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I present a new method for identifying historic tropical cyclone activity utilizing frequencies of intra-annual density fluctuations in longleaf pine in western Florida. In addition, in this work I provide information about the causal factors that determine the formation of intra-annual density fluctuations (IADFs) in longleaf pine latewood. Specifically, I test the viability of using L+ IADFs in longleaf pine latewood as a proxy for historic tropical cyclone frequency and precipitation for the period 1950–2017. The stabilized frequency of L+ IADF occurrence is significantly ($p < 0.01$) associated with PDSI for the months June through October indicating that high amounts of late growing-season moisture promote the formation of IADFs in latewood. I find the strongest relationships between PDSI and IADF occurrence during September and October, indicating the influence of tropical cyclone (TC)-sourced precipitation on IADF formation. High IADF stabilized frequencies (i.e., > 0.50) nearly always (88%) coincide with a TC tracking into the study area, and I find a significant ($p < 0.01$) relationship between TC-sourced precipitation and the stabilized frequency of L+ IADFs. Via this relationship, reconstruction of historic tropical cyclone frequency and precipitation is probable, which would allow for increased understanding of historic tropical cyclone activity prior to the historic climate record.

TROPICAL CYCLONE FREQUENCY INFERRED FROM

INTRA-ANNUAL DENSITY FLUCTUATIONS

IN LONGLEAF PINE

by

Tyler J. Mitchell

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Approved by

Committee Chair

APPROVAL PAGE

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All these people have made every day in the Carolina Tree-Ring Science Laboratory special, and I am thankful for them all. A wise person once told me that most of the important things in life require the help of others, and I can confirm that this sentiment is true. I hope one day I can pay it back.

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# CHAPTER I

# INTRODUCTION

Tropical cyclones (TCs) are an important feature in regard to species distributions in the southeastern United States and the destructive capabilities of these storm systems are well documented. While work on historic tropical frequency and intensity exists, it is historically limited by the availability of high-resolution satellite imagery or climate data. This data limitation has limited the potential to examine historic TC frequency and precipitation directly, and proxy measures must be used to examine TC activity further.

Previous work using data from tree-rings exists to reconstruct both tropical cyclone frequency and precipitation multiple centuries (Miller et al. 2006; Lewis et al. 2011; Knapp et al. 2016; Labotka et al. 2016), and in this work I present a new method that may effectively document both historic tropical cyclone frequency and precipitation using intra-annual density fluctuations (IADFs) in longleaf pine (*Pinus palustris*) latewood. To my knowledge, no work in North America uses IADFs in latewood to reconstruct climatic events. However, previous investigations primarily located in Mediterranean Europe have used IADFs to capture historic climatic variability (Schulman 1938; Rigling et al. 2002; Campelo et al. 2007; Vieira et al. 2009, 2010; Edmondson 2010; de Luis et al. 2011a; Rozas et al. 2011; Palakit et al. 2012; Zalloni et al. 2016). This manuscript serves to compare the methodology of using IADFs to reconstruct climate events in western Florida, a region that is climatically dissimilar to

Mediterranean Europe, and thus provides information about the formation of IADFs in a new region.

The aim of the following manuscript is to 1) test the viability of using IADFs in longleaf pine latewood as a proxy for tropical cyclone frequency and precipitation for the period 1950–2017; and 2) discuss how the reconstruction of tropical cyclone-sourced frequency and precipitation from remnant longleaf stumps could increase the understanding of historic tropical cyclone activity prior to the historic climate record.

CHAPTER II

# TROPICAL CYCLONE FREQUENCY INFERRED FROM INTRA-ANNUAL DENSITY FLUCTUATIONS IN LONGLEAF PINE

This chapter will be submitted to *Climate Research*.

