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Aboveground Biomass and Carbon Accumulation 19 Years Post-Windthrow and Salvage Logging

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Abstract: Natural disturbances shape forest ecosystem characteristics, including carbon storage and structure. Often, natural disturbances are compounded with anthropogenic disturbances, which may alter the trajectory of forest carbon stock recovery. Heterogeneous levels of disturbance severity in compound disturbance events add an additional layer of complexity. This paper examines the effect of a moderate-severity wind disturbance and subsequent salvage logging on forest biomass and carbon stock recovery over 19 years. We investigate the recovery of aboveground tree biomass following a wind disturbance and salvage logging and examine the role of wind disturbance severity on biomass accumulation rates. We use pre-disturbance, 3 years post-wind disturbance and 19 years post-wind disturbance measurements of tree biomass across two adjacent sites at Natchez Trace State Forest for Site A and Site B in east central Tennessee. We found no significant difference in the carbon storage at Site A (pre = 92 MgC/ha; 19 years post-disturbance = 83 MgC/ha) or Site B (pre = 66 MgC/ha; 19 years post-disturbance = 67) when comparing the pre-disturbance level of aboveground tree carbon storage with the 19-years post-disturbance levels. Furthermore, we found no evidence that salvage logging reduced the rate of live tree carbon accumulation. The corresponding rates of mean annual carbon accumulation (MgC/ha) are as follows: Site A Unsalvaged (1.07), Site A Salvaged (1.25) and Site B Salvaged (2.02). Contrary to our prediction, greater wind damage severity was weakly associated with higher rates of biomass accumulation (R^2 = 0.17). While we found no negative effect of salvage logging on the aboveground tree carbon accumulation rate, salvage logging alters other carbon pools, including coarse woody debris. Salvage logging did not reduce the rate of carbon stock recovery, and a higher wind disturbance severity was associated with a greater rate of carbon stock recovery.

Keywords: wind disturbance; disturbance severity; anthropogenic disturbance; carbon storage; salvaging

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1. Introduction

Forests are major drivers of the global carbon cycle, storing 80% of aboveground terrestrial carbon [1]. Mid-and late-successional forests store carbon in tree biomass, the soil and organic material, with the majority of aboveground carbon stored in tree trunks and large branches [2]. Disturbances causing tree damage or mortality can release carbon into the atmosphere, potentially shifting a forest from a carbon sink to a carbon source. It may take decades for a disturbed forest to fully recover to pre-disturbance levels of carbon storage [3–5]. Moreover, the many natural disturbances that forests experience—including wind disturbance, fire and flooding—are often compounded with anthropogenic disturbances [6,7]. Developing an understanding of how changing disturbance patterns, including return time, impact the global carbon cycle is crucial, as forests are increasingly being managed with the goal of offsetting anthropogenic carbon emissions [8,9].

Carbon dynamics and recovery are not well known after wind disturbances of different severities and frequencies, and work is needed to determine how compound disturbances, which include wind disturbance, alter the carbon stock recovery trajectory [3,10–13]. A forest's response to compound disturbances may show different patterns, according to the severity of the overlapping disturbances [14]. Moderate-severity disturbances are more common and less studied than severe disturbances, representing a crucial driver of forest dynamics that impacts the ecosystem's structure and functions differently when compared with stand-replacing disturbances [15–17]. Disturbance severity, which is necessarily increased with compound disturbances, is negatively correlated with biomass and carbon stock recovery rates [13,18–20]. In a future where disturbance regimes may be modified by climate change [9,21], it is important to study the length of time it takes for a forest to reach pre-disturbance levels of biomass and carbon storage following compounded moderate-severity disturbances.

