

Article

Tropical Cyclone Response in Annual Tree Growth at Three Different Coastal Sites Along the Gulf of Mexico, USA

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Abstract: Coastal forests are highly vulnerable to disturbances from tropical cyclones (TCs), yet the long-term impacts of storm surges on tree growth remain understudied. This study examines the relationship between TC-induced storm surges and annual tree-ring growth in *Pinus elliottii* at three coastal sites along the northern Gulf of Mexico. Using dendrochronological methods, we analyzed total ring width, earlywood, and latewood growth patterns to assess suppressions in response to past TC activity. Our results indicate that storm surge events consistently cause growth suppression, with recovery periods averaging two to three years. However, suppression patterns vary by site, with trees in more protected locations displaying stronger correlations with TC storm surge events, while those in chronically stressed environments exhibit frequent growth limitations independent of TCs. For example, only 38% of suppression events at the unprotected Gulf State Park correspond with TC storm surge events, and this increases to 67% at the protected Weeks Bay NERR site. Additionally, latewood ring width corresponds with TC storm surge events more than total or earlywood ring width. These findings highlight the complexity of TC impacts on coastal tree growth, emphasizing the importance of site-specific factors such as topographic position and hydrological conditions. Understanding these interactions is critical for improving paleotempestology reconstructions and informing forest management strategies in coastal environments facing increasing TC activity due to climate change.



Academic Editor: Angelo Rita

Received: 30 January 2025

Revised: 27 February 2025

Accepted: 6 March 2025

Published: 8 March 2025

Citation: Tucker, C.S.; Crowell, A.C.; Stan, K.D.; Patterson, T.W. Tropical Cyclone Response in Annual Tree Growth at Three Different Coastal Sites Along the Gulf of Mexico, USA. *Forests* **2025**, *16*, 476. <https://doi.org/10.3390/f16030476>

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Keywords: coastal forests; hurricane; storm surge; dendrochronology; *Pinus elliottii*

1. Introduction

Coastal forests sit at the interface of environmental and human interactions, with complex dynamics between economic development, natural disasters, and stress from local site conditions [1]. In subtropical coastal forests, one such influential disturbance regime is tropical cyclones (TCs) [2]. TCs can produce complex influences on forest structure, function, and productivity due to heavy rainfall, high winds, and storm surges, among other effects [3–12]. The relationship between tropical cyclones and resulting forest impacts is not straightforward; however, local site conditions and the geographic location of trees influence the resultant level of stress. Trees proximal to the coastline exhibit decreased growth in subsequent years following TCs [6,8], due to the high winds and saltwater inundation from storm surges. Inland trees in flooded swamps, by contrast, have shown increased growth due to the influx of oxygenated water [10,12]. TC frequency and intensity are projected to increase in the Gulf of Mexico as a consequence of global climate change, underscoring the need to understand their impact on these vulnerable coastal forests

today [13]. These forests also often serve as buffers for nearby human communities to reduce the impact of such storms on human infrastructure, reinforcing the importance of understanding these complex interactions [1].

Dendrochronology, the study of tree rings, examines annual tree-ring growth to understand the influence of environmental conditions on annual radial growth variability, which in turn is used as a proxy data source when instrumental data are unavailable. These growth rings are one the ways to record the impact of TCs and they provide a mechanism to compare local and regional stressors as well as environmental conditions. Previous work has detailed the resilience of lower coastal plain trees to TC impacts [14], while also highlighting the detrimental effects of TC high winds and storm surges [15–19]. Tree rings have also been used to document the influence of microsite characteristics on both forest health and climate-influenced growth changes [20,21]. The south Florida slash pine (*Pinus elliotii* var. *densa*), for example, showed a relationship between basal area, age, and elevation when two pine rockland savanna islands were considered [21]. The trees located at a slightly higher elevation had a larger basal area and were older than the younger and smaller trees growing less than one meter below. These differences highlight the protective nature of the topographic growing position during TC storm surge events where 2–3 m of topographic variability result in inundation versus protection.