## 2.1 Abstract

I present a new method for identifying historic tropical cyclone activity utilizing frequencies of intra-annual density fluctuations in longleaf pine in western Florida. In addition, in this work I provide information about the causal factors that determine the formation of intra-annual density fluctuations (IADFs) in longleaf pine latewood. Specifically, I test the viability of using L+ IADFs in longleaf pine latewood as a proxy for historic tropical cyclone frequency and precipitation for the period 1950–2017. The stabilized frequency of L+ IADF occurrence is significantly ($p < 0.01$) associated with PDSI for the months June through October indicating that high amounts of late growing-season moisture promote the formation of IADFs in latewood. I find the strongest relationships between PDSI and IADF occurrence during September and October, indicating the influence of tropical cyclone (TC)-sourced precipitation on IADF formation. High IADF stabilized frequencies (i.e., > 0.50) nearly always (88%) coincide with a TC tracking into the study area, and I find a significant ($p < 0.01$) relationship between TC-sourced precipitation and the stabilized frequency of L+ IADFs. Via this relationship, reconstruction of historic tropical cyclone frequency and precipitation is

probable, which would allow for increased understanding of historic tropical cyclone activity prior to the historic climate record.

## 2.2 Introduction

Longleaf pine (*Pinus palustris* Mill.) is a long-lived (> 400 years) tree species found in the Atlantic and Gulf coastal plains from eastern Texas to Virginia (Burns and Honkala 1990; Frost 2007). The species was once the dominant pine of the coastal plains but has since declined in range from approximately 37 million to 1.75 million hectares due to anthropogenic influences including deforestation, fire suppression, and land-use changes (Frost 1993, 2007; Van Lear et al. 2005; Brockway et al. 2007; Oswalt et al. 2012; McIntyre et al. 2018). Longleaf pine is classified as a sturdy tree, likely due to a high heartwood-to-sapwood ratio (hence its historical use for ship masts), and the resin-laden tree is wind firm to hurricane-force winds (Gaby 1985; Conner et al. 1994; Provencher et al. 2001), yet highly dependent upon tropical cyclone precipitation (Knapp et al. 2016).

Climate-tree growth relationships for longleaf pine are well understood (Lodewick 1930; Coile 1936; Schumacher and Day 1939; Devall et al. 1991; Meldahl et al. 1999; Henderson and Grissino-Mayer 2009; Knapp et al. 2016; Mitchell et al. 2019). Generally, sufficient warm season current- and prior-year precipitation, including tropical cyclone precipitation, and cooler summer temperatures are associated with increased radial growth in longleaf pine in Alabama (Meldahl et al. 1999), Florida (Lodewick 1930; Schumacher and Day 1939; Henderson and Grissino-Mayer 2009), Georgia (Coile 1936), Mississippi (Devall et al. 1991), North Carolina (Knapp et al. 2016; Patterson et al. 2016; Mitchell et al. 2019), South Carolina (Henderson and Grissino-Mayer 2009), and Texas (Henderson and Grissino-Mayer 2009).

Interannual ring-width variations in longleaf pine latewood are high for a species growing in mesic climates (e.g., Henderson and Grissino-Mayer 2009; Knapp et al. 2016; Mitchell et al. 2019) with mean sensitivities, which indicate year-to-year variability, matching that of species found in semiarid environments of the American West (e.g., Knapp et al. 2001). High sensitivity to mid-to-late summer precipitation may be a result of site preferability to sandy, well-drained soils, yet high mean sensitivity values found with longleaf pine growing in the well-developed, humus-rich loamy soils of the North Carolina piedmont (Mitchell et al. 2019) suggests the species may also be particularly in-tune with summer precipitation amounts regardless of local environmental conditions.

