



The University of West Florida Campus Ecosystem Study: age-diameter and growth relationships of longleaf pine using hurricane-induced windthrows

Frank S. Gilliam¹ · Heather N. Patten¹ · Sarah K. Rabinowitz¹

Accepted: 6 December 2021

© The Author(s), under exclusive licence to Springer Science+Business Media, LLC, part of Springer Nature 2021

Abstract

The campus of the University of West Florida (UWF) was constructed among second-growth longleaf pine (*Pinus palustris*) stands that survived extensive logging in the Florida Panhandle. Previous studies on longleaf pine on the main UWF campus have estimated, based on a model from old-growth longleaf in southern Georgia, that oldest stems were just under 200 yr old and that > 80% of stems on the main UWF are between 50 and 125 years old. More accurate age data can be obtained from disks collected locally from recently fallen trees. On 16 September 2020, Hurricane Sally impacted UWF as a Category 2 storm, with winds reaching 49 m/sec. Our study took advantage of longleaf pine blowdowns by Sally to obtain cross-sections for age determinations. Two natural areas of the UWF campus were chosen for sampling: the Edward Ball Nature Trail and the Baars-Firestone Wildlife Sanctuary. For each sampled section, diameter at breast height (DBH) and number and width of annual rings were recorded. Based on a total of 50 sampled trees, linear regression revealed a statistically significant ($P < 0.00001$; $R^2 = 0.82$) relationship between DBH and age. Applying this to DBH measurements of 2,165 stems on the main campus indicates that the oldest longleaf pines are ~ 130 years old (mean age = 63.9 ± 0.4 yr), consistent with cessation of historically widespread harvesting in the region. Mean age for the Trails site (55.7 ± 1.6 yr) was significantly lower than that of the Sanctuary (66.7 ± 2.0 yr), suggesting that they represent sites of contrasting land-use history. Annual growth rates of older pines were mostly negatively correlated with temperature. Directions of stem windthrows did not vary between natural areas and were consistent with characteristics of the eyewall of Hurricane Sally with strongest wind gusts moving from a southeast to northwest direction. This study confirms that college/university campuses can be used as a units of ecological study in a way that takes advantage of stochastic events such as tropical cyclones.

Keywords Urban interface · Longleaf pine · Tropical cyclones · Climate change

Introduction

Previous work on the campus of the University of West Florida (UWF)—the UWF Campus Ecosystem Study (CES)—has focused on the following research aims: (1) population structure of longleaf pine (*Pinus palustris* Mill.) on the main campus and effects of burrowing by gopher tortoises (*Gopherus polyphemus* Daudin) (Gilliam et al. 2020) and (2) composition, structure, and soil fertility of chronically unburned remnant longleaf stands in campus natural areas

(Gilliam et al. 2021). This work has taken advantage not only of the uniqueness of the urban interface created by college/university campuses, but also of the design of the campus as initially envisioned by John Jarvis, who was influenced by the Scottish landscape designer, Ian McHarg. McHarg's classic text, *Design with Nature* (McHarg 1995), greatly informed Jarvis' philosophy of campus design, wherein tree cutting was minimized and natural contours were maintained to the extent possible (Jarvis 2008).

Tracts of land purchased by the State of Florida for campus construction in 1963 were largely composed of stands of longleaf pine at various stages of recovery following widespread harvesting that ceased approximately a century prior to construction (Marse 2007; Knight et al. 2011). Thus, a major impetus for the initial phase of the CES was to assess the size and age structure of longleaf pines on the

✉ Frank S. Gilliam
fgilliam@uwf.edu

¹ Department of Biology, University of West Florida,
Pensacola, FL 32514, USA

main campus, encompassing the areas of various permanent structures (e.g., classroom and academic department buildings), parking lots, and green spaces. In the absence of more suitable models, the initial CES used a linear age/diameter equation from the Wade Tract of southern Georgia (Platt et al. 1988) to estimate age based on diameter at breast height (DBH) measurements of more than 2,000 longleaf stems (Gilliam et al. 2020). In addition to findings regarding the profound effects that gopher tortoises have on soil fertility and herbaceous plant communities, conclusions of the original CES suggested that the oldest longleaf pines were just under 200 yr old and that greater than 80% of stems on the main UWF were between 50 and 125 years old.

The second phase of the CES involved a forest community analysis of two campus natural areas which were essentially chronically unburned remnant longleaf stands. Particular emphasis was placed on the size structure of longleaf pine in these areas for comparison between the two areas, as well as the main campus (Gilliam et al. 2021). Consistent with other sites experiencing chronic fire exclusion (Varner et al. 2005; Gilliam and Platt 2006; Hiers et al. 2014; Addington et al. 2015; Rother et al. 2020), the second phase of the CES found a notable establishment of numerous hardwood species among widely-spaced mature longleaf pine stems (Fig. 1). Conclusions of this study suggested that the two natural areas

Fig. 1 Mature longleaf pines that have become established in chronically unburned stands. The more open aspect of this view reflects canopy gaps created by Hurricane Sally-mediated windthrown pines



on the campus of UWF were originally tracts of land under separate ownership at the time of campus design in 1963, based on contrasts in size distributions of longleaf stems.

There remains ongoing debate regarding the relationship between stem age and diameter (Speer 2010). Some of this arises from the methodological challenges of determining age from increment cores, wherein the core might miss the true beginnings of growth, include false rings, or both. Although the use of cross-sections of tree stems is superior to increment cores in alleviating both these concerns, it has its own limitations in that it either requires harvesting a live tree or sampling a fallen tree that fell at an unknown time in the past. Limitations regarding cross-sections can be overcome by combining cross-dating with discrete events that cause widespread windthrows of stems, such as tropical cyclones or tornadoes.

