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

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Abstract

The campus of the University of West Florida 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 that 65% of these pines are 75 to 125 years old, with estimates based on a model from old-growth longleaf in southern Georgia. To obtain more accurate age data, one can use an increment corer to collect samples from live trees on site; more accurately, disks can be collected from recently fallen trees. On 16 September 2020, Hurricane Sally impacted UWF as a Category 2 storm, with winds reaching 125 kph. Our study took advantage of longleaf pines blowdowns by Sally to obtain cross-sections for age determinations. Two on-campus natural areas 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 of annual rings were recorded. Based on a total of 50 sampled trees, linear regression revealed a highly significant ($P<0.00001$; $r^2=0.84$) relationship between DBH and age. Applying this to DBH measures 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 wide-spread 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 represented sites of contrasting land-use history. Direction of stem windthrows did not vary between natural areas and was consistent with characteristics of the eyewall of Hurricane Sally with strongest wind gusts moving from a southeast to northwest direction.

Introduction

Previous work on the campus of the University of West Florida—the UWF Campus Ecosystem Study (CES)—has focused on (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 very design of the campus as initially envisioned by John Jarvis, who was greatly influenced by the Scottish landscape designer, Ian McHarg. McHarg's classic text, *Design with Nature,* which has been revised to a 25th edition (McHarg 1995), formed the basis of Jarvis' philosophy of campus design, wherein tree cutting was minimized and natural contours were maintained to the extent possible (Jarvis 2008).

The various 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 main campus, comprising 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, that study 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 measurements of >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 that study suggested that oldest longleaf pines were just under 200 yr old and that >80% of stems on the main UWF are 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 of 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), this study found a notable establishment of numerous hardwood species among widely-spaced mature longleaf pine stems. Conclusions of this study suggested that the two natural areas on the campus of UWF (see Methods for description) 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 2009). Some of this arises from the methodological challenges of determining age from increment cores, wherein the core might either (1) miss the true beginning of growth or (2) 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.

On the other hand, a great deal of work has been devoted to using longleaf pine for dendroclimatological studies (Knapp et al. 2016). These have varied greatly regarding both the specific focus and the temporal scale in which they endeavor 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 precipitation in August and 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 tree core/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.

On 16 September 2021, 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 hours with 165 km/h winds (maximum sustained winds 175 km/h) and as much as 76 cm of rainfall. With >$7 billion in damage, it 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 especially longleaf pine, were widespread. This was particularly pronounced in the stands of the campus natural areas sampled previously by Gilliam et al. (2021).

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 growth rates of trees 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 the University of West Florida (UWF), Pensacola, Florida (Figure 1). 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 them, including basal area of longleaf pine and extractable soil nutrients (except for NH_4 and K, which were slightly, but significantly, higher for Trails soil) (Table 2). Soil of both areas is 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 2), the natural areas exhibit contrasting longleaf pine size structure. Mean diameter at breast height is 20% higher in Sanctuary stands than in Trail stands, 35.9±1.1 and 30.1±0.5 cm, respectively, (significant difference at $P<0.05$—Gilliam et al. 2021).

Field sampling and laboratory analysis

Beginning in May 2021, both Trails and Sanctuary areas were exhaustively searched for windthrown longleaf stems. 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 (Figure 1). Direction of fall was also recorded for each windthrow.

Because of the dense nature of these chronically-unburned longleaf stands, it was 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 higher wind gusts as their canopies extend far above the hardwood trees. Initial reconnaissance supported this expectation for both sites, constraining the lower range of diameters. 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).

A cross-section sample of each stem was taken at 1.5 m from the base. After diameter was accurately measured (nearest 0.1 cm) on these samples, they were taken back to the laboratory for a visual count of annual rings. Widths of rings 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 2009). Visual counts and measurements were necessitated because our laboratory lacks digitizing instrumentation. We were, however, able to submit random samples to the UWF Tree Ring Analysis and Interpretation Laboratory. Their tree ring counts, using a WinDENDRO™ system, were in essentially exact agreement with ours.