Ecologically driven processes also influence longleaf pine radial growth such that high soil-field capacity and frequent low-intensity fires support the health of the longleaf pine ecosystem by facilitating germination, reducing interspecific competition and either limiting or preventing the establishment of either non-native or invasive species (Chapman 1932; Wells 1942; Harper 1962; Glitzenstein et al. 1995; Varner and Kush 2004; Van Lear et al. 2005; Mitchell et al. 2006; Frost 2007; Brockway et al. 2007; Oswalt et al. 2012). Longleaf pine is classified as a shade-intolerant species and frequent (i.e., 1–10-year return interval) low-intensity fires are attributed to the historic dominance of the species in the southeastern United States (Chapman 1932; Harper 1962; Glitzenstein et al. 1995).

Here I present a proxy method for identifying historic tropical cyclone activity utilizing frequencies of intra-annual density fluctuations (IADFs) in tree rings sampled from longleaf pine in western Florida. In addition, I provide information about the causal factors that determine the formation of IADFs in longleaf pine latewood. I also examine the potential El Niño-Southern Oscillation (ENSO) influence on IADF formation as previous work indicates the influence of ENSO variability on precipitation regimes in the southeastern United States (Rajagopalan et al. 2000; Mo and Schemm 2008; Wang et al. 2010), though the influence is spatially and seasonally dependent (Rajagopalan et al. 2000; Mo and Schemm 2008; Wang et al. 2010; Li et al. 2013). To my knowledge, this is the first work to examine intra-annual density fluctuations in longleaf pine, and the first in North America to analyze intra-annual density fluctuations in latewood. Specifically, I: 1) test the viability of using IADFs in longleaf pine latewood as a proxy for tropical cyclone frequency and precipitation for the period 1950–2017; and 2) discuss how the reconstruction of tropical cyclone-sourced frequency and precipitation from remnant longleaf stumps could increase the understanding of historic tropical cyclone activity prior to the historic climate record. Previous investigations indicate that longleaf pine records variations in historic tropical cyclone precipitation in latewood, and the method proposed in this work could act as an additional confirmatory metric of historic tropical cyclone frequency and precipitation (Miller et al. 2006; Lewis et al. 2011; Knapp et al. 2016; Labotka et al. 2016).

### 2.2.1 Intra-annual density fluctuations (IADFs)

Longleaf pine has a high frequency of radial-growth anomalies including false and missing rings (Henderson and Grissino-Mayer 2009), suggesting that the temporal inconsistency of tropical cyclone-derived precipitation that modulates latewood growth (Knapp et al. 2016) may be recorded in the ring widths as IADFs. Intra-annual density fluctuations (Figure 1) are defined as anomalous variations in wood density where earlywood-(latewood-) like cells are present within latewood (earlywood) (Fritts 1976).

Types of IADFs are classified based upon where the anomalous growth occurs relative to the annual growth ring (Campelo et al. 2007) as follows: **Type E** --latewood-like cells within earlywood; **Type E+** --“transition” cells within earlywood to latewood; **Type L** -- earlywood-like cells within latewood; and, **Type L+** -- earlywood-like cells between latewood and the earlywood of the next annual ring (Campelo et al. 2007) (Figure 1). Here, I focus on IADFs found in longleaf latewood growth as latewood variations are more climatically sensitive than either earlywood or totalwood (Lodewick 1930; Meldahl et al. 1999; Henderson and Grissino-Mayer 2009; Knapp et al. 2016; Patterson et al. 2016). Specifically, I examine L+ types of IADFs as their location within latewood corresponds with late-summer precipitation, which is when longleaf pine is typically most stressed by soil-moisture deficiencies.