On the other hand, a great deal of work has been devoted to using longleaf pine for dendroclimatological and dendroecological studies (Devall et al. 1991; Knapp et al. 2016; Petterson and Knapp 2016). These have varied greatly regarding both the specific focus and the temporal scale in which they endeavored to discern relationships between climate and growth. Devall et al. (1991) used a climate model with time-varying parameters that was fit to tree rings in southern Mississippi, finding that August rainfall and the February Palmer Drought Severity Index (PDSI) best predicted growth. Using tree-ring data from sites in North and South Carolina, Patterson and Knapp (2016) found that masting was related both to radial growth and, in unthinned stands, PDSI. Kaiser et al. (2020) applied ring width/

climate relationships toward understanding the selection of longleaf stems as cavity trees by the endangered red-cockaded woodpecker (*Dryobates borealis* Vieillot), endemic to longleaf pine ecosystems. Differentiating between types of radial growth (i.e., earlywood, latewood), Soulé et al. (2021) sampled longleaf stands in the Coastal Plain of the Carolinas and concluded that radial growth is primarily driven by late summer moisture availability.

Recent work has specifically focused on longleaf pine and tropical cyclone climatology using tree rings. Lewis et al. (2011) combined tree rings with individual isotope models (^{18}O) to examine tropical cyclone records for Big Thicket National Preserve, Texas. Mitchell et al. (2019) developed a novel approach toward identifying historical tropical cyclone activity by utilizing frequencies of intra-annual density fluctuations in longleaf pine in western Florida. Working in south-central Georgia, Collins-Key and Altman (2021) detected tropical cyclones from climate and oscillation signal-free chronologies.

On 16 September 2020, a Category 2 tropical cyclone (Hurricane Sally) made landfall across Gulf Shores, Alabama, eventually exerting a profound impact on Pensacola—including the campus of UWF—which experienced the slow-moving eyewall for 12 h with 45.8 m/sec winds (maximum sustained winds 48.6 m/sec) and as much as 76 cm of rainfall (Fig. 2). With more than \$7 billion in damage, Hurricane Sally was the most destructive storm in the region in the past 20 years. Although the UWF campus sustained only minor damage to buildings, windthrows among larger trees—such as live oak (*Quercus virginiana* Mill.), but

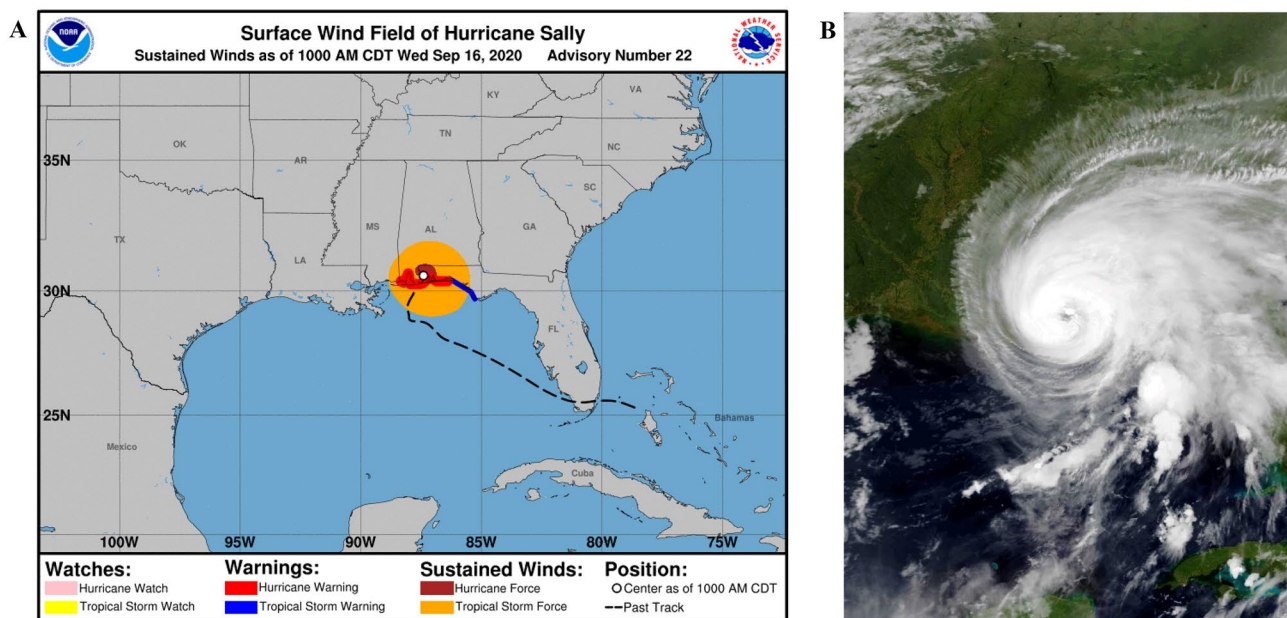


Fig. 2 Track/status of Hurricane Sally 16 September 2020 (A); satellite photograph of Hurricane Sally (B). Graphic and image from NOAA National Hurricane Center

especially longleaf pine—were widespread. This was particularly pronounced in the stands of the campus natural areas sampled previously by Gilliam et al. (2021). It should be noted that although windthrows of longleaf stems also occurred on the main campus, these were not available for our study because of rapid removal by the UWF Physical Plant for reasons of safety.