Salvage logging (sometimes called sanitary logging) is tree harvesting following natural disturbance such as fire or windthrow, and it is a common second disturbance in forests that increases the cumulative severity above that of the prior natural disturbance while also impacting forest carbon dynamics [22]. While salvage logging is often justified as a way to mitigate the effects of future disturbances, particularly fires, a recent review suggested that the costs to ecosystem functions may outweigh these potential benefits. A case-by-case assessment is needed to determine the best course of action following a natural disturbance [23]. Salvage logging may alter the physical structure, biodiversity or composition, forest regeneration processes and ecosystem services [24–29]. Salvage logging acts as a homogenizing influence on a forest's physical structure, removing carbon stored in legacies from the forest which would otherwise decay and contribute to the organic material of the forest floor [30,31]. Research suggests that biological legacies increase the resilience of forests and lead to a faster rate of recovery of carbon stocks; however, compounded disturbances may dampen this effect [21]. Because salvage logging is a compound disturbance that reduces biological legacies—standing and fallen biomass post-wind disturbance—it may reduce the ability of a forest to store carbon and increase the amount of time it takes for a forest to recover its carbon storage [32,33]. However, the majority of studies on the effects of salvage logging are short-term (>5 years), finding transitory effects of salvage logging (see [34]). There is a need for long-term studies to determine whether salvage logging has permanent effects on a forest system [35]. This study seeks to test whether salvage logging has reduced the ability of a forest to store carbon 19 years post-disturbance.

We examined aboveground tree biomass and carbon stocks following a moderate-severity wind disturbance that was partially salvage logged by revisiting the site after 19 years. Specifically, we asked the following questions: (1) Has aboveground tree biomass reached pre-disturbance levels after 19 years? (2) Does salvage logging reduce the rate of recovery of live tree carbon stocks? (3) Is greater wind damage severity associated with lower biomass accumulation?

2. Study Area and Methods

2.1. Study Area

Natchez Trace State Park (NTSP) is in west central Tennessee, USA (35.7982, −88.2648). Originally part of a federal land reclamation project of eroded farmland in 1935, the state of Tennessee took ownership in 1955. Before it was reclaimed, the site experienced frequent disturbances, including cultivation for agriculture, grazing and logging. Loblolly pine was planted in some areas to control erosion and for harvesting. In the remaining second-growth hardwood forest, clearcutting was performed with the intent of encouraging the natural regeneration of hardwoods [36].

Site Description

Soil and climate: NTSP is part of the East Gulf Coastal Plain section of the Coastal Plain physiographic province [37]. McNairy Sand is the predominant strata, and soils of the study area are predominantly from the Lexington–Smithdale complex [36,37]. The soils include (1) Ruston fine sandy loam, moderately eroded and with a steep phase; (2) Ruston sandy clay loam, severely eroded with a moderately steep phase; (3) moderately gullied land Lexington–Ruston materials, and (4) Lexington–Ruston soils with severely eroded sloping phases [38]. With a humid subtropical climate, the area has an average yearly precipitation of 1230 mm. The average yearly low temperature is in January (5 °C), and the high is in July (26 °C) [39].

Tree species composition: The forests are a mix of hardwoods and loblolly pine (*Pinus taeda* L.), with some upland areas more loblolly-dominant and lowland areas more hardwood-dominant. Common canopy species include oaks (*Quercus alba* L., *Quercus coccinea* Muenchh., *Quercus marilandica* Muenchh. and *Quercus velutina* Lam.), hickories (*Carya cordiformis* (Wangenh.) K.Koch and *Carya tomentosa* Sarg.), and beech (*Fagus grandifolia* Ehrh.). Midstory and understory trees include red maple (*Acer rubrum* L.), musclewood (*Carpinus caroliniana* Walter), dogwood (*Cornus florida* L.), sweetgum (*Liquidambar styraciflua* L.), sourwood (*Oxydendron arboretum* (L.) DC.), blackgum (*Nyssa sylvatica* Marshall), sassafras (*Sassafras albidum* (Nutt.) Nees) and black cherry (*Prunus serotina* Ehrh.).

Wind disturbance and salvage logging: A May 1999 downburst impacted approximately 3000 ha in the southern portion of the NTSF. Over the course of the >1.5 h storm, the forest was damaged by wind speeds of over 90 km/h and gusts that exceeded 145 km/h, creating high spatial heterogeneity in damage severity [40]. Most of the impacted forest was salvage logged by 2001. Downed trees were cut with chainsaws and removed by motorized skidders in harvest units, with one salvage logging landing area per affected watershed. The forests were left to regenerate naturally after salvage logging. Approximately 6 ha were not salvaged [40].