Data analysis

Stem age was compared to diameter for 50 sampled longleaf stems with linear regression (Zar 2009). To assess potential relationships with climate variables, backwards stepwise linear regression was run for ring widths (in mm) from all trees ≥65 yr with annual climate data for Pensacola, Florida (https://www.ncdc.noaa.gov/cag/divisional/time-series/0801/tavg/ann/6/1928-2020?base_prd=true&begbaseyear=1901&endbaseyear=2000). The original model was:

$$\textit{ring width} = \textit{Ppt} + \textit{PDSI} + \textit{PHDI} + T_{max} + T_{mean} + T_{min} + \textit{Days} > 19\ C + \textit{Days} < 19\ C$$

with 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), Days >19 C being degree days >19 C, and Days <19 C 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 (Zar 2009).

Results and Discussion

Linear regression revealed that stem age was highly 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. As already discussed, there is ongoing debate regarding stem age/diameter relationships for trees (Speer 2009). Despite this, several studies have demonstrated significant relationships. Kenefic and Nyland (1999) found a highly 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 (Figure 3). 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 was constructed. Further differences between old-growth stands reflect contrasting fire regimes. The Wade Tract has experienced annual prescribed fire dating back to the 19th 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. The full, or saturated, model included total annual precipitation, the Palmer Drought Severity Index, Palmer Hydrological Drought Index, mean annual temperatures (maximum, mean, minimum), degree days >19 C, and degree days <19 C. Although calculations 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. To wit, Gilliam et al. (2018) demonstrated that degree days <19 C was a highly significant predictor of net nitrogen mineralization and nitrification over a quarter century in mineral soil of a central Appalachian hardwood forest ecosystem.

All but two trees exhibited a significant relationship with at least one of these factors remaining in the model, as per the backwards stepwise process (see Methods for details). Half of the trees included only one factor, three included two factors, and one included three factors in the final model, a pattern that appeared unrelated to stem age (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 and Grissino-Mayer 2009), 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), 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. 5) support the findings of Gilliam et al. (2020)—based on DBH measurements of 2165 stems—that longleaf stems on the main UWF campus are remnant stands following wide-spread harvesting of longleaf pine throughout northwest Florida >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.

Among the destructive characteristics of Hurricane Sally following landfall on 16 September was its slow-moving nature, moving as slowly as 3 km hr^{-1} and exposing the UWF campus and surrounding area to the eyewall for ~12 hr (Fig. 6A, B). The most violent wind gusts occurred near mesovortices along the inner edge of the eyewall (Berg and Reinhart 2021). Consistent with eyewall characteristics, wherein strongest winds move from southeast to northwest in the front right sector, 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.

Conclusion—*longleaf pine and the campus as a unit of ecological study*

Results of this study underscore 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 units 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).

The UWF CES comprises a series of connected studies on the remnant longleaf stands from which the campus was originally carved, as each has sequentially built on the previous one. Certainly, the random event of a hurricane was never part of the original plan of CES. On the other hand, studies such as this point to their importance as they take allow researchers to advantage of the stochastic nature of our environment.

Declarations

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Disclosure of potential conflict of interests

The authors have no conflict of interest to declare.

Availability of data and materials

All data from this study are available from FSG upon request.

Code availability Not applicable

Research involving Human Participants and/or Animals Not applicable

Informed consent Not applicable

Consent for publication

All authors consent for this paper to be published.

Authors' 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.

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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

Table 2. Results of stepwise linear regression of mature longleaf pine versus climate variables. See Methods for the original model and definitions of variables. Top values shown for a given variable is its regression coefficient, below which is its P value. For Site, ‘S’ indicates Sanctuary, ‘T’ indicates Trail. Age is in yr.

Tree	Site	Age	Ppt	PDSI	PHDI	T_{max}	T_{mean}	T_{min}	Days >19C	Days <19C
1	S	71	-	-	-	-	-	-	-	-
6	S	81	-	-	-	-	-	-	-0.0034 0.05	-
7	S	92	-	-	-	-	-	-	-0.0037 0.00001	-
8	S	86	-	-	-	-	-	-	-	-
9	S	71	-	-	-	-	-	-	-0.36 0.01	-
11	S	67	0.036 0.05	-	-	-	-	-0.377 0.01	-	-
14	S	65	-	-	-	0.603 0.05	-0.918 0.001	-	-	-
17	S	70	-	-	0.178 0.05	-	-	-0.649 0.00001	-	-
25	T	74	-	-	-	-	-	-	-0.007 0.0001	-
30	T	73	-	-	-	-10.5 0.05	-	-	0.046 0.05	-0.053 0.05
44	T	68	-	-	-	-	-	-0.888 0.001	-	-
65	T	65	-	-	-	-	-	-0.532 0.00001	-	-