The purpose of this study was to take advantage of hurricane-caused longleaf stem windthrows to develop a locally-derived age/diameter model and quantify temporal patterns of tree-growth rates to assess relationships with climate variables. More specifically, we addressed the following questions: (1) is there a significant relationship between stem age (determined as the number of annual rings in stem cross sections) and measured diameter for longleaf pine at UWF? and (2) what is the relationship between ring width and long-term annual means for climate variables, including precipitation, drought, and temperature?

Methods

Study site

The study site primarily comprised two natural areas on the campus of UWF, Pensacola, Florida (Fig. 3). These were the Edward Ball Nature Trails (hereafter, “Trails”) (30° 33′ 8″ N, 87° 13′ 29″ W) and the Baars-Firestone Wildlife Sanctuary (hereafter, “Sanctuary”) (30° 32′ 38″ N, 87° 12′ 6″ W). Previous sampling in these areas has revealed numerous similarities between the two natural areas, including basal area of longleaf pine and extractable soil nutrients (except for NH₄ and K, which were slightly but significantly higher for Trails soil) (Table 1). Soils in both areas are predominantly of the Troup series, consisting of very deep, somewhat excessively drained, soils that formed in sandy and loamy marine sediments. Troup soils are loamy, kaolinitic, thermic Grossarenic Kandiudults with a seasonal high water table below a depth of 2 m throughout the year (USDA 2004).

Despite similarities in basal area (Table 1), the natural areas exhibit differences in longleaf pine size structure. Mean diameter at breast height is 20% higher in Sanctuary stands than in Trail’s stands, at 35.9 ± 1.1 and 30.1 ± 0.5 cm, respectively, significantly different at $P < 0.05$ (Gilliam et al. 2021). Although forest stands in urban interfaces can exhibit characteristics of anthropogenic impacts, such as alterations in hydrology and soil fertility and invasive species, these stands are relatively free of anthropogenic influences other than the chronic exclusion of fire, based on findings of Gilliam et al. (2021).

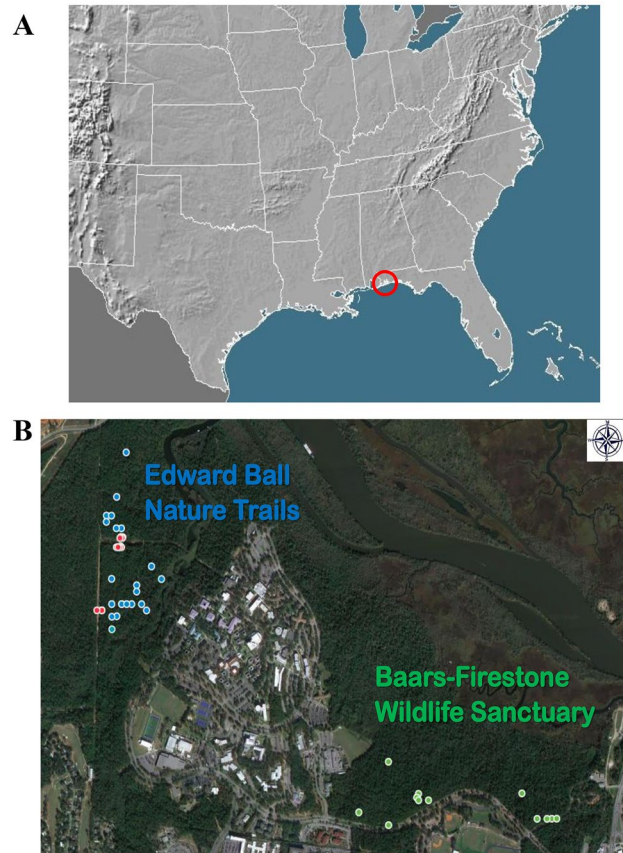


Fig. 3 Map of the southeastern United States with general location of UWF campus indicated with red circle (A); map of the campus (B). The two natural areas sampled for sampled windthrown longleaf pine stems are indicated: Edward Ball Nature Trails (“Trails”) and Baars-Firestone Wildlife Sanctuary (“Sanctuary”). Windthrow locations are indicated as blue and green circles for Trails and Sanctuary, respectively. Locations of live-harvested trees are indicated as red circles

Field sampling and laboratory analysis

Beginning in May 2021, both Trails and Sanctuary areas were haphazardly searched for windthrown longleaf stems; 40 stems were determined to be safe for sampling and used in this study. Each stem was numbered with a wire flag for later sampling and measured for diameter at 1.5 m from base of tree, with GPS coordinates determined for re-location and mapping (Fig. 3). Direction of fall was also recorded for each windthrow to assess relationships with prevailing direction of winds associated with the storm. A digital compass was aligned with the stem and direction was recorded in degrees from 0—360.

Because of the sparse distribution of longleaf stems of these chronically unburned stands, we anticipated that the winds associated with Hurricane Sally would selectively blow down primarily larger, and much taller, pines. That is, these taller pines would experience disproportionately

Table 1 T-test comparisons between sample sites for basal area of longleaf pine (Pine BA), soil organic matter (OM), soil pH, and extractable soil nutrients. Significant differences ($P < 0.05$) between sites indicated by an asterisk. Data taken from Gilliam et al. (2021)

Site	Pine BA	OM	pH	NH ₄ -N	NO ₃ -N	Ca	K	Mg
	m ² /ha	%		μg/g	μg/g	μg/g	μg/g	μg/g
Trails	13.4 ± 1.3	1.50 ± 0.11	4.67 ± 0.04	3.65 ± 0.29 *	0.30 ± 0.02	21.9 ± 1.8	7.8 ± 0.4 *	5.6 ± 0.4
Sanctuary	12.2 ± 1.1	1.37 ± 0.13	4.77 ± 0.05	2.69 ± 0.13	0.37 ± 0.04	24.8 ± 7.7	6.0 ± 0.5	5.5 ± 0.9

higher wind gusts as their canopies extend far above the hardwood trees. In fact, Zampieri et al. (2020) found that the lower densities of mature longleaf made them more susceptible to wind flow in extreme wind events. Initial reconnaissance supported this expectation for both sites, with no windthrows of longleaf stems < 15 cm DBH. Accordingly, harvests of 10 smaller live longleaf pines were made to extend the range of diameters to more closely resemble the range of DBH measurements (i.e., 5–70 cm) reported for the UWF campus in Gilliam et al. (2020). Thus, a total of 50 stems were sampled in this study.