2.2. Methods and Analysis

Plots were established as part of a study reported by Peterson and Leach [40]. The wind-damaged area of the NTSF was divided into two sites for the purpose of replication: Site A and Site B (Figure 1). These sites had similar forest compositions—with a greater starting abundance of *P. taeda* at Site B—and topographies, but they were separated by approximately 2.5 km. Site A bordered a reservoir. Sixteen 30 × 30 m sampling plots were established at each of the two sites in a stratified randomized design, with half of the plots in each site salvaged and the other half of the plots left unsalvaged. The wind damage severity and salvage logging intensity varied by plot. The plots were established at least 50 m from the wind disturbance patch edges. The tree species and diameter at breast height (DBH) for individuals ≥5 cm DBH were surveyed within each sampling plot in 2001, the third growing season after the wind disturbance. Trees that appeared dead prior to the 1999 wind disturbance were not included in the survey. The wind disturbance severity was calculated as the proportion of the biomass that was felled. Of the trees that were felled by the wind disturbance, individuals that were later removed by salvage logging were apparent by their remaining stumps. In the 2001 sample, the diameter at breast height and the diameter at the trunk base were measured for each tree. A projected stem DBH was calculated for the salvaged individuals based on the diameter of the trunk base in the 2001 sample data per species, allowing us to calculate the amount of biomass that was salvaged. We developed linear regressions of this relationship for the two most commonly salvaged species, *P. taeda* and *Q. alba* (Figures S1 and S2). This information made it possible to reconstruct the 1999 pre-wind disturbance forest by, in a way, resurrecting individuals that were felled by the wind disturbance.

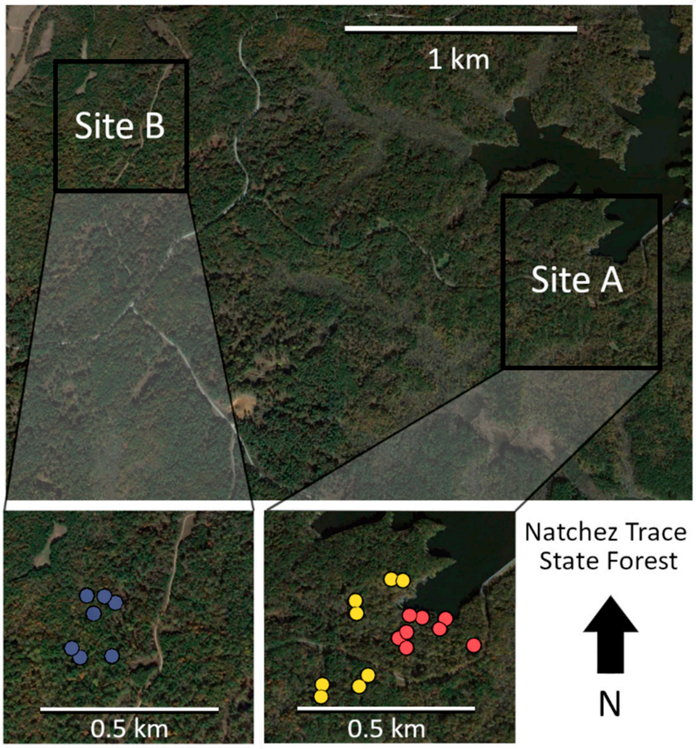

Figure 1. Study areas within Natchez Trace State Forest, Tennessee, USA with Site A to the east and Site B to the west. Plots are marked within each site. Site A Unsalvaged plots are marked in red, Site A Salvaged plots are marked in yellow and Site B Salvaged plots are marked in blue. Imagery: Google Earth Landsat, Copernicus 2019.

The tree species and DBH for individuals >5 cm DBH were resurveyed in 2020 at Site A and Site B. Sixteen 30 × 30 m sampling plots were measured at Site A (half of them salvage logged and half of them unsalvaged), and seven sampling plots were measured at Site B (all salvage logged). The remaining plots at Site B were left unsampled because they were subsequently salvaged in 2001 after the sampling. We were not able to relocate one plot in Site B.

Species-specific allometric equations were used to calculate the individual dry weight aboveground tree biomass for each plot, summed within the plots and scaled to the ha level [41]. The aboveground live tree carbon stocks were estimated from the dry weight biomass, with the assumption that carbon represented 50% of the total aboveground biomass (see Lamlon et al. [42] for discussion of this approximation). The aboveground biomass and carbon stocks for the study areas were converted on a per ha basis.