Table 3. Median and mean (±1SE) stem age for longleaf pine stems on main campus and in study sites: Baars-Firestone Wildlife Sanctuary and Edward Ball Nature Trails. Means subjected to analysis of variance and least significance difference test. Means with the same superscript are not significantly different 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]

Figure legends

Figure 1. Map of the campus of the University of West Florida. 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.

Figure 2. Mature longleaf pines with hardwoods that have become established in chronically unburned stands. The more open aspect of this view reflects canopy opening by Hurricane Sally-mediated windthrown pines.

Figure 3. Linear regression of longleaf age (yr) versus diameter (cm) at 1.5 m from base.

Figure 4. Linear regressions (lines only, data points omitted for clarity) age 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 are significant at $P<0.00001$.

Figure 5. Age-class frequency distributions of longleaf stems at UWF, 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).

Figure 6. Track/status of Hurricane Sally 16 September 2020 (A); satellite photograph of Hurricane Sally (B). Graphic and image from NOAA National Hurricane Center.

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

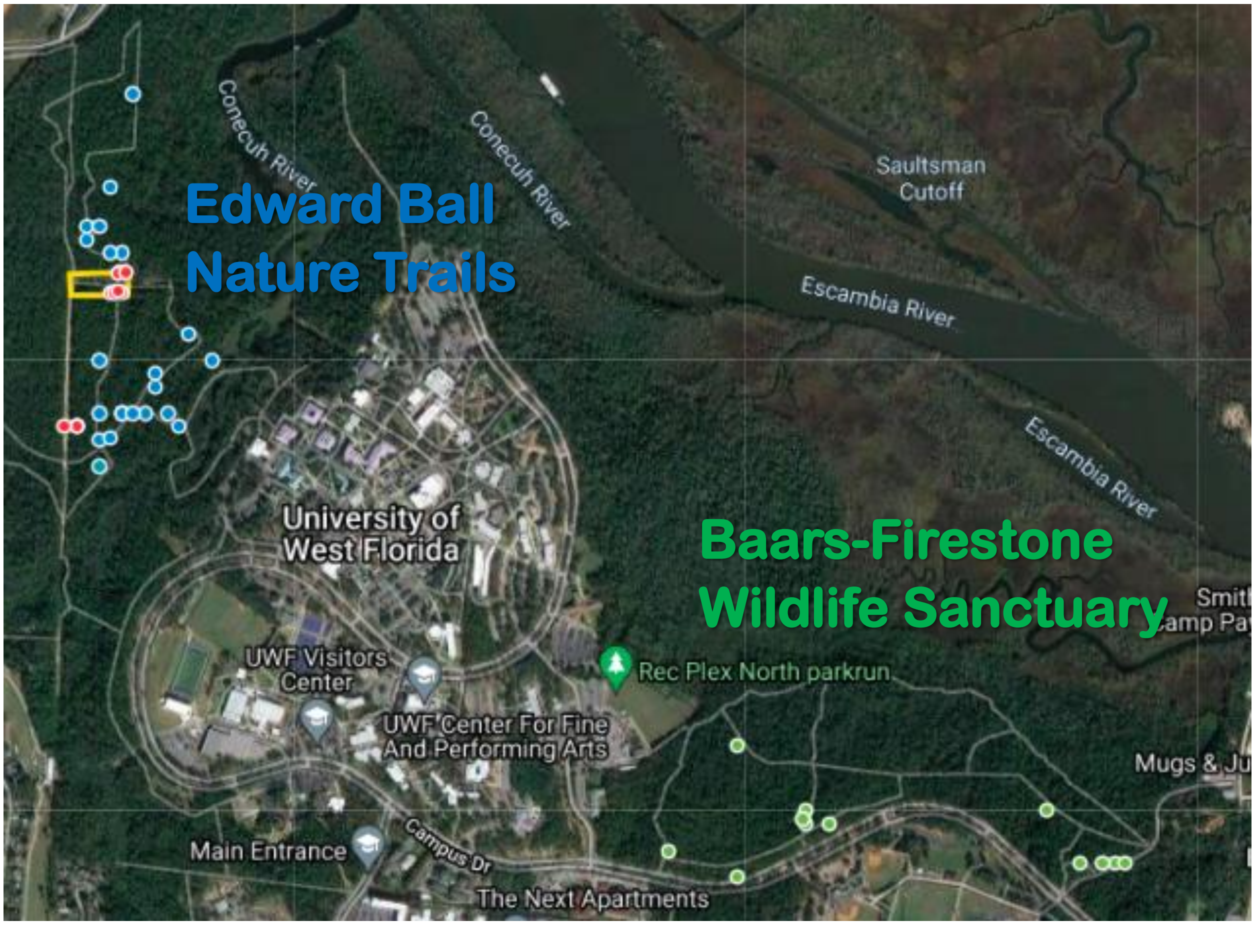
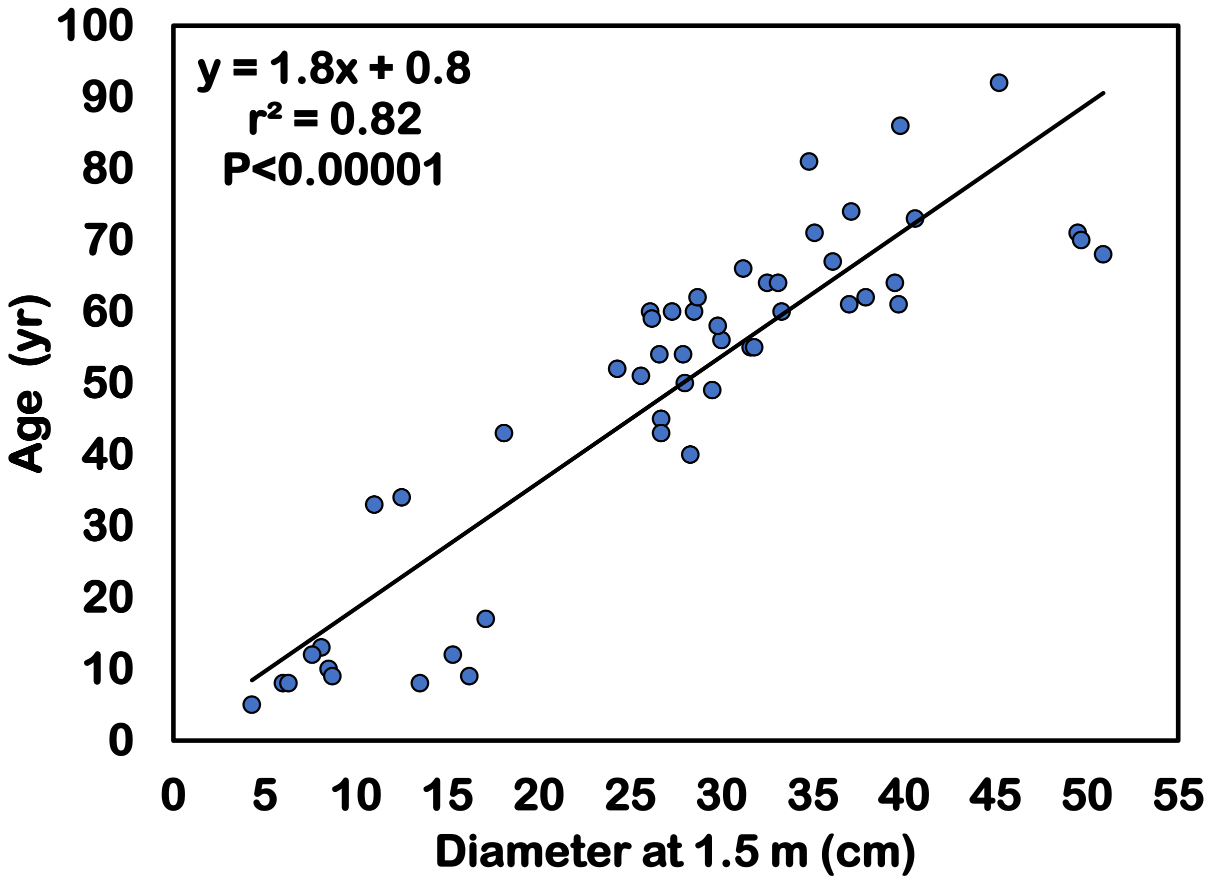