As all windthrown pine stems were uprooted (i.e., no snap-offs), we measured 1.5 m from the horizontal base to take a cross-section sample of each stem (DBH). After DBH was accurately measured (nearest 0.1 cm) for these samples, they were taken back to the laboratory for a visual count of annual rings. Ring widths were measured to the nearest 0.01 mm with a Neiko Tools digital caliper. Using whole cross-sections allowed for visual inspection to avoid the counting of false rings (Speer 2010). Visual counts and measurements were necessitated because our laboratory lacks digitizing instrumentation that is often available for such studies. As a check on our methods, we were, however, able to submit a random selection of 24 samples to the UWF Tree Ring Analysis and Interpretation Laboratory. Their tree-ring counts used a WinDENDRO™ system and cross-dating with skeleton plots (Holmes 1983), yielding tree ages that were consistently in close agreement with our measurements.

Data analysis

Stem age was compared to diameter for 50 sampled longleaf stems using linear regression (Zar 2009). To assess potential relationships with climate variables, backwards stepwise linear regression was run for raw, non-standardized ring widths (in mm) from all trees ≥ 65 yr (a total of 12 stems) with annual climate data for Pensacola, Florida (NOAA 2021). The original model was:

$$RW = Ppt + PDSI + PHDI + T_{max} + T_{mean} + T_{min} + D_{warm} + D_{cool}$$

with RW being ring width, Ppt being annual precipitation (cm), PDSI being annual Palmer Drought Severity Index,

PHDI being annual Palmer Hydrological Drought Index, T_{max} , T_{mean} , T_{min} being annual temperature means (maximum, mean, minimum, respectively, C), D_{warm} being degree days > 19 °C, and D_{cool} being degree days < 19 °C. This technique eliminates variables from the original model sequentially until all remaining variables in the model produce F statistics significant at a given probability level (in this case $P < 0.05$), and has been used widely in dendroecological studies (Speer et al. 2001; Trouet and Taylor 2010; Collins-Key and Altman 2021). All analyses were performed with Statistix 9, Analytical Software, Tallahassee, FL.

Results and discussion

Linear regression revealed that stem age was significantly related to diameter: $A = 1.8 * D + 0.8$, $R^2 = 0.82$, $P < 0.00001$, where A is stem age (yr), and D is stem diameter (cm) at 1.5 m from base (DBH) (Fig. 4). As already mentioned, there is ongoing debate regarding stem age/diameter relationships for trees (Speer 2010). Despite this, several studies have demonstrated significant relationships. Kenefic and

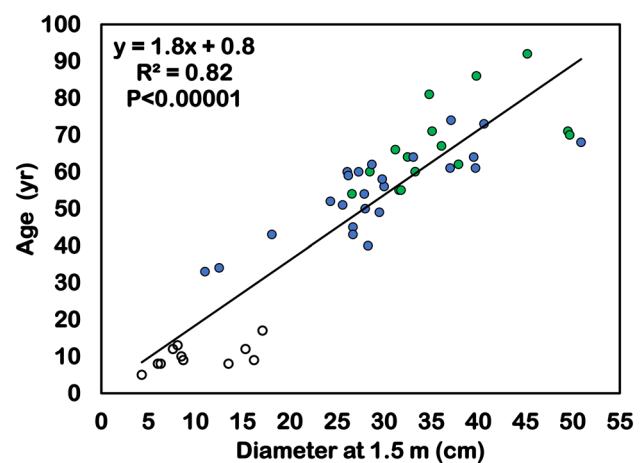


Fig. 4 Linear regression of longleaf age (yr) versus diameter (cm) at 1.5 m from base. Regression line is based on all 50 stems sampled, with Trails samples as blue symbols, Sanctuary samples as green symbols, and harvested stems as open symbols

Nyland (1999) found a significant relationship in mixed-age hardwood stands of the northeastern United States.

More relevant to our study, significant age/diameter relationships were found for two old-growth longleaf stands: the Wade Tract of southern Georgia (Platt et al. 1988) and the Boyd Tract of North Carolina sandhills (Gilliam and Platt 1999). For the Wade Tract, the linear model was: $A = 2.9 * D - 7.7$ ($R^2 = 0.81$, $P < 0.00001$), whereas for the Boyd Tract, the linear model was: $A = 3.8 * D + 8.1$ ($R^2 = 0.48$, $P < 0.00001$). Thus, there is a wide discrepancy among all three, suggesting that age/diameter relationships may be highly site dependent (Fig. 5). Indeed, these three models represent sharply contrasting stand conditions.

The steeper slopes among regression equations are the Wade and Boyd Tracts and reflect their old-growth nature. That is, for a given DBH, these models predict older stem ages which greatly exceed those of second-growth stands, such as those from which the UWF model was constructed. Further differences between old-growth stands reflect contrasting fire regimes. The Wade Tract has experienced annual prescribed fire dating back to the nineteenth century which maintains vigorous longleaf regeneration, whereas the Boyd Tract had experienced fire exclusion during this same period which has allowed for the establishment of large hardwood trees, such as oaks and hickories, that has suppressed longleaf regeneration. Thus, nearly 50% of stems at the Wade Tract are <25 yr old, contrasting with <10% for the Boyd Tract (Gilliam et al. 2006).