To evaluate the pre-wind disturbance, 3 years post-wind disturbance and 19 years post-wind disturbance biomass and carbon accumulation, we compared the mean biomass (Mg/ha) and carbon storage (MgC/ha) and the standard error (SE) for each site. We ran a paired T-test to determine whether sites had reached pre-disturbance levels of aboveground biomass storage ($\alpha = 0.05$). To calculate the rate of biomass and carbon accumulation, we assumed a constant rate of accumulation between the 3 years post-wind disturbance and 19 years post-wind disturbance intervals. To assess the effect of disturbance severity on biomass accumulation, we developed a linear regression of wind disturbance severity (% biomass felled) and relative change in biomass from 2001 to 2020. We also tested for the significance of this model using an F-test.

3. Results

3.1. Biomass and Carbon Stocks Pre-Disturbance and 3 Years Post-Disturbance

Prior to any disturbance, the mean aboveground tree dry weight biomass in Site A Unsalvaged was 183 Mg/ha (standard deviation = 33.25), 183 Mg/ha in Site A Salvaged (standard deviation = 58.36) and 131 Mg/ha in Site B Salvaged (standard deviation = 32.46). The corresponding amounts of pre-disturbance live tree carbon stocks were 92 Mg/ha (standard deviation = 16.62) for Site A Unsalvaged, 92 Mg/ha (standard deviation = 29.18) for Site A Salvaged and 46 Mg/ha (standard deviation = 16.23) for Site B Salvaged. The range of biomass for each site was as follows: Site A Unsalvaged 136–225 Mg/ha, Site A Salvaged 80–251 Mg/ha and Site B Salvaged 95–186 Mg/ha (Figure 2). For all plots pooled within a site, the three species that contributed the most total biomass (Mg/ha) were as follows: *Q. alba* (48), *P. taeda* (29) and *Quercus stellata* Wangenh. (22) for Site A Unsalvaged; *Q. alba* (68), *Quercus rubra* L. (23) and *Q. velutina* (19) for Site A Salvaged; and *P. taeda* (70), *Q. stellata* (15) and *Liriodendron tulipifera* L. (10) for Site B Salvaged. Note the especially high dominance of *P. taeda* in Site B.

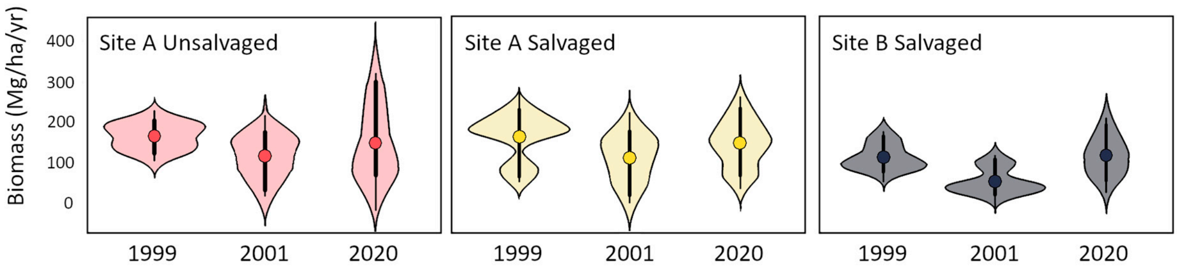

Figure 2. Dry weight biomass (Mg/ha/yr) presented with violin plots at three time points: pre-disturbance (1999), 3 years post-wind disturbance (2001) and 19 years post-wind disturbance (2020). Salvage logging took place before the 2001 sampling for sites where salvaging is indicated. Within the violin plots, the filled circle indicates the median, and the thick rectangle indicates quartiles. The width of the violin plot curve indicates the density of the points.

The wind disturbance had a mean severity of 29.6% (standard deviation = 22%) at Site A Unsalvaged, 33.4% (standard deviation = 18.9%) at Site A Salvaged and 49.1% (standard deviation = 13.5%) at Site B Salvaged. The wind disturbance severity ($F_{2,20}$ = 2.23; p = 0.13) and salvage logging intensity (t(13) = 0.73; p = 0.48) were not significantly different among the study areas (Table S1).

The approximate mean tree dry weight biomass that was felled by the tornado (both stored in standing dead trees and in coarse woody debris) for each site in 2001 was as follows: 52 Mg/ha (range = 3–115) for Site A Unsalvaged, 12 Mg/ha (range = 4–23) for Site A Salvaged and 15 Mg/ha (range = 4–37) for Site B Salvaged.