Research is needed on the interplay between site characteristics and TC effects on coastal forest growth patterns, and there is limited work on how these interactions change at the edge of a tree's habitable range. Studying the edge responses under extreme event conditions can inform our fundamental understanding of ecosystem processes and resilience limits while providing insights into critical management strategies in these sensitive sites. In other words, the literature on radial growth response to TC storm surge inundation is limited to two studies from two sites [3,8], and thus severely limits our understanding of this process and prohibits any robust ecological planning during an increased threat of TC frequency under global climate change. To better characterize tree response to TC stressors, this study compares three nearby sites along the northern Gulf of Mexico (hereafter GOM) with varying distances and topographic positions from the water's edge. These sites were chosen as they are dominated by *Pinus elliotii* var. *elliotii* (hereafter *P. elliotii*) of at least 75 years of age and are all impacted by the same TCs, allowing for the direct comparison of TC and microsite characteristic interactions.

2. Materials and Methods

2.1. Site Selection

Study sites were chosen based on the availability of trees old enough to produce at least 75 years of tree-ring data. In previous research, *Pinus elliotii* growing in coastal locations in the northern GOM have been suitable for this research [3,8]. Additionally, sites were chosen for their proximity to the coast (<1 km from saltwater) because saltwater, and ultimately a lack of freshwater, creates environmental conditions similar to drought. Stressful environments like the desert southwest are chosen for tree-ring research because trees in those areas are more sensitive to climatic factors that drive growth. Additionally, trees along the northern GOM coast are likely to have experienced TC activity. All areas of the northern GOM coastline experience TCs at least once per decade [22]. Ultimately, three public land areas were chosen for study-site locations (Figure 1): Gulf State Park, Alabama (GSP); Weeks Bay National Estuarine Research Reserve, Alabama (WB); and Topsail Hill Preserve State Park, Florida (TSH).

At all sites, *P. elliotii* was a common canopy tree species. At WB (30.37° N, 86.29° W), *P. elliotii* occurred along the southeastern shore of Mobile Bay approximately 400 m inland from a flat beach–marsh complex. At GSP (30.26° N, 87.63° W) and TSH (30.34° N,

87.82° W), *P. elliotii* occurred along the shoreline of an inland freshwater lake approximately 1 km inland from a beach on the GOM.

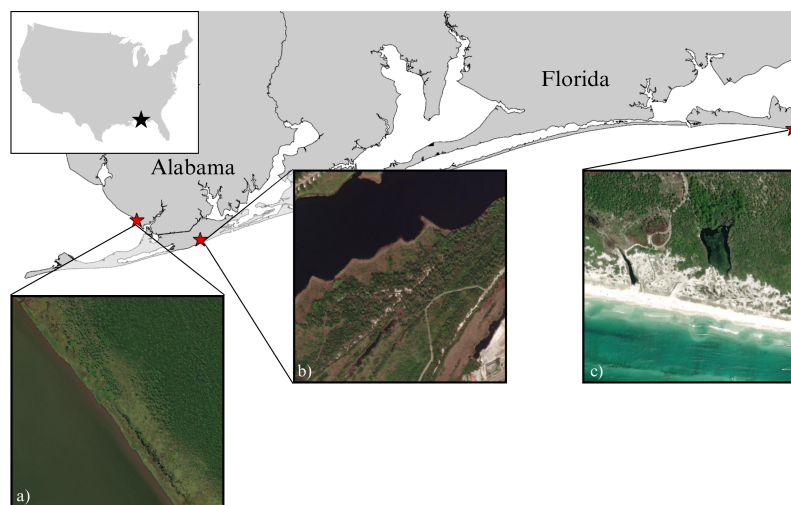


Figure 1. Map of study-site locations at (a) Weeks Bay National Estuarine Research Reserve, Alabama; (b) Gulf State Park, Alabama; and (c) Topsail Hill Preserve State Park, Florida.

2.2. Tree-Ring Data

Concurrent with previous dendrochronology research, trees at each site were selected for their large size, aged appearance, dominance in the canopy, and location away from competing trees [23,24]. Additionally, trees with significant scarring, rot, and damage and/or dead trees were excluded from sampling. Two cores were obtained from trees at each site using a Hagl f increment borer (Hagl f Sweden of Langsele, L ngsele, Sweden) at approximately breast height (1.37 m). Two cores allowed each tree to be crossdated at the individual tree level. Tree cores were stored in paper straws in the field for safety in transport and were labeled with a site code and tree number (its order of field sampling). In the lab, samples were air dried and then mounted into wooden mounts with water-based glue for protection during processing. To be able to identify clear tree-ring boundaries under magnification, each sample was sanded with a belt sander using progressively finer sandpaper (120, 220, 320, 400, and 600 grit) to reveal a smooth surface.