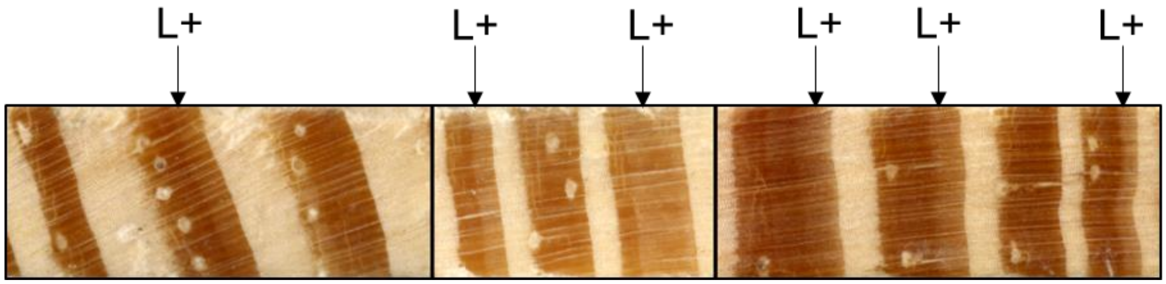


Figure 1. Examples of Six L+ Intra-Annual Density Fluctuations (IADF) from Three Samples of Longleaf Pine Trees Sampled for This Study. The L+ IADF Is Characterized by Less Dense (Thus Lighter) Cells at The End of The Latewood (i.e., Darker) Band.

Much of the work that examines IADF formation and the causal mechanisms of formation has been based on tree species native to the Mediterranean region and western Europe including Aleppo pine (*Pinus halepensis)* (de Luis et al. 2011a, b; Novak et al. 2013; Zalloni et al. 2016), maritime pine (*Pinus pinaster)* (Vieira et al. 2009, 2010; Rozas et al. 2011; Campelo et al. 2015; Zalloni et al. 2016), Scots pine (*Pinus sylvestris)* (Rigling et al. 2002), and stone pine (*Pinus pinea)* (Campelo et al. 2007; Zalloni et al. 2016). Conversely, only a few studies have worked with North American tree species (Schulman 1938; Copenheaver et al. 2006; Edmondson 2010; Marchand and Filion 2011) and to my knowledge, no North American study has examined IADFs in latewood.

Several factors may regulate IADF occurrence (Battipaglia et al. 2016). Tree age and IADF frequency are inversely related in multiple species of *Pinus* such that IADFs occur more frequently in younger individuals (Copenheaver et al. 2006; Vieira et al. 2009, 2010; Campelo et al. 2015; Zalloni et al. 2016). The relationship between tree age and IADF frequency is likely due to younger trees generally having longer growing seasons and a faster response to climatic conditions (Vieira et al. 2008). Additionally, a relationship between IADF occurrence and total tree-ring width has been reported indicating that wider rings exhibit a higher frequency of IADFs compared to narrower, suppressed rings (Copenheaver et al. 2006; Campelo et al. 2013; Zalloni et al. 2016). The relationship between tree-ring width and IADF occurrence is not fully understood because of numerous confounding factors. Tree age, tree-ring width, soil field capacity and growing-season length are predisposing factors of IADF occurrence that should be controlled for while examining the shorter-term triggering factors of IADF formation (Marchand and Filion 2011; Campelo et al. 2015). Additionally, objective, quantitative assessment of IADFs from different environments and species is needed to increase understanding on IADF formation (Battipaglia et al. 2016).

Climate and weather conditions have a significant influence and control on IADF formation. Previous investigations (Schulman 1938; Rigling et al. 2002; Campelo et al. 2007; Vieira et al. 2009, 2010; Edmondson 2010; de Luis et al. 2011a; Rozas et al. 2011; Palakit et al. 2012; Zalloni et al. 2016) report that IADFs present in earlywood (types E and E+) are generally linked to anomalous and unseasonal precipitation and temperature regimes in spring and early summer while IADFs present in latewood (types L and L+) are generally linked to either unseasonal precipitation or temperature regimes during late summer and fall. The relationship between climate and IADF formation allows for climate reconstructions to be produced at intra-seasonal resolution and the synchronistic occurrence of IADFs between individual trees and chronologies confirms the external-sourcing of the triggering mechanism. For example, L+ IADFs may suggest above-average precipitation in late summer and early fall. Additional research focused on *Pinus* species outside of the areas where IADF research has been prevalent (Battipaglia et al. 2016) has the potential to increase understanding of IADF formation and potentially create the ability for reconstructions of intra-seasonal climatic anomalies in the region. Specifically, the examination of IADF frequency for longleaf pine will help establish if similar growth anomalies exist within the *Pinus* genus beyond the Mediterranean region and under a climatic regime characterized by wet (i.e., > 5 cm rainfall/month) summers.