In 2001, after 3 years post-wind disturbance with more recent salvage logging, the aboveground biomass was lower than the pre-disturbance biomass for all sites, with Site A Unsalvaged storing 131 Mg/ha (standard deviation = 52.38), Site A Salvaged storing 125 Mg/ha (standard deviation = 56.14) and Site B Salvaged storing 69 Mg/ha (standard deviation = 33.62).

3.2. Has the Biomass Reached Pre-Disturbance Levels After 19 Years?

Site A Unsalvaged showed a greater variation in plot-level biomass (range = 80–325 Mg/ha) when compared with both Site A Salvaged (range = 80–255 Mg/ha) and Site B Salvaged (range = 71–215 Mg/ha) (Figure 1). The coefficient of variation (CV)—a measure of dispersion around the mean—quantified this pattern further; Site A Unsalvaged had the greatest CV with a value of 55, followed by Site A Salvaged with a value of 37.8 and Site B Salvaged with a value of 36.8.

There was no significant difference between the pre-disturbance and 19 years post-disturbance levels of aboveground dry weight biomass for Site A Unsalvaged (t(7) = −0.71;

p = 0.25), Site A Salvaged (t(7) = −1.02; p = 0.17) and Site B Salvaged (t(6) = 0.14; p = 0.45). In 2020, Site A Unsalvaged stored 165 Mg/ha (standard deviation = 90.42), Site A Salvaged stored 163 Mg/ha (standard deviation = 61.7), and Site B Salvage stored 134 Mg/ha (standard deviation = 49.39).

Site A Unsalvaged and Site B Salvaged showed similar patterns of biomass accumulation, adding a mean amount of 34 Mg/ha and 40 Mg/ha within 19 years, respectively. This represented 90% of the original biomass. Assuming a linear trend of mean annual biomass accumulation, we found that Site A Unsalvaged accumulated 2.13 Mg/ha each year, Site A Salvaged accumulated 2.5 Mg/ha each year, and Site B Salvaged accumulated 4.06 Mg/ha each year. The corresponding rates of mean annual carbon accumulation (Mg/ha) were as follows: Site A Unsalvaged (1.07), Site A Salvaged (1.25) and Site B Salvaged (2.02).

3.3. *Is Greater Damage Severity Associated with Lower Biomass Accumulation?*

When we examined the relative biomass change from 3 years post-wind disturbance to 19 years post-wind disturbance for all three sites pooled, we found a positive linear relationship (R^2 = 0.17) between the wind disturbance severity and biomass accumulation ($F_{1,21}$ = 4.43; p = 0.475) (Figure 3). When the three sites were examined individually, only Site B Salvage showed a significant relationship ($F_{1,6}$ = 6.65; p = 0.0495; R^2 = 0.57).