To provide a sufficiently long time period, we selected all sampled stems that were at least 65 years old to assess potential relationships with annual climate variable for the region surrounding the UWF campus using backwards

stepwise multiple regression. Although the calculation of degree days was initially developed to address human comfort, they represent an effective integration of both temperature and duration that is potentially relevant to organisms, from microbes to plants and animals. For example, Gilliam et al. (2018) demonstrated that degree days < 19 °C was a significant predictor of net nitrogen mineralization and nitrification over a quarter century in mineral soil of a central Appalachian hardwood forest ecosystem.

Ten of the twelve trees had significant correlations between ring width and one or more temperature variables. Five of these were with D_{warm} and four others were with T_{min} . Only two of the twelve had significant correlations between ring width and a moisture variable, but both of those had also had a more highly significant correlation with a temperature variable (Table 2). Further, several trees displayed final models with only temperature-related variables, but none with only precipitation/drought variables. Thus, in contrast to some earlier studies on growth/climate relationships (Henderson 2006), results based on our limited number of samples suggest that temperature, not moisture, may be limiting growth of longleaf pine at our site.

As discussed previously, when the initial phase of the UWF CES measured the DBH of all longleaf pines on the main campus (2,165 stems), the only age/diameter model available for estimating age of measured stems was that of the Wade Tract. Estimates included maximum ages of ~200 yr and mean/median ages of 92 and 94 yr, respectively. Work of the present study has yielded a locally-derived model that is more relevant to the land-use history and local climate and soils of the region. Applying this model to longleaf DBH measurements from the main campus yielded maximum ages of ~130 yr and mean and median ages of 63 and 64 yr, respectively. Notably, this maximum comports better than that from the Wade model with what is known about the land-use history of the region that surrounds and includes the UWF campus (Marse 2007; Jarvis 2008; Knight et al. 2011).

We applied our model to longleaf stems sampled in the two natural areas by Gilliam et al. (2021), which allows us to compare not only age structure between natural areas, but also with the main campus. In many respects, age-class distributions for longleaf pine were similar among the main campus and the Wildlife Sanctuary and Nature Trails sites, with all three exhibiting a strong central tendency, i.e., ~70–80% of stems occurring in the 40–70 cm classes for all three sites (Fig. 5). On the other hand, there were also sharp contrasts between Sanctuary and Trails sites. For example, although nearly 50% of stems in the Sanctuary site were >70 yr old, <20% were >70 yr old in the Trails site (Fig. 5). Site comparisons further suggest a closer similarity of the Sanctuary to the main campus than the Trails. Median age was 64 and 69 yr for the main campus and Sanctuary, respectively, and 58 yr for the Trails (Table 3). Mean stem age did not vary significantly between the main campus and Sanctuary (62.7 ± 0.4 and 66.7 ± 2.1 , respectively),

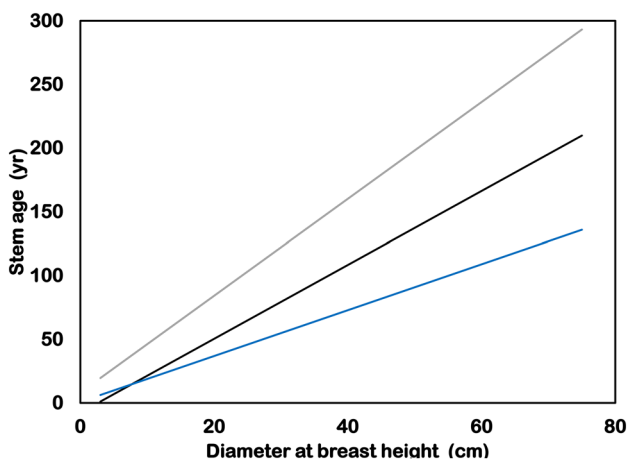


Fig. 5 Linear regressions (lines only, data points omitted for clarity) of stem age versus diameter at breast height (DBH) for three longleaf pine sites: Boyd Tract, NC (gray line: $A = 3.8 * D + 8.1$, $R^2 = 0.48$), Wade Tract, GA (black line: $A = 2.9 * D - 7.7$, $R^2 = 0.81$), UWF campus (blue line: $A = 1.8 * D + 0.8$, $R^2 = 0.82$). The range of DBH values chosen to reflect that at UWF campus. All were significant at $P < 0.00001$

Table 2 Results of stepwise linear regression of longleaf pine stems > 65 yr versus climate variables. Ppt= annual precipitation (cm), PDSI= annual Palmer Drought Severity Index, PHDI= annual Palmer Hydrological Drought Index, T_{max}, T_{mean}, T_{min} = annual temperature means (maximum, mean, minimum, respectively, C), D_{warm} = degree days > 19 °C, and D_{cool} = degree days < 19 °C. Top values shown for a given variable is its regression coefficient (R²), below which is its significance value. For Site, ‘S’ indicates Sanctuary, ‘T’ indicates Trails. Age is in yr

Tree	Site	Age	Ppt	PDSI	PHDI	T _{max}	T _{mean}	T _{min}	D _{warm}	D _{cool}
1	S	71	–	–	–	–	–	–	–	–
6	S	81	–	–	–	–	–	–	–0.0034	–
7	S	92	–	–	–	–	–	–	0.05	–
8	S	86	–	–	–	–	–	–	–0.0037	–
9	S	71	–	–	–	–	–	–	0.00001	–
11	S	67	0.036	–	–	–	–	–0.377	–	–
14	S	65	0.05	–	–	0.603	–0.918	–	0.01	–
17	S	70	–	–	0.178	–	–	–0.649	–	–
25	T	74	–	–	0.05	–	–	–	0.00001	–
30	T	73	–	–	–	–10.5	–	–	0.046	–0.053
44	T	68	–	–	–	0.05	–	–0.888	0.05	–
65	T	65	–	–	–	–	–	–0.532	–	–
									0.001	–
									0.00001	–

but means for both were significantly higher ($P < 0.0001$) than the Trails (55.7 ± 1.6 yr) (Table 3).