Tree cores were visually crossdated using the list method [25], and total ring widths (TRWs), earlywood ring widths (ERWs), and latewood ring widths (LRWs) were measured to the nearest 0.001 mm using the computer program *CooRecorder* 9.8.4 [26]. Seasonwood (i.e., earlywood and latewood) was defined as the break in tree-ring anatomy when the first appearance of cell-wall thickening became apparent visually (Figure 2). Following standard dendrochronology methods, a final verification of crossdating accuracy was performed utilizing the quality control program *COFECHA* [27]. Finally, three site-level time series were created by standardizing and averaging all crossdated and measured tree cores in the computer program *ARSTAN* [27]. During active detrending in *ARSTAN*, the best fit to remove growth trends and standardize ring-width series was a spline with a 50% frequency response cutoff equal to two-thirds of the length of each series (67% spline), which is a commonly used detrending method in dendrochronology [28]. For this study, we chose the standard chronology time series output from *ARSTAN* for all analyses. Chronologies were produced for all seasonwood (i.e., TRWs, ERWs, LRWs) at all sites.

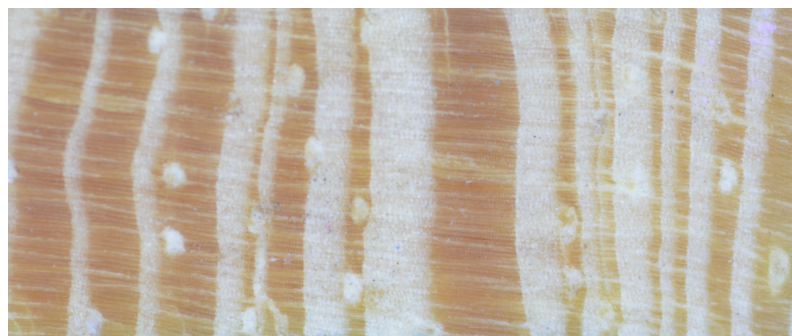


Figure 2. Amicrophotograph of *Pinus elliottii* tree rings from a core sample taken from Gulf State Park, Alabama. Tree growth in this photograph occurs from the years 2002 to 2016 from left to right in this sample. Note the suppressed latewood (darker color) in the years 2005–2007 and 2009–2013.

2.3. Tropical Cyclone Data

Storm surge and storm tide (i.e., surge plus tidal increase) data for TCs were obtained through the SURGEDAT website interactive map maintained by Louisiana State University. Continuous data are available on SURGEDAT for 1950–2022. The authors of [8] used a threshold of storm surge values within 80km of the study site, and we used that same threshold to provide consistency in analyses. Additionally, TC track data (e.g., maximum category, minimum pressure, and maximum wind speed) were obtained through the National Center for Environmental Information’s IBTrACs dataset and the National Hurricane Center’s HURDAT2 dataset. The average width of an Atlantic hurricane is 480 km; therefore, we set a threshold for all non-storm-surge TC analyses for 250 km.

2.4. Analyses

Year-to-year comparisons displayed years of growth pattern changes; however, previous research has more appropriately used tree-ring data to create suppression chronologies [6,8]. Tree growth suppression describes tree-ring width as a function of percent growth from year to year. Tree growth may both increase and decrease as a result of environmental factors, and a running hypothesis for this study states that TC storm surges cause a decrease in annual tree growth. For this study, we prepared a suppression chronology by first creating a moving average of tree-ring width to normalize large changes in growth within decadal-scale growth trends:

$$G = \frac{yr_0 + yr_{-1} + yr_{-2} + yr_{-3} + yr_{-4}}{5}, \quad (1)$$

where G represents average growth through the five years of the current year (yr_0) and the previous four years ($yr_0 - yr_{-4}$). Percent change is defined as

$$\Delta\% = \frac{G_{curr} - G_{prev}}{G_{prev}} \times 100, \quad (2)$$

where $\Delta\%$ represents percent change in the current year, G_{curr} represents a five-year average growth including the current year, and G_{prev} represents the previous year’s five-year growth average. When $\Delta\%$ is negative, growth in the current year is less than the previous five-year average. We used the percent change calculations as a threshold for comparison with storm surge data.