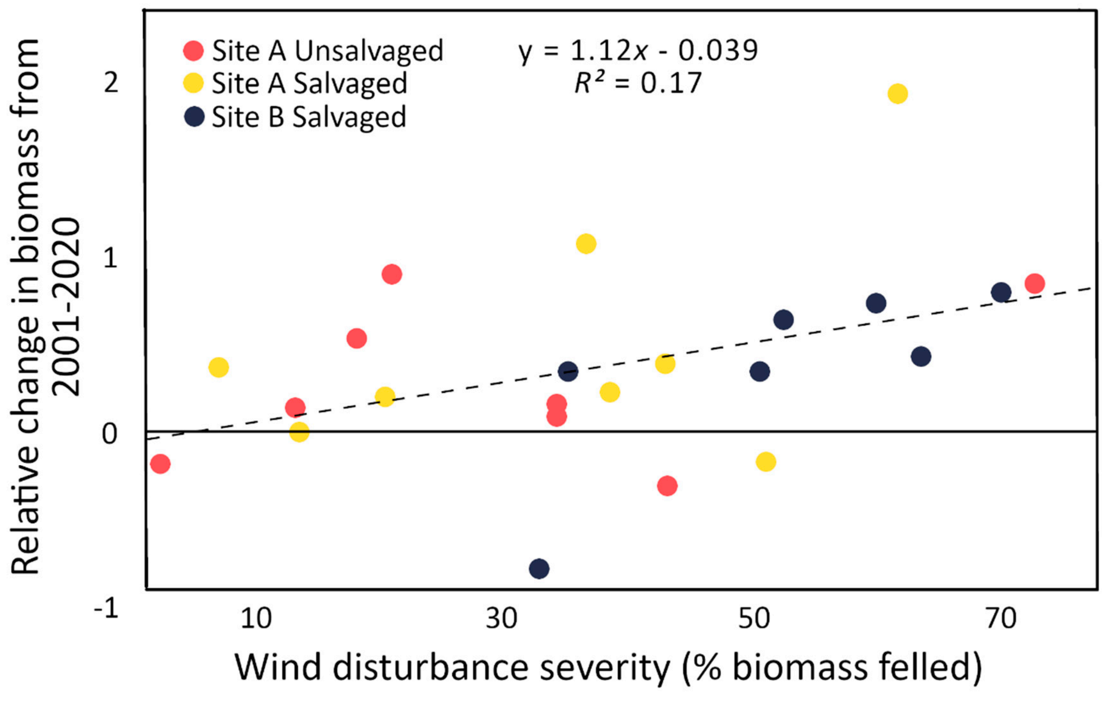

Figure 3. A linear regression between wind disturbance severity (% biomass felled) and total relative change in biomass from 2001 to 2020. The regression formula is y = 1.12x − 0.039, with an R^2 of 0.17. Points associated with Site A Unsalvaged are in red, Site A Salvaged are in yellow and Site B Salvaged are in dark blue.

4. Discussion

This study examined aboveground dry weight biomass and carbon accumulation post-wind disturbance and salvage logging. The effects of intermediate-severity wind disturbances are understudied, but provide insight into forest structure, composition and carbon storage, because intermediate-severity events are common [15]. A preliminary analysis (part of a separate planned publication of this work) of the >30 cm DBH individuals that survived the 1999 windthrow showed that these large individuals represented nearly half of the 2020 biomass. For Site A Unsalvaged, Site A Salvaged and Site B Salvaged, these large surviving trees represented 58.9%, 54.5% and 41.3% of the total 2020 biomass, respectively. This suggests that biological legacies were a major fraction of the post-disturbance carbon pools after this intermediate-severity disturbance.

Research on carbon stock recovery following a high-severity disturbance has found the following patterns: a slow start, followed by a rapid increase and then a gradual decline as the carbon storage approaches its carbon carrying capacity [3–5,10]. How rapidly a forest recovers carbon stocks depends on the disturbance severity and legacies remaining post-disturbance. For instance, sites where trees remained alive or sprouted from damaged trunks accumulated carbon stocks more rapidly than high-severity disturbances that primarily regenerated from seeds [10,43–45]. The present study area represented a moderate-severity disturbance where biological legacies remained. One study site reached pre-disturbance levels of carbon storage, and the other two study sites nearly reached pre-disturbance levels within 19 years post-disturbance. These sites have by now almost certainly entered a phase where the carbon storage rate is decreasing. Based on our estimation of the annual carbon accumulation (MgC/ha), we estimate that Site A Unsalvaged will reach pre-disturbance levels of carbon storage in 8.4 more years (2028), and Site A Salvaged will reach pre-disturbance levels of carbon storage in 7.2 more years (2027).

Anthropogenic disturbances can have a homogenizing effect on the structure, biomass, composition, soil resources and diversity of forests [31,46–48]. The land of NTSF has, for the last 60–80 years, undergone recovery driven by natural processes, which may begin to increase heterogeneity at the stand and landscape scale. Differences in forest characteristics evident before the 1999 wind disturbance may have been the result of the natural trajectory of the forest, given differences in topography and the environment. For instance, the plots ascribed to Site A Unsalvaged and Site A Salvaged were closer in proximity to one another and shared a remarkably similar level of mean carbon storage (both 92 MgC/ha). They were also dominated by *Q. alba*. Site B Salvaged was further to the west, had a different pre-disturbance dominant species (*P. taeda*) and had a lower pre-disturbance level of carbon storage (66 MgC/ha). The 1999 wind disturbance impacted the forest heterogeneously, generating different amounts of dead and downed woody material throughout the impacted areas, which contributed to the structural complexity of the forest (see [14,43]). Salvage logging subsequently removed many of these structural components, again homogenizing the forest [30,32]. From the 19 years of recovery, Site A Unsalvaged had the greatest variation in plot-level biomass when compared with both Site A Salvaged and Site B Salvaged. We propose that this greater variation in biomass was a result of increased structural heterogeneity caused by a natural disturbance; post-disturbance salvage logging decreased the heterogeneity.