Results from this study strengthen earlier conclusions of the UWF CES, based on these patterns of similarity and contrast. That is, the overall similarities in age-class distributions (e.g., Fig. 6) support the findings of Gilliam et al. (2020)—based on DBH measurements of 2,165 stems—that longleaf stems on the main UWF campus are remnant stands following widespread harvesting of longleaf pine throughout northwest Florida more than 100 yr ago (Knight et al. 2011). On the other hand, sharp contrasts in age-related stand structure between the two natural areas (Table 3) support conclusions of Gilliam et al. (2021) that Sanctuary and Trail sites, which occur ~2 km apart on opposite sides of the main campus, were likely originally property of different ownership and contrasting land-use history.

Table 3 Median and mean ($\pm 1SE$) stem age for longleaf pine stems on main campus and in the study sites (Baars-Firestone Wildlife Sanctuary and Edward Ball Nature Trails), using the new model based on the current study. Means subjected to analysis of variance and least significance difference test. Means with the same superscript are not significantly different among sites at $P < 0.0001$

Site	N stems	Median yr	Mean yr
Main campus	2165	64	62.7 ± 0.4^a
Wildlife Sanctuary	68	69	66.7 ± 2.1^a
Nature Trails	105	58	55.7 ± 1.6^b

Among the destructive characteristics of Hurricane Sally following landfall on 16 September was its slow-moving nature, moving as slowly as 0.8 m sec^{-1} and exposing the UWF campus and surrounding area to the eyewall for ~12 h (Fig. 2A, B). The most violent wind gusts occurred near mesovortices along the inner edge of the eyewall, with multiple mesovortices having significant updrafts along the inner

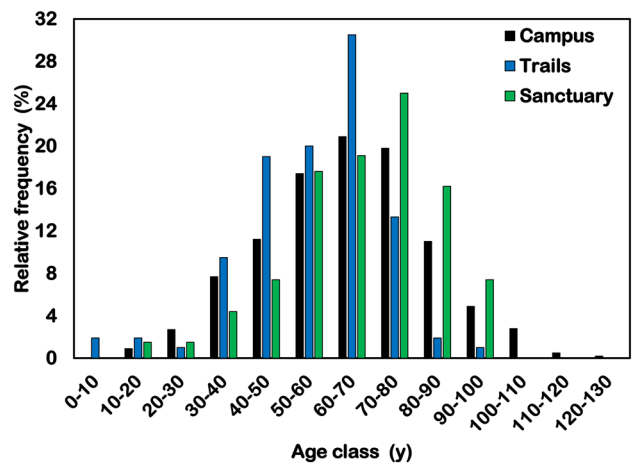
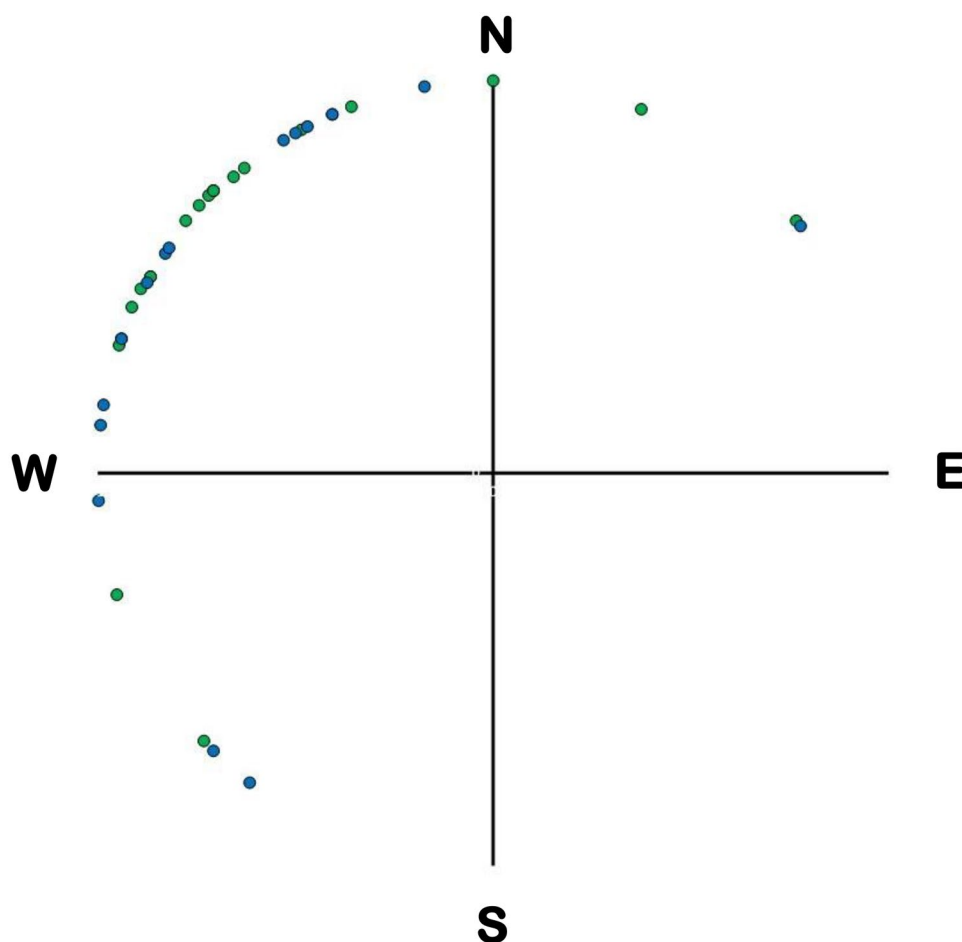