We defined years when $\Delta\% \geq -10\%$ as suppression years and created a suppression chronology of binary values (0 for no suppression and 1 for suppression). These suppression chronologies were then compared to a binary dataset of storm surge activity (0 for no suppression and 1 for suppression). Finally, “recovery periods” were defined as the number of years after the current year in which $\Delta\%$ was negative.

Superposed epoch analysis (SEA) was used to analyze the statistical relationship between TC storm surge and growth suppression events [8]. SEA diagnoses temporal relationships between climate variables and tree growth by comparing statistical windows of past, present, and future climate conditions during each growth year individually. This method is particularly useful when comparing event-based datasets that are not continuous and may have a limited number of samples on which to base statistical significance. SEA uses 1000 bootstrapped Monte Carlo simulations to model the effects of TCs on tree growth and to assess the significance of the results. The mean and standard deviations of these simulations are recorded and compared with the uncertainty discovered by running multiple simulations. The model also compares those simulations to user-defined lag years before and after the year of occurrence. Event years were chosen for analysis based on all sites receiving at least 2.0 m of storm surges in a given year. This analysis was completed in the R statistical programming language using methods defined in [29].

3. Results

3.1. Storm Surge Records

A total of 66 TCs were tracked within 250 km of all study sites from the common period among all datasets (1950–2017). Of those 66 TCs, 55% strengthened to reach categorized hurricane status. The year 2005 had the highest frequency impacting the study sites: three hurricanes and one tropical storm. The most active month across all sites was August: 27% of the 66 TCs occurred in August. This was closely followed by September with 26% of all recorded TCs. Of the 66 TCs, 65% caused storm surges or tides at at least one study site. Among all sites, storm surge events averaged 1.14 m and storm tides averaged 1.39 m. The highest storm surge/tide values were associated with Hurricanes Katrina (2005), Ivan (2004), Opal (1995), Frederic (1979), and Eloise (1975) with storm surge values exceeding 3.1 m. The absolute highest storm surge value among all sites was 4.75 m west of Miramar Beach (approximately five and a half miles from TSH), which was caused by Hurricane Opal in 1995.

3.2. Tree-Ring Records

To determine the quality of crossdating and agreement among tree growth at each site, we compared the correlation of tree cores with the average of all trees at the site. Descriptive statistics of total tree-ring width from each site indicated that series intercorrelations and year-to-year variability (i.e., average mean sensitivity) were within the ranges obtained from previous studies using the species *P. elliotii* as well as studies in this region [3,6,8]. Series intercorrelation and average mean sensitivity were highest at WB (Table 1). The longest period of record for this study was at TSH (1872–2020), and WB allowed for the highest number of successfully crossdated ring-width series ($n = 29$). Values for LWRs and ERWs were found to be similar to TRWs.

Table 1. Descriptive statistics for *P. elliotii* tree-ring data at Gulf State Park, Alabama (GSP); Weeks Bay National Estuarine Research Reserve, Alabama (WB); and Topsail Hill Preserve State Park, Florida (TSH).

Site	Period of Record	Number of Series	Series Intercorrelation	Average Mean Sensitivity
GSP	1921–2017	20	0.554	0.383
WB	1923–2019	29	0.716	0.466
TSH	1872–2020	24	0.553	0.348

For all datasets, the lowest growth occurred during the years following 2005 (Figure 3). This pattern was similar for TRWs, ERWs, and LRWs, and the pattern after 2004/2005 was

most pronounced for ring width at GSP. Additionally, the years following 1965, 1979, and 1995 also indicated low ring widths at all three sites. No other common periods of low growth existed for all three sites.