Edward Ball
Nature Trails
Conecuh River
Conecuh River
Saultsman
Cutoff
Escambia River
Escambia River
University of
West Florida
Baars-Firestone
Wildlife Sanctuary
Rec Plex North parkrun
UWF Visitors
Center
UWF Center For Fine
And Performing Arts
Main Entrance
Campus Dr
The Next Apartments

Figure 1

Figure 2


y = 1.8x + 0.8
r² = 0.82
P<0.00001
Age (yr)
Diameter at 1.5 m (cm)
0
10
20
30
40
50
60
70
80
90
100
0
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10
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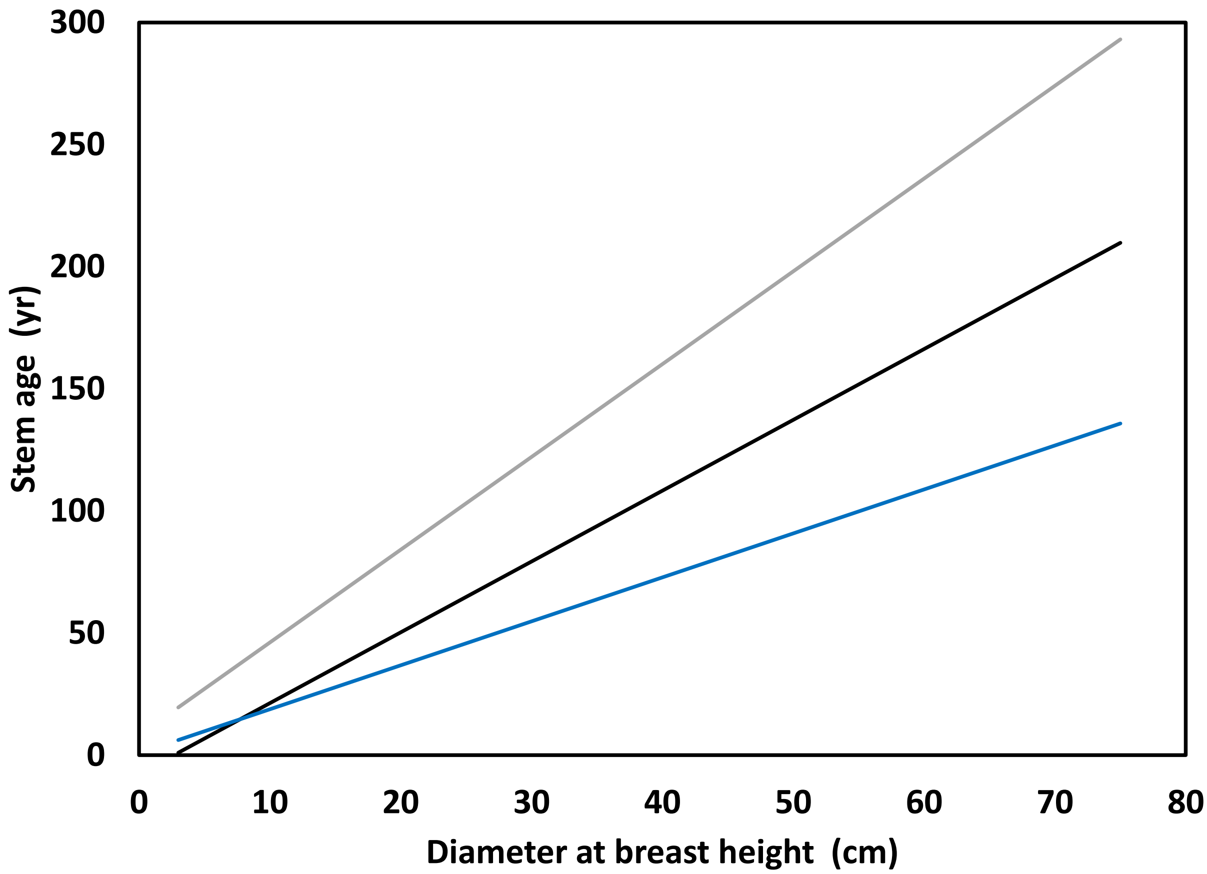
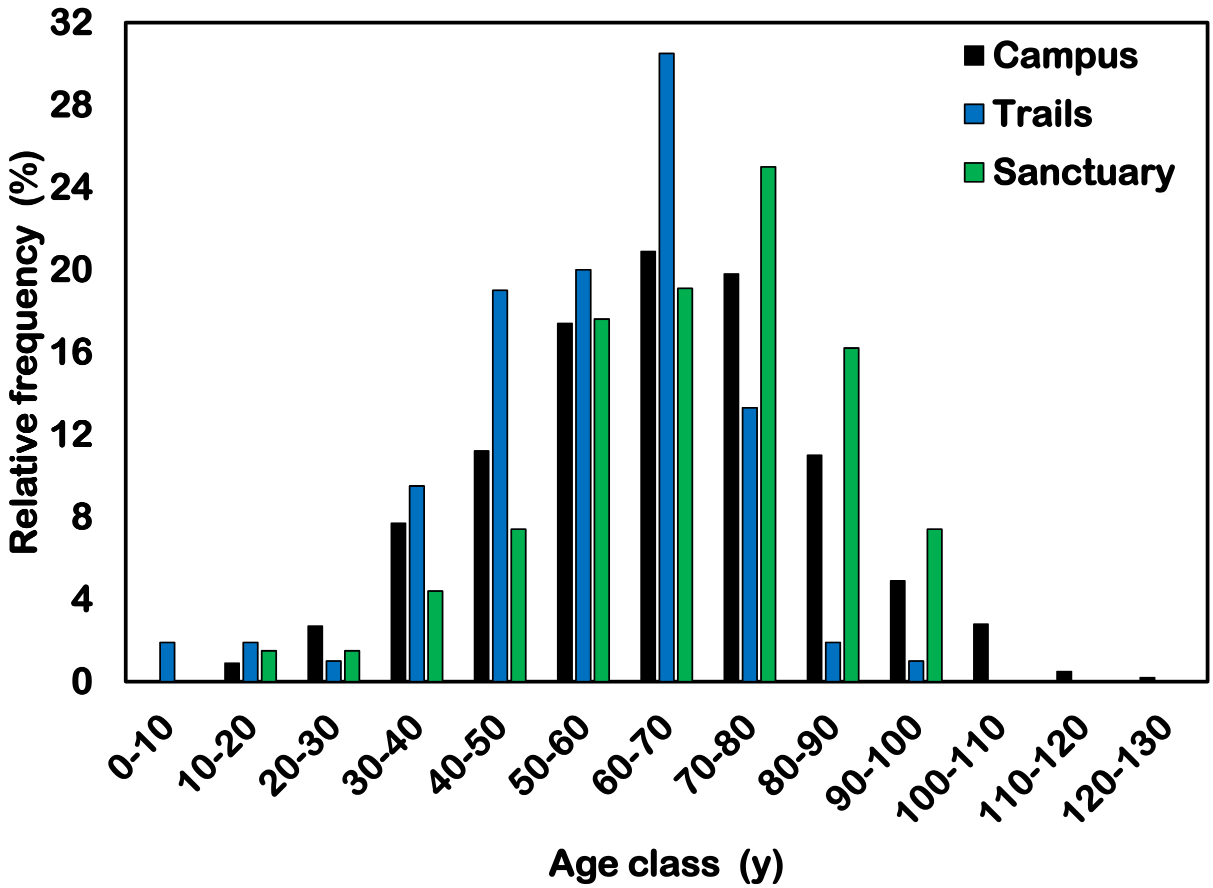
45
50
55