### 2.2.2 Longleaf pine latewood as a TCP proxy

Multiple proxy measures exist to reconstruct tropical cyclone activity using longleaf pine tree-ring data (Miller et al. 2006; Lewis et al. 2011; Knapp et al. 2016; Labotka et al. 2016). Based on samples collected in North Carolina, Knapp et al. (2016) found variations in latewood ring-width had high fidelity ($r = 0.71$, $p < 0.01$) with tropical cyclone precipitation (TCP) and reconstructed TCP variability to the 1700s. Variations in $\delta^{18}O$ isotope in longleaf pine latewood also have effectively documented historic tropical cyclone frequency in southern Georgia (Miller et al. 2006; Labotka et al. 2016) and southeastern Texas (Lewis et al. 2011).

Here I present a dendroclimatic proxy measure that may effectively detect tropical cyclone frequency and precipitation in the southeastern United States. I specifically examine the potential diagnostic role of L+ IADFs as a marker to identify the passage of tropical cyclones in western Florida. I then discuss how these findings could be applied to other areas of the southeastern U.S. as a proxy method of identifying tropical cyclone passage prior to historic record keeping.

## 2.3 Materials and Methods

### 2.3.1 Study sites

I analyzed IADF occurrence in longleaf pine at three field sites in the Gulf Coastal Plain of western Florida (Figure 2). The selected sites (Naval Live Oaks Reservation [NLO], Blackwater River State Park [BRP], Blackwater River State Forest [BRF]) are in an area where the climatic influence of the Gulf of Mexico and tropical cyclones occurs, which may increase the occurrence of IADFs. Warm Gulf of Mexico sea-surface temperatures (SSTs) supply the study areas with increased precipitation (severe and non-severe) and warmer temperatures (Molina et al. 2016). Previous investigations on IADF occurrence generally occur along tree populations with an oceanic influence, so sites were selected in part to increase comparability with previous work.