Contrary to our prediction, the relative change in biomass from 3 years post-disturbance to 19 years post-disturbance showed a positive linear relationship with the wind disturbance severity level, indicating that more disturbed sites recovered biomass more rapidly than sites with a lower-severity disturbance. Some of the trend was confounded with the fact that Site B Salvaged was dominated (both pre- and post-disturbance) by faster-growing *P. taeda*, thus causing some of the difference in biomass accumulation rates. However, even for sites that had more balanced species dominance, the accumulation rates were greater for areas with higher disturbance severities. We suspect that this is likely to be a result of increased resource availability where the disturbance severity killed more trees. We posit that more severe disturbances lead to more resources that are available for remaining trees to accumulate biomass more rapidly than areas that experience lower-severity disturbances. While past work has indicated that a high disturbance severity may interact differently with subsequent disturbances and alter the carbon stock recovery trajectory [22,34,49], we did not find evidence for this. However, our study did not measure the recovery between years 3–19, and in the context of natural disturbances, the studied wind disturbance was considered to be of a moderate severity.

A central question in forest disturbance ecology is whether salvage logging following a natural disturbance negatively affects a forest. This has been examined in the context of species diversity, composition, nutrient cycling, ecosystem services and many other forest characteristics [22,35,50]. A recent framework has been developed to assess the utility of salvage logging in mitigating future disturbances with potential damage to ecosystem functions, and it emphasizes that assessments are highly context-specific [23]. While some studies have found evidence that combined disturbances may reduce carbon storage [5], this study found no negative effect of salvage logging on the carbon accumulation post-wind disturbance. While we found no effect of salvage logging on aboveground tree carbon accumulation after a moderate-severity wind disturbance, salvage logging affects other carbon pools, most significantly coarse woody debris [30,31]. The removal of such large amounts of coarse woody debris may impact soil organic materials and ultimately ecosystem properties, such as soil respiration and carbon storage potential [32,33]. We suggest that ongoing long-term studies of recovery post-wind disturbance and salvage logging will reveal whether salvage logging impacts biomass accumulation in mature forests when resources may be more limited.

5. Conclusions

This study examined the effects of wind disturbance and combined wind and salvage logging disturbance on aboveground tree biomass and carbon storage. After 19 years, the study sites reached pre-disturbance levels of carbon storage. Salvage logging did not reduce the rate of carbon stock recovery, and a higher wind disturbance severity was associated with a greater rate of carbon stock recovery. We suggest that forest management practices focus on increasing the resilience to disturbances to promote recovery. Adopting frameworks that weigh the costs of salvage logging on forests will ensure that salvage logging does not negatively impact forest ecosystem functions.

Supplementary Materials: The following are available online at https://www.mdpi.com/1999-4907/12/2/173/s1, Figure S1: A linear regression between diameter (cm) of stem at trunk base and diameter (cm) of stem at breast height for *P. taeda* at Natchez Trace State Forest; Figure S2: A linear regression between diameter (cm) of stem at trunk base and diameter (cm) of stem at breast height for *Q. alba* at Natchez Trace State Forest; Table S1: Detailed information on the dry weight aboveground tree biomass (Mg/ha) and disturbance severity pre-disturbance, 3 years post-wind disturbance, and 19 years post-wind disturbance for the study areas at Natchez Trace State Forest.

Author Contributions: Conceptualization, C.A.O. and C.J.P.; methodology, C.J.P.; software, C.A.O.; validation, C.A.O. and C.J.P.; formal analysis, C.A.O.; investigation, C.A.O.; resources, C.A.O. and C.J.P.; data curation, C.A.O. and C.J.P.; writing—original draft preparation, C.A.O.; writing—review and editing, C.J.P.; visualization, C.A.O.; supervision, C.J.P.; project administration, C.A.O. and C.J.P.; funding acquisition, C.A.O. and C.J.P. All authors have read and agreed to the published version of the manuscript.

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Data Availability Statement: Data available in a publicly accessible repository. The data presented in this study are openly available in Oldfield, Callie (2021), "Woody stem composition and diameter at Natchez Trace State Forest", Mendeley Data, V1, doi:10.17632/ng4mk3xsx2.1.

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