track. Plots inside the tornado track had 49.52% lower basal area in plots inside the tornado track ($F_{2,30} = 18.280$, $p < 0.001$) than the plots outside ($p < 0.001$) and on the edge ($p < 0.001$) of the tornado track. Carbon was 50.20% lower ($F_{2,30} = 14.900$, $p < 0.001$) in plots inside of the tornado track as compared to the plots outside ($p < 0.001$) and edge ($p < 0.001$).

In year three, these spatial trends persisted (Table 1; Fig. 2). Tree density remained the lowest in plots located inside of tornado track ($F_{2,30} = 17.930$, $p < 0.001$) as compared to those on the edge ($p < 0.001$) and outside ($p < 0.001$). Volume exhibited a modest increase but still remained the lowest in plots inside the tornado track ($F_{2,30} = 5.600$, $p = 0.009$) with respect to plots on the edge ($p = 0.023$) and outside ($p = 0.015$) the tornado track. Similarly, basal area remained low ($F_{2,30} = 8.158$, $p = 0.002$) when compared to plots on the edge ($p = 0.005$) and outside ($p = 0.025$). Lastly, aboveground carbon biomass remained lower ($F_{2,30} = 5.379$, $p = 0.010$) in plots located on the inside of the tornado tracks as compared to plots on the edge ($p = 0.025$) and outside ($p = 0.019$).

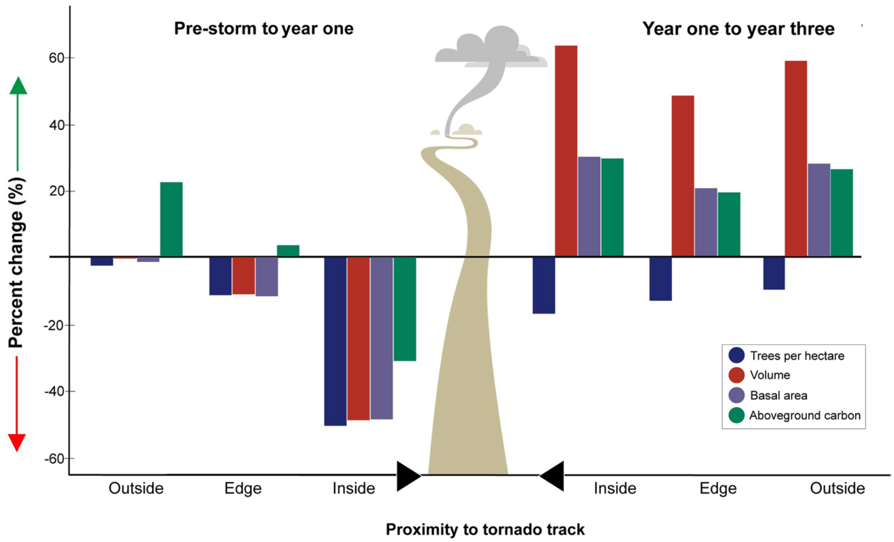

Fig. 3 Percent change of forest metrics between before and after the storm (year one) as well as between year one and three growing seasons after the storm (year three), separated by sampling time and proximity to the tornado track in North Carolina, US

Sampling Timeframe

For plots located inside the path of the tornado, all stand metrics varied by the sampling timeframe and showed an overall modest recovery but a reduction in tree density (Table 1; Figs. 2 and 3). Tree density was different across sampling timeframes ($Chi^2 = 104.843$, $p < 0.001$), with pre-storm levels being higher than year one ($p < 0.001$) and year three ($p < 0.001$). Volume was also different by sampling timeframes ($Chi^2 = 18.888$, $p < 0.001$) with levels dropping at year one ($p = 0.001$) but increasing again at year three ($p = 0.008$). Basal area also differed by sampling time ($Chi^2 = 33.772$, $p < 0.001$), with levels remaining higher at pre-storm levels than year one ($p < 0.001$) and year three ($p < 0.001$). Carbon was different as well ($Chi^2 = 9.226$, $p = 0.010$), although only between a decrease between pre-storm and year one levels ($p = 0.007$).