Fig. 6 Age-class frequency distributions of longleaf stems at UWF based on the age/DBH model generated in this study, including the main campus (black bars, from Gilliam et al. 2020) and each of the two natural areas (blue and green bars, from Gilliam et al. 2021)

Fig. 7 Directions of fall for longleaf pine stems in two natural areas on UWF campus. Each point represents one windthrow stem, except in some cases where direction was identical: blue = Edward Ball Nature Trails; green = Baars-Firestone Wildlife Sanctuary



edge of the eyewall (Berg and Reinhart 2021). Consistent with eyewall characteristics, wherein strongest winds move from southeast to northwest in the right-front quadrant, 80% of longleaf pine windthrows were in a northwest direction (Fig. 7). Further, there was no difference between the Trails and Sanctuary sites with respect to direction of fall. This analysis provides critical ground-based data regarding storm behavior, in this case with evidence of the extended duration of prevailing strong winds resulting from the slow movement of the hurricane.

Results of this study further exemplify the importance of college/university campuses as a unique type of urban interface (Copenheaver et al. 2014; Cole and Bennington 2017; Roman et al. 2017). This arises not only because of their physical nature, with buildings, parking lots, and green spaces, but also because of their very nature as centers of teaching and research. Thus, college/university campuses can be viewed as a unit of ecological study. Indeed, several campuses within the distribution of longleaf pine have done just that, e.g., Berry College in Georgia (Cipollini et al. 2019) and Stetson University in Florida (Cole and Bennington 2017).

Conclusion

The UWF CES comprises a series of connected studies on the remnant longleaf stands from which the campus was originally constructed, with each of these has sequentially building on the previous one. Certainly, the random event of a hurricane was never part of the original plan of CES. Studies such as this emphasize their importance as they allow researchers to take advantage of the stochastic nature of our environment, in this case the occurrence of a hurricane.

Acknowledgements We gratefully acknowledge the University of West Florida Office of Undergraduate Research and its funding support through the Summer Undergraduate Research Program. We also thank Jeremy Bondurant, Travis Green, and C.J. Patrick for logistical support. We are indebted to Darrel Williams and Jason Ortegren for their confirmations of ring counts with WinDENDRO™ and crossdating. Finally, we thank Stewart Ware, Savannah Collins-Key, and two anonymous reviewers for invaluable comments that improved the manuscript.

Author contributions FSG and HNP conceived the research; HNP, SKR, and FSG collected the data; FSG analyzed the data; FSG, HNP, and SKR wrote the paper.

Funding This work was not supported by external funding.

Availability of data and materials All data from this study are available from FSG upon request.

Declarations

Informed consent Not applicable.

Consent for publication All authors consent for this paper to be published.

Research involving human participants and/or animals Not applicable.

Conflict of interests The authors have no conflict of interest to declare.