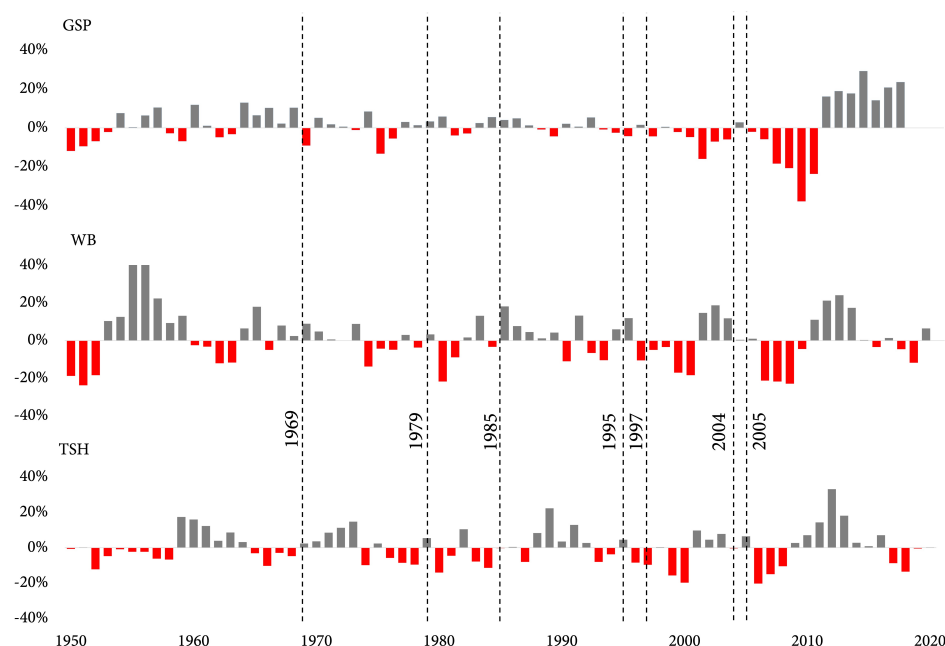


Figure 3. Suppression chronologies (i.e., percent change in 5-year average growth) for Gulf State Park, Alabama (GSP); Weeks Bay National Estuarine Research Reserve, Alabama (WB); and Topsail Hills Preserve State Park, Florida (TSH). Red bars indicate years when growth was suppressed. Vertical dashed lines indicate years when at least 2.0 m of storm surges impacted all sites.

A principle question for this study was to determine the relationship between coastal tree growth (i.e., tree-ring suppression chronologies) and tropical cyclone storm surge events. Overall, our results indicate that 25–67% of the years with low tree–tree growth (i.e., suppression years) correspond with the year following storm surge events (Table 2). This pattern was most prominent at WB and least prominent at GSP. Additionally, this pattern was strongest for LRWs and weakest for ERWs across all sites. However, 72–100% of years with at least one tropical cyclone storm surge event correspond with suppressed growth the following year. This pattern was most prominent at GSP and least prominent at WB. Additionally, this pattern was strongest for ERWs and weakest for LRWs across all sites. Taken together, these results indicate that not every suppression is caused by a storm surge event, but nearly every storm surge event causes a suppression. Years to recovery for all sites for TRWs and ERWs averaged nearly three years, though recovery in LRWs was shorter at two years.

SEA was conducted for all years when 2.0 m or greater storm surges impacted all study sites. These years were 1969, 1979, 1985, 1995, 1997, 1998, 2004, and 2005. The results of SEA indicated that significant results exist for Weeks Bay suppression chronology only (Figure 4). In the year following a tropical cyclone storm surge of 2.0 m or greater, the 5-year average growth was suppressed by more than 10% in the year directly following TC storm surge occurrence ($p < 0.05$). Though suppression did occur for the other two sites, the results were much weaker and not statistically significant in the year following TC storm surge occurrence.

Table 2. Results for comparison between total ring width (TRW), earlywood ring width (ERW), and latewood ring width (LRW) suppression chronologies and storm surge chronologies for Gulf State Park, Alabama (GSP); Weeks Bay National Estuarine Research Reserve, Alabama (WB); and Topsail Hill Preserve State Park, Florida (TSH). Column **A** shows the percentages of suppression years that corresponded with storm surge years, while Column **B** shows the percentages of storm surge years that corresponded with suppression years. Averages for all analyses are included in the final three rows.