Figure 3



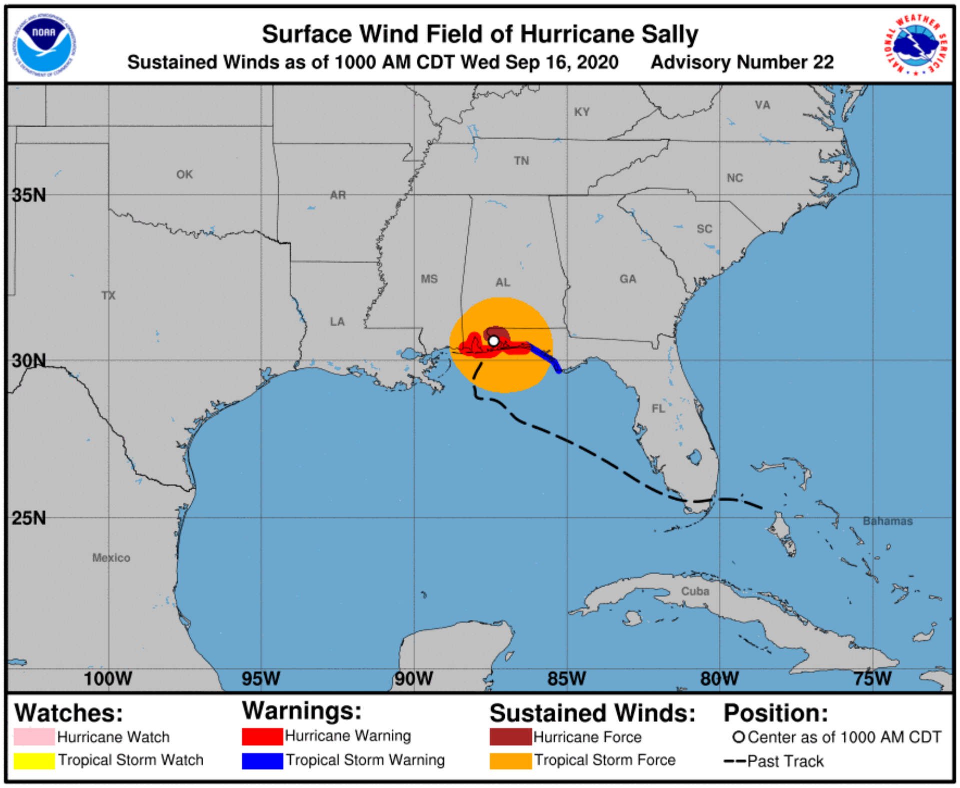
Stem age (yr)
300
250
200
150
100
50
0
0
10
20
30
40
50
60
70
80
Diameter at breast height (cm)

Figure 4



391

392 Figure 5


Surface Wind Field of Hurricane Sally
Sustained Winds as of 1000 AM CDT Wed Sep 16, 2020
Advisory Number 22
KY
VA
OK
TN
NC
35N
AR
SC
MS
AL
GA
TX
LA
30N
FL
25N
Bahamas
Mexico
Cuba
100W
95W
90W
85W
80W
75W
Watches:
Hurricane Watch
Tropical Storm Watch
Warnings:
Hurricane Warning
Tropical Storm Warning
Sustained Winds:
Hurricane Force
Tropical Storm Force
Position:
Center as of 1000 AM CDT
Past Track