References

- Addington RN, Knapp BO, Sorrell GG, Elmore ML, Wang GG, Walker JL (2015) Factors affecting broadleaf woody vegetation in upland pine forests managed for longleaf pine restoration. *For Ecol Manag* 354:130–138
- Berg R, Reinhart BJ (2021) National hurricane center tropical cyclone report: Hurricane Sally (AL 192020). National Oceanic and Atmospheric Administration, National Weather Service, Washington, DC
- Cipollini M, Felch P, Dingley NR, Maddox C (2019) Changes in tree canopy, understory vegetation, and fuel composition after 10 years of restoration management in an old-growth mountain longleaf pine forest. *Nat Areas J* 39:197–211
- Cole K, Bennington C (2017) From the ground up: natural history education in an urban campus restoration. *Southeast Nat* 16:132–145
- Collins-Key SA, Altman J (2021) Detecting tropical cyclones from climate- and oscillation-free tree-ring width chronology of longleaf pine in south-central Georgia. *Glob Planet Chang* 201:103490
- Copenheaver CA, Seiler JR, Peterson JA, Evans AM, McVay JL, White JH (2014) Stadium Woods: A dendroecological analysis of an old-growth forest fragment on a university campus. *Dendrochronologia* 32:62–70
- Devall MS, Grender JM, Koretz J (1991) Dendroecological analysis of a longleaf pine *Pinus palustris* forest in Mississippi. *Vegetatio* 93:1–8
- Gilliam FS, Harmon EE, Boyles SC (2020) The University of West Florida Campus Ecosystem Study: Gopher tortoise and longleaf pine populations in an urban interface. *Urban Ecosyst* 23:355–362
- Gilliam FS, Detzel SJ, Bray KD, Major EA (2021) The University of West Florida campus ecosystem study: the college/university campus as a unit for study of the ecology of longleaf pine. *Urban Ecosyst* 24:1073–1082.
- Gilliam FS, Platt WJ (1999) Effects of long-term fire exclusion on tree species composition and stand structure in an old-growth *Pinus palustris* (longleaf pine) forest. *Plant Ecol* 140:15–26
- Gilliam FS, Platt WJ (2006) Conservation and restoration of the longleaf pine ecosystem. *Appl Veg Sci* 9:7–10
- Gilliam FS, Platt WJ, Peet RK (2006) Natural disturbances and the physiognomy of pine savannas: a phenomenological model. *Appl Veg Sci* 9:83–96
- Gilliam FS, Walter CA, Adams MB, Peterjohn, (2018) Nitrogen (N) dynamics in the mineral soil of a Central Appalachian hardwood forest during a quarter century of whole-watershed N additions. *Ecosystems* 21:1489–1504
- Henderson JP (2006) Dendroclimatological analysis and Fire History of Longleaf Pine (*Pinus palustris* Mill.) in the Atlantic and Gulf Coastal Plain. Ph.D. Dissertation, University of Tennessee, Knoxville
- Hiers JK, Walters JR, Mitchel RJ, Varner JM, Conner LM, Blanc LA, Stowe J (2014) Ecological value of retaining pyrophytic oaks in longleaf pine ecosystems. *J Wildlife Manage* 78:383–393
- Holmes RL (1983) Computer-assisted quality control in tree-ring dating and measurement. *Tree-Ring Bull* 43:69–78
- Jarvis JE (2008) The next larger picture: an anecdotal history of the master planning of the campus of the University of West Florida and the design and construction of its buildings for the initial thirty-something years; a memoir, of sorts. Pioneer Series/University of West Florida Foundation Inc, Pensacola
- Kaiser AL, Soulé P, van de Gevel, Knapp P, Bhuta A, Walters J, Montpellier (2020) Dendroecological investigation of red-cockaded woodpecker cavity tree selection in endangered longleaf pine forests. *For Ecol Manag* 473:118291
- Kenefic LS, Nyland RD (1999) Sugar maple height-diameter and age-diameter relationships in an uneven-aged northern hardwood stand. *North J Appl for* 16:43–47
- Knapp PA, Maxwell JT, Soulé PT (2016) Tropical cyclone rainfall variability in coastal North Carolina derived from longleaf pine (*Pinus palustris* Mill.): AD 1771–2014. *Clim Chang* 135:311–323
- Knight GR, Oetting JB, Cross L (2011) Atlas of Florida's natural heritage—biodiversity, landscapes, stewardship, and opportunities. Institute of Science and Public Affairs, Florida State University, Tallahassee
- Lewis DB, Finkelstein DB, Grissino-Mayer HD, Mora CI, Perfect E (2011) A multitree perspective of the tree ring tropical cyclone record from longleaf pine (*Pinus palustris* Mill.), Big Thicket National Preserve, Texas, United States. *J Geophys Res* 116:G02017
- Marse C (2007) Rising Fiery Constellation: a Portrait of the University of West Florida from Birth to Forty. Pioneer Series, Pensacola
- McHarg IL (1995) Design with nature, 25th edn. John Wiley & Sons, Hoboken, NJ
- Mitchell TJ, Knapp PA, Ortegren JT (2019) Tropical cyclone frequency inferred from intra-annual density fluctuations in longleaf pine in Florida, USA. *Clim Res* 78:249–259
- National Oceanic and Atmospheric Administration. National Centers for Environmental Information (2021) https://www.ncdc.noaa.gov/cag/divisional/time-series/0801/tavg/ann/6/1928-2020?base_prd=true&begbaseyear=1901&endbaseyear=2000
- Patterson TW, Knapp PA (2016) Stand dynamics influence masting/radial growth relationships in *Pinus palustris* Mill. *Castanea* 81:314–322
- Platt WJ, Evans GW, Rathbun SL (1988) The population dynamics of a long-lived conifer (*Pinus palustris*). *Am Nat* 131:491–525
- Roman LA, Fristensky JP, Eisenman TS, Greenfield EJ, Lundgren RE, Cerwinka CE, Hewitt DA, Welsh CC (2017) Growing canopy on a college campus: understanding urban forest change through archival records and aerial photography. *Environ Manage* 60:1042–1061
- Rother MT, Huffman JM, Guiterman CH, Robertson KM, Jones N (2020) A history of recurrent, low-severity fire without fire exclusion in southeastern pine savannas, USA. *For Ecol Manag* 475:118406
- Soulé PT, Knapp PA, Maxwell JT, Mitchell TJ (2021) A comparison of the climate response of longleaf pine (*Pinus palustris* Mill.) trees among standardized measures of earlywood, latewood, adjusted latewood, and totalwood radial growth. *Trees* 35:1065–1074
- Speer JH, Swetnam TW, Wickman BE, Youngblood A (2001) Changes in Pandora Moth outbreak dynamics during the past 622 years. *Ecology* 82:679–697
- Speer JH (2010) Fundamentals of tree ring research. University of Arizona Press, Tucson

- Trouet V, Taylor AH (2010) Multi-century variability in the Pacific North American circulation pattern reconstructed from tree rings. *Clim Dyn* 35:963–963
- USDA (2004) Soil survey of Escambia County, Florida. United States Department of Agriculture, Natural Resources Conservation Service, Washington, DC
- Varner JM III, Gordon DR, Putz FE, Hiers JK (2005) Restoring fire to long-unburned *Pinus palustris* ecosystems: novel fire effects and consequences for long-unburned ecosystems. *Restor Ecol* 13:536–544
- Zampieri NE, Pau S, Okamoto DK (2020) The impact of Hurricane Michael on longleaf pine habitats in Florida. *Sci Rep* 10:8483
- Zar JH (2009) *Biostatistical analysis*, 5th edn. Prentice-Hall, Englewood Cliffs

Publisher's note Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.