Site	Seasonwood	A	B	Years to Recovery
GSP	TRW	37.5%	100%	2.5
	ERW	25.0%	100%	2.3
	LRW	56.3%	87.5%	2.3
WB	TRW	66.7%	80.0%	2.5
	ERW	61.1%	87.5%	2.6
	LRW	66.7%	72.7%	2.0
TSH	TRW	40.0%	85.7%	3.0
	ERW	35.0%	100%	3.3
	LRW	45.0%	80.0%	1.6
All	TRW	48.1%	88.6%	2.7
	ERW	40.4%	95.8%	2.7
	LRW	56.0%	80.1%	2.0

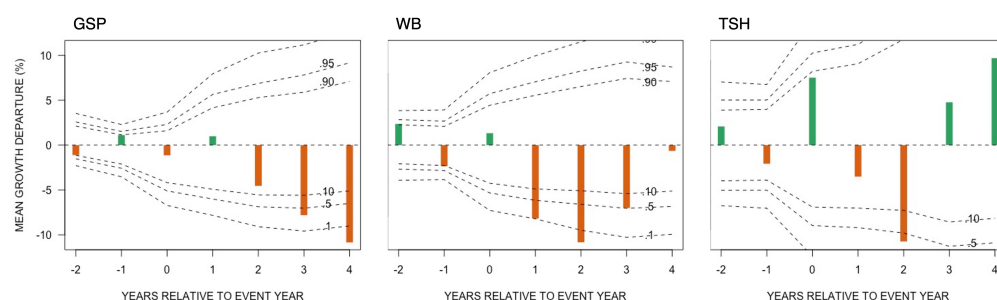


Figure 4. Superposed epoch analysis of Gulf State Park, Alabama (GSP); Weeks Bay National Estuarine Research Reserve, Alabama (WB); and Topsail Hill Preserve State Park, Florida (TSH) suppression chronologies and TC storm surges. Red bars indicate negative departure in growth, and green bars indicate positive departure in growth. In the year following a tropical cyclone storm surge of 2.0 m or greater, the 5-year average growth was suppressed by more than 10% at WB only.

4. Discussion

Annual tree growth is a function of multiple factors. While TCs may only represent hours to days in one year of tree growth, TCs have a measurable effect on annual tree-ring widths.

4.1. Effects of TCs

Larger, longer-lasting suppressions may be tied to a TC stacking effect. Previous research has come to similar conclusions [8,10,12,30,31]. If one TC storm surge event occurs in isolation, then suppression may be minimal. However, multiple storm surge events within the same year, or during subsequent years, can lead to higher magnitude suppressions. This phenomenon occurred after the 2004 and 2005 hurricane seasons, which were both active years in the record with multiple large storm surge events. All sites exhibited a multi-year suppression in TRWs and LRWs beginning in 2006. Growth did not return to the average for at least three years following the start of those suppressions.

Some TC storm surge events elude the tree-ring record, and the cause of these non-recording events is poorly understood. One possible explanation is that TC precipitation

can be so intense that it has possibly negated the effects of storm surge inundation [7,32,33]. If a site suffered from drought prior to TC passage, a release will occasionally occur from the influx of rainwater, masking the impacts of storm surge. This may also be the case if a TC storm surge during a specific event was purged by its own heavy TC precipitation. Additionally, rain preceding storm surge inundation could fill the water table with fresh water and not permit saltwater to infiltrate the soil. While speculative, we believe some function of TC rainfall concurring with storm surge inundation could influence non-recording event frequency and more research would be required to confirm this influence.

Our study indicated that as much as two-thirds of all suppressions correspond with TC storm surge events. These results are consistent with previous research indicating that 77% of false rings correspond with TC precipitation [12], 73% of high-growth years correspond with high TC activity [7], and 83% of negative tree-ring $\delta^{18}\text{O}$ values correspond with TC events [4]. The compounding effects of stacking TCs, TC precipitation, extreme TC winds, and TC storm surges likely have dissimilar effects on different tree-ring proxies. Additionally, each TC makes landfall in different locations with different forward speeds and may not permit precipitation, extreme winds, and storm surges to infiltrate the site in the same ways for each TC.

4.2. Seasonwood

Storm surge events nearly always cause suppressions in ERWs (Table 2, Column B). Previous research shows that the majority of annual diameter growth for most tree species in this region, including *Pinus* spp., ends in September [34,35], when the Atlantic hurricane season reaches its peak [36]. ERW is the first growth following most TCs at these sites and is thus more likely to be affected by the previous year's climate; LRW size in the year following a TC is also dependent on the climate of that year.