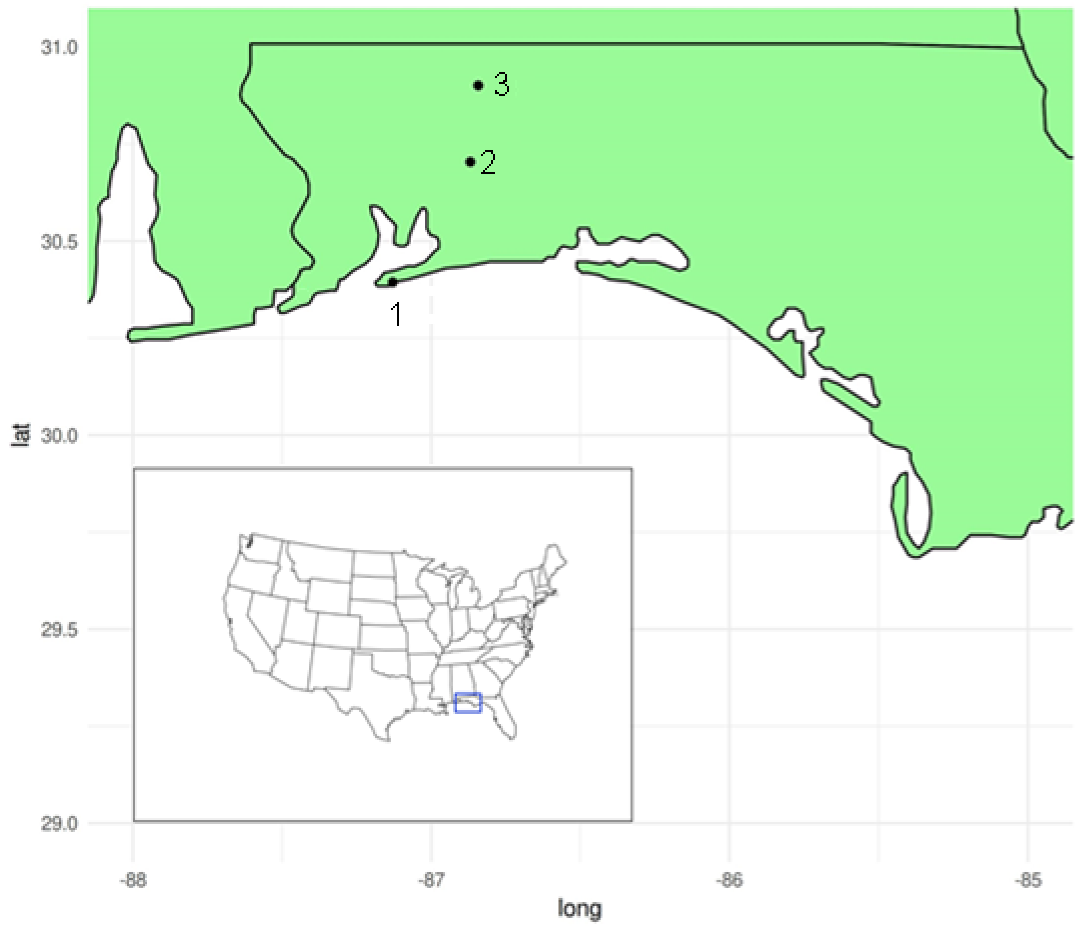


Figure 2. Field Collection Sites: 1. Naval Live Oaks Reservation (NLO) 2. Blackwater River State Park (BRP) 3. Blackwater River State Forest (BRF).

The study region is affected by several climatic features that may influence radial growth including winters with minimal days (i.e., ≤ 2) below subfreezing conditions and the influence of tropical cyclone-induced heavy rainfall events (i.e., >250 mm/event). In addition, the study region is climatically dissimilar to Mediterranean Europe, as summer precipitation in the study region is a significant precipitation source, while in Mediterranean Europe summer precipitation is a minor source (e.g., approximately < 10%) of total annual precipitation near Galicia and Valencia in Spain.

I selected three sites based on potential climate and land-use management characteristics that may influence the frequency of IADFs and thus suggest IADF frequency is affected by site conditions. Naval Live Oaks (NLO) was selected because it is located immediately adjacent to Gulf of Mexico and experiences moderated temperature extremes relative to the two inland sites that are 38 km (BRP) and 60 km (BRF) northeast of NLO. NLO is characterized by sandy soils (77% Lakeland sand and similar soils) while the inland sites are primarily composed of loamy sands and similar soils (85% Troup loamy sand). The coastal site is at an elevation of approximately 2 to 9 m, while the inland sites range from 12 to 41 m at BFP and from 30 to 62 m at BFR. Both BRP and BRF are more frequently burned than NLO, suggesting that land management is considerably different between sites.

### 2.3.2 Longleaf pine tree-ring data

At each of the three field sites, I sampled 10–15 trees in open-canopy environments (Figure 3) obtaining two core samples per tree ($n$ = 20-30). I used a 5.15-mm diameter increment borer following standard dendrochronological field sampling techniques (Stokes and Smiley 1996) and sampled from south-facing slopes when possible to maximize the climate signal contained in the latewood. I recorded tree height, stem diameter and geographic location for each tree. After field collection, core samples were dried, then mounted and glued onto wooden strips. Mounted cores were sanded with progressively finer sand paper ranging from 120–600 *u*m to reveal cellular structure, scanned at high resolution (DPI $\geq$ 1200) and tree ring-widths were measured using the program WinDENDRO™ at 0.001-mm precision (Guay 2012). Raw tree-ring widths were checked for accuracy using the program COFECHA to confirm crossdating (Holmes 1983). In addition, I tested multiple standardization techniques including basal area increment, negative exponential, and raw ring widths and found the best correlations with climate using negative exponential standardization. I standardized each core's growth using negative exponential standardization to examine individual core sensitivity to climate.