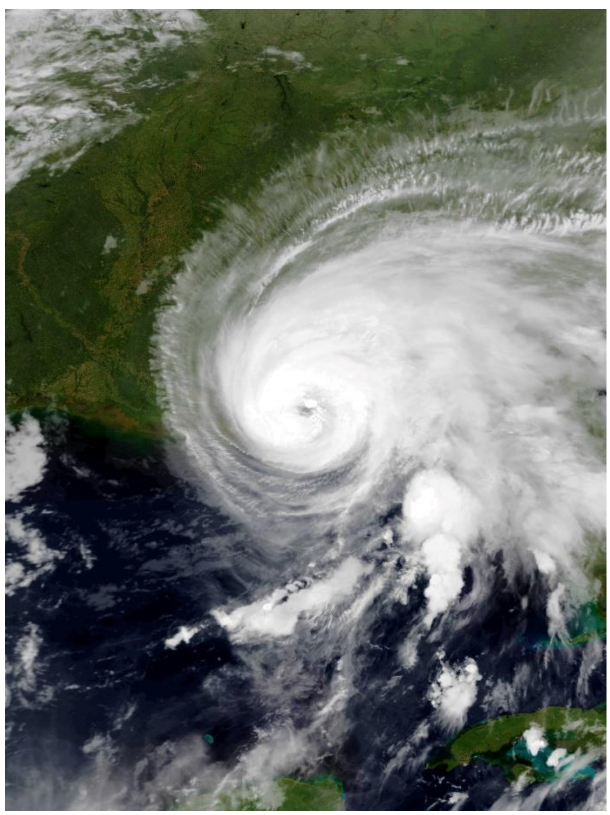


Figure 6

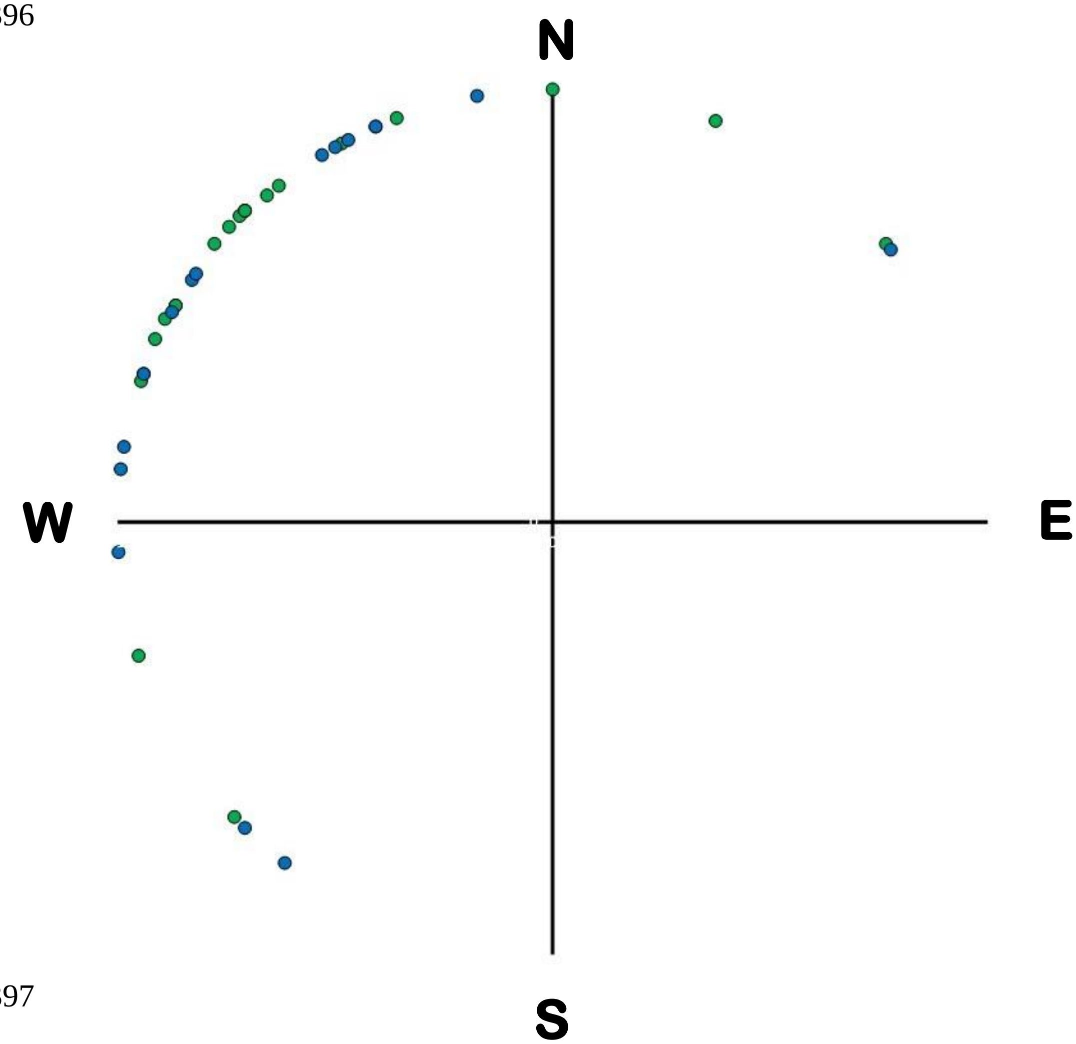


Figure 7