In plots located on the edge of the tornado track, stand metrics varied by time, albeit less pronounced than metrics from plots inside the tornado track (Table 1; Fig. 2). Tree density decreased over time ($Chi^2 = 32.990$, $p < 0.001$), with all sampling points being significantly different in pairwise comparisons: levels declined between pre-storm and year one ($p = 0.004$) and further declined by year three, being lower than both year one ($p = 0.028$) and pre-storm levels ($p < 0.001$). Volume, conversely, significantly increased ($Chi^2 = 14.877$, $p < 0.01$) with year three being significantly higher than pre-storm ($p = 0.040$) and year one levels ($p < 0.001$). Basal area also increased over time ($Chi^2 = 6.557$, $p = 0.038$), being slightly higher at year three than year one ($p = 0.044$). Similarly, carbon showed a marginal difference ($Chi^2 = 6.033$, $p = 0.049$) across sampling times, being slightly higher at year three as compared to pre-storm levels ($p = 0.048$).

Undisturbed plots outside the tornado path exhibited minimal changes in tree density over time, but increases in volume, basal area, and aboveground carbon at the third growing season (Table 1). Tree density was not different by sampling time ($Chi^2 = 4.268$, $p = 0.118$). Volume, though, did differ by sampling time ($Chi^2 = 31.221$, $p < 0.001$), with year three levels being higher than those of pre-storm ($p < 0.001$) and year one ($p < 0.001$) levels. Basal area ($Chi^2 = 14.636$, $p < 0.001$) mirrored this trend: year three levels were higher at pre-storm ($p = 0.003$) and year one ($p = 0.002$) sampling periods. Again, carbon ($Chi^2 = 23.118$, $p < 0.001$) increased over time, with levels being higher in year three than in pre-storm ($p < 0.001$) and year one ($p = 0.008$) sampling periods. These changes reflect continued growth in the absence of disturbance.

Tree Damage

We classified individual tree damage after the tornado to gauge the influence on the spatial structure of resulting damage. The proportion of tree conditions varied by proximity to the tornado (Fig. 4; $Estimate_{(outside)} = 4.311$, $p < 0.001$). For trees located inside the tornado track, approximately half remained intact and standing, while ~ 13% were completely uprooted, ~ 23% broke at the lower bole, ~ 9% broke

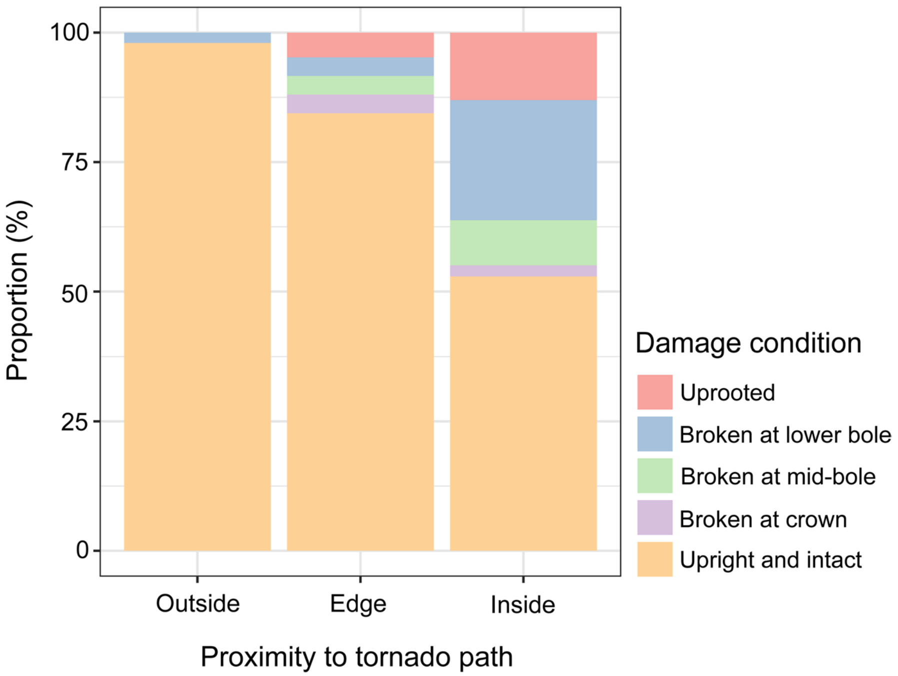

Fig. 4 Proportion of tree damage category per sampling location assigned to each tree immediately after an EF-3 tornado in North Carolina, US

at mid-bole, and ~ 2% broke at the crown. Nearly all trees located in the undisturbed plots, outside of the tornado track, were intact, with only 2% having broken at the lower bole. For trees located in plots on the edge of the tornado track, about 84% of trees remained standing and intact, ~ 5% were completely uprooted, while the remaining trees were evenly split between being either broken at lower, mid, and upper boles (~ 4% each).