However, suppressions of LRWs correspond more readily to TC storm surge events in a predictive capacity (Table 2, Column A). While TC storm surge nearly always causes a suppression in ERWs, the suppressions in ERWs are clearly caused by more TC storm surge events. For example, at GSP, only 25% of ERW suppressions correspond with storm surges, which means that 75% of ERW suppressions at GSP are caused by something other than TC storm surges. In contrast, LRW suppressions at WB are frequently caused by TC storm surges (67%). In other words, nothing causes suppressions in LRWs as often as TC storm surge events. Similar to previous studies [7–9,37], LRW in *Pinus* spp. is a more reliable indicator of climate than the ERW or TRW.

4.3. Shoreline Geography, Ecological Amplitude, and Site Selection

Each of the three sites used in this study has differing geography (Figure 1). At GSP, a beach–dune complex 200 m from the Gulf of Mexico, trees grow at low elevations on the landscape, often below sea level, in a frequently flooded, poorly drained area. At WB, a protected shoreline in Mobile Bay behind the Fort Morgan Peninsula, trees grow above sea level in a well-drained freshwater swamp. At TSH, a mature beach–dune complex with a high foredune 200 m from the Gulf of Mexico, trees grow atop and behind dunes in well-drained soils.

Images of each site show (1) dead snags of the low-lying GSP (Figure 5), (2) the thick canopy of trees at WB (Figure 6), and (3) a classic pine savanna, open-canopy forest with a lush understory at TSH (Figure 7). Trees at GSP are less protected and clearly more stressed by local environmental conditions than those at WB or TSH. Additionally, the brackish conditions and protection from the Fort Morgan Peninsula protect trees at WB than at TSH.

We believe these geographic environmental conditions are related to the site-specific results in this study. Growth at WB was the most responsive to storm surge events, while trees at GSP were the least responsive (Figure 2). The Fort Morgan Peninsula protecting WB and

the tall dunes at TSH protect the trees at these sites from regular saltwater inundation and high winds [38]. These results are also supported by SEA tests conducted on suppression chronologies (Figure 4). The results for these tests in the year immediately following TC storm surge occurrence were strongest and only statistically significant for Weeks Bay NERR, Alabama. Shoreline geography can have disruptive effects on growth–climate analyses in tree-ring data, and GSP and TSH sites did not have strong statistical relationships with TC storm surge data.



Figure 5. An image of dead snags near a site used in this study at Gulf State Park, Alabama.

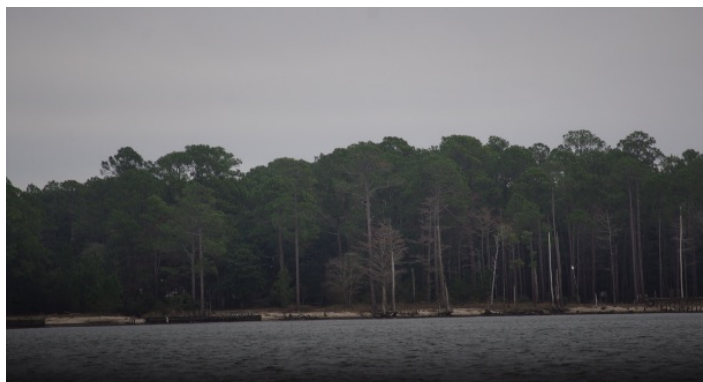


Figure 6. An image of the Swift Tract, a site used in this study, at Weeks Bay National Estuarine Research Reserve, Alabama.



Figure 7. An image of the pine savanna site used in this study at Topsail Hills Preserve State Park, Florida.