Discussion

Our spatially stratified, plot-level dataset provides rare empirical insight into both the immediate and short-term structural and carbon responses of planted loblolly pine stands to a catastrophic tornado (Fig. 3). Our study provided the following insights: 1) there were significant reductions in tree density, volume, basal area, and aboveground carbon, with metrics being reduced by half inside the tornado track as compared to the edge or outside of the track; 2) stand metrics were not different between the edge of the tornado track and outside of it, indicating sharply defined damage zones; 3) decreases in tree density persisted after the tornado, indicating delayed mortality; and 4) despite the damage, tree volume and carbon were statistically indistinguishable from pre-storm levels in plots located inside the tornado track than those measured in year three, showing a modest recovery (Fig. 3).

Damage was highly localized to the tornado track, with inside-track plots experiencing approximately 50% reductions in all stand metrics relative to the edge and undisturbed areas. Tornadoes are characterized by a rotating column of wind at extremely high velocities and, as such, have concentrated areas of damage (Dao et al. 2014; Davies-Jones 2015; Peterson 2000a). While resulting damage can be influenced by forest structure, topography, and storm severity (Torresani et al. 2024; Cannon et al. 2016), similar patterns of concentrated damage are consistent throughout the literature (e.g., Hanson and Lorimer 2007; DeCoster 1996). It's unclear how the damage by this tornado was impacted by topographical features; however, it touched down as EF-0 in suburban areas and then as it moved more northeastern it gained strength to become an EF-3 (260 km/h), with a maximum width of 250 m (National Weather Service 2021), when it reached the forest stands that were studied here.

Interestingly, the stand metrics between plots on the edge and the outside of the tornado track largely did not differ. This is in contrast to the often-observed gradient of increasing damage with proximity to the site of wind disturbance (e.g., Cowden et al. 2014; Cox et al. 2016; Willson et al. 2020). In this study, the hard edges created after the tornadic event may be a result of the homogeneity of the trees, as they were evenly spaced, composed of the same species, and were the same age cohort. Indeed, susceptibility to wind damage can be modulated by a tree's species or size (Peterson 2000a; 2007), and thus, a more structurally and compositionally diverse forest would have a more heterogeneous pattern of damage. Moreover, higher functional and structural diversity can provide a buffer-like effect, diffusing intense winds and, thus, reducing such high localized damage and increasing recovery (Barrere et al. 2024). This suggests that in homogenous forest landscapes (i.e., even-aged conspecific pine stands), salvage operations and replanting efforts may be concentrated primarily within the tornado track and not necessarily around it, thus, reducing losses and economic impacts.

Gap and edge formation from a tornado can significantly influence forest dynamics, especially as canopy loss may favor early successional species or those that thrive under higher light availability, shifting competitive dynamics within a stand (Farrior et al. 2013). Understory and hardwood competition, especially in managed pine stands, can lower productivity of pines via competition for nutrients and water (Carter et al. 1984; Nambiar and Sands 1993; Rantis and Johnson 2002). While an increase in understory vegetation was observed in the field (see Fig. 1) and resource competition may have increased, areas that experienced the most damage (i.e., plots on the inside of the track) showed significant signs of recovery. Tree volume per ha of residual trees, for example, returned to pre-storm levels after three growing seasons. These findings are similar to those observed in other wind-disturbed managed stands, where after 2–3 growing seasons, the forest conditions are more similar to the undisturbed areas (Nelson et al. 2008; White et al. 2014). If managers cannot salvage windthrown areas immediately, our results suggest two options for recouping some economic losses: conducting a salvage thinning to promote growth of remaining sawtimber-sized trees or delaying salvage operations for a few additional years. To that end, we found that the pattern of damage measured by each tree's condition post-storm depended on the proximity to the tornado track, with a higher diversity of damage type in trees that were located in the inside of the tornado track. The height of stem-breakage can indeed influence recovered timber value. For example, a study that simulated breakage of *P. sylvestris* L. at different heights (3, 5, and 7 m) concluded that the lowest recovered timber value was with trees that broke at 3 m, thus decreasing the monetary value by 35% (Dubrovskis et al. 2018).

Beyond immediate structural loss we observed continued declines in tree density over time, most notably within the tornado path, but also in edge plots. Delayed mortality is often observed after wind disturbances and can continue to occur for decades after the event (Harmon and Pabst 2019), despite tornadoes often being categorized as a singular and abrupt event. These declines in tree density would support more immediate salvage operations post-tornado versus waiting on stand recovery. Strong winds can inflict aboveground (e.g., stem and limb breakage, damage by flying debris) and belowground damage (e.g. damage to the roots that has been linked to sublethal damage; Dickens et al. 2016). Even in the absence of complete mechanical failure, trees may shunt resources towards repairing any damage from the storm and away from defenses, leaving them vulnerable to delayed mortality due to other stressors, such as pests and pathogens (Pickett and White 1985; Gandhi 2005; Palm-Hellenurm et al. 2024). Stress induced by injuries compounded by abrupt changes in environment and resource availability may also have a synergistically negative effect on trees. Moreover, newly downed and dead trees attract subcortical insects and provide a substrate for colonization and breeding, facilitating the possibility of an outbreak, and leaving the debris unsalvageable (Göthlin et al. 2000; Gandhi 2005; Gandhi et al. 2007). These cascading effects highlight the importance of rapid assessment and timely management interventions.

Forest carbon dynamics following disturbance have been increasingly studied across a range of disturbance regimes (e.g., wind and fire), though responses remain highly variable depending on disturbance severity, forest type, and post-disturbance management (e.g., Raymond et al. 2015; Williams et al. 2012; Seidl et al. 2014). However, empirical, field-based assessments of short-term carbon dynamics following tornado disturbance in managed pine systems remain limited. Our findings revealed that aboveground carbon stocks were reduced by half in tornado-affected plots and recovered only partially over three growing seasons. The partial carbon recovery we observed suggests that tornado-induced carbon losses can persist for many years, even when volume appears recovered. This distinction is important because many carbon models assume that structural recovery is a proxy for carbon recovery, which may overestimate post-disturbance sequestration in managed pine systems (e.g., Williams et al. 2012). Additionally, the rise in the frequency and magnitude of disturbance events has been projected to offset management strategies that are aimed at carbon sequestration operations (Williams et al. 2014; Seidl et al. 2014). For example, Ziemblińska and others (2018) found that a Scots pine (*P. sylvestris* L.) forest became a significant carbon source after a tornadic event and estimated that it would continue to be a source upwards of six years, depending on the post-disturbance management strategy. Quantifying and modeling large-scale changes in forest carbon stocks after a specific disturbance can inform preventative strategies to mitigate substantial loss and shape subsequent recovery efforts, especially if carbon storage is the primary management objective.

Conclusions

Our results highlight the importance of spatially and temporally explicit assessments when evaluating tornado damage in managed pine systems. The high degree of localized loss points to the vulnerability of single species forest systems under extreme wind events. Despite some post-storm recovery, stand metrics, such as tree density and basal area, remained below pre-disturbance levels three growing seasons after the event. For the forest sector, these findings point to the value of targeted post-disturbance assessments to determine how much salvage logging or replanting is economically feasible, particularly in areas where the size, severity, and accessibility of the tornado path warrant intervention, and if edges continue to lose trees with time. In contrast, smaller or fragmented damage zones may be better suited to passive recovery and monitoring, especially in edge areas where delayed mortality can still occur. These findings also have broader implications for forest inventory, growth projections, and carbon accounting, where disturbance effects are often represented using simplified or spatially uniform assumptions. Importantly, damage assessments and monitoring are also important for voluntary carbon reporting and projects. Integrating standardized field-based metrics with remote sensing and disturbance modeling tools can support more comprehensive, scalable assessments. Together, these findings provide an empirical foundation for improving short-term disturbance representation in managed pine systems, with implications for carbon accounting, risk assessment, and future modeling of wind-driven forest dynamics.

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Declarations

Competing interests The authors have no competing interests to declare that are relevant to the content of this article.

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