Dendrochronologists often use the principles of site selection and ecological amplitude to select sites with trees that will produce growth patterns that relate to the environmental conditions at a given site [23,39]. For example, the GOM coastline is seemingly a useful area to select when assessing the effects of TCs on tree growth (principle of site selection) because TCs are common in this region [22,40]. Additionally, the GOM coastline is near the edge of the latitudinal range for *P. elliottii*, and therefore, tree-ring response to environmental conditions should be enhanced (principle of ecological amplitude). However, unprotected sites in low-lying areas like the conditions at GSP are so environmentally stressful that the trees at these locations suppress growth incredibly frequently. For example, suppressions at GSP are only related to TC storm surges 25% of the time, but 100% of storm surges cause suppressions. The dichotomy of these results suggests that GSP trees produce many suppressions throughout their life for reasons seemingly unrelated to TCs (i.e., 4x more than a TC storm surge alone). In contrast, 67% of trees at WB produce suppressions following TC storm surges, and only 72% of storm surges cause suppression. The simple fact that these two percentages are similar shows that TC storm surges are important drivers of suppressions at a site where trees are healthy and protected.

In dendrochronology theory, the principle of ecological amplitude suggests that tree growth is more sensitive to environmental factors at the edge of the species' spatial range [39]. In the case of this study, for example, one might expect that *P. elliottii* would be especially sensitive to its environment given its location on the Gulf Coast near the edge of its spatial range. However, the results of this study indicate that this principle may not hold true when analyzing trees so stressed by their environment that they barely survive.

In the mid-20th century, Schulman and others believed that the oldest bristlecone pine existed at the edge of its spatial range in western Nevada [41,42]. However, Currey later debunked this claim with a 4900-year-old tree in eastern Nevada near the center of its range [43]. While those studies debated spatial range and age rather than spatial range and climate sensitivity, the principle of ecological amplitude may not always remain constant. With multiproxy analysis and better technology, an analysis of a species's dendrochronological potential may not be limited by ecological amplitude. Rather, a thorough investigation of that species across both its spatial and ecological range is an important factor regarding its use as a dendroclimatic proxy.

5. Conclusions

Much of the recent TC research projects an increase in the occurrence of larger TCs with higher wind speeds, heavier precipitation, and higher storm surges under future climate scenarios. Paleoclimate archives such as tropical and subtropical coastal trees will be useful in obtaining reconstructed climate data for TC storm surges and precipitation during the past millennium. However, few studies analyze the effects of TCs on annual tree growth. Previous dendrochronological research indicates that *P. elliottii* radial growth trends could be used to identify long- and short-term growth patterns associated with TC passage along the Gulf of Mexico coast [8,10,30]. Our study indicates that this is true at three additional sites, and seasonwood analysis may be more powerful than TRW alone.

Furthermore, the geography of each site is important for understanding the impacts of coastal stressors and TCs together. Coastal sites that are more susceptible to multiplying stressors (e.g., frequent inundation, poorly drained soils, and constant sea breeze) produce trees that do not grow enough in any given year to produce an annual ring necessary for dendrochronological analysis. Therefore, less protected sites (i.e., closer to open saltwater) with multiplying stressors are not the best sites for understanding the impact of TCs separate from the impacts of other stressors (e.g., drought, fire, disease, and pests). This idea is in opposition with two basic principles of dendrochronology: the concept of site selection

and the concept of ecological amplitude. However, understanding this conundrum can lead future researchers to proper field sites for analyzing annual tree growth response with TCs. Additionally, future research investigating the impact of TC storm surges on growth will require finding older trees and remnant wood samples for producing reconstructions, and multiproxy tree-ring analyses (e.g., anatomical and chemical tree-ring features) will be necessary to fully understand the signal of TCs in annual tree growth.

Author Contributions: Conceptualization, C.S.T.; Methodology, C.S.T. and T.W.P.; Validation, C.S.T.; Formal analysis, A.C.C. and T.W.P.; Data curation, A.C.C.; Writing—original draft, A.C.C. and T.W.P.; Writing—review & editing, C.S.T. and K.D.S.; Supervision, C.S.T. and T.W.P. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Data Availability Statement: The datasets presented in this article are not readily available because the data are part of an ongoing study. Requests to access the datasets should be directed to first author Clay Tucker.

Acknowledgments: We thank Franklin Heitmuller and David Holt for their guidance and participation during edits in a previous draft of this manuscript. We also thank the staff at Gulf State Park and Weeks Bay National Estuarine Research Reserve in Alabama and Topsail Hill Preserve State Park in Florida for their help with access and site procurement for this research.

Conflicts of Interest: The authors declare no conflicts of interest.

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