Figure 3. Open-Canopy Longleaf Pine Forest Environment at Blackwater River State Forest. I Sampled in Open-Canopy Environments to Reduce Potential Confounding Factors on Radial Growth.

### 2.3.3 Intra-annual density fluctuations

After crossdating I inspected each core for cellular-level radial-growth anomalies and classified in agreement with previous investigations (Campelo et al. 2007). The frequency of IADFs per year (*F)* was calculated as $F = N / n$ where $N$ is the number of IADFs each year and $n$ is the total sample depth at that given year. The decreasing sample depth *(n)* through time potentially creates a bias which was corrected using an adjusted frequency equation (Osborn et al. 1997). The stabilized IADF frequency, $f$, was calculated by $f = Fn^{0.5}$.

### 2.3.4 Climate and weather data

Monthly climate data (e.g., PDSI, minimum temperature, maximum temperature, average temperature, and precipitation) for Climate Division 1 in northwest Florida were collected from NOAA's National Climate Data Center during the period 1950–2017 (available online at: https://www7.ncdc.noaa.gov/CDO/CDODivisionalSelect.jsp). For the same period, daily precipitation data were collected from NOAA's National Centers for Environmental Information to determine TC-sourced precipitation (TCP) (NCEI 2018) (available online at: https://www.ncdc.noaa.gov/data-access/land-based-station-data). Additionally, I collected El Niño-Southern Oscillation (ENSO) data for the 3.4 region from NOAA to determine the influence of ENSO on the frequency and formation of IADFs (available online at: www.esrl.noaa.gov/psd/gcos_wgsp/Timeseries/Nino34/).

### 2.3.5 Tropical cyclone data

To determine if a tropical cyclone (TC) tracked into the study area, I examined historic TC tracks from the International Best Track Archive for Climate Stewardship (IBTrACS) (Knapp et al. 2010). To determine TC influence on the study area I used a 223 km (the average rain-field size at landfall) TC-moisture plume buffer radius for the months July, August, September and October (Matyas 2010). I excluded June and November as a TC occurring in either June or November would likely not be picked up in the latewood of that year (Lodewick 1930). I collected TCP values for the days when a TC influenced the study area in agreement with past investigations (Knapp et al. 2016).

### 2.3.6 Analyses

To determine if site-specific differences exist in L+ IADF occurrence, I used an analysis of variance (ANOVA) and Tukey-Kramer post-hoc procedures to determine if the mean L+ IADF occurrence at each site was significantly different. In addition, I tested each study site's tree characteristics (i.e., age, diameter, height) to determine if there were significant site-specific differences in tree morphology and age.

I examined each core's relationship with climate to determine if the climate sensitivity of a tree contributes to a higher proportion of L+ IADFs during the common data period (1972–2017). I correlated each core's standardized growth with monthly PDSI and used a Mann–Whitney $U$ test to determine if the group of cores that were significantly associated with climate were different than the group of cores with no significant relationship to climate regarding total L+ IADFs.

I tested the relationship between the stabilized frequency of IADF occurrence and climatic variables (monthly PDSI, TCP) using Spearman rank-order correlation to determine the influence of summer precipitation on L+ IADF formation. I also tested whether a tropical cyclone influenced the study region for each year that the stabilized frequency of IADF occurrence is > 0. I examined climate (precipitation, ENSO and ENSO phase) during the occurrence of non-TC positives (i.e., an L+ IADF in a year without TC influence) to determine what causes an L+ in the region in years with no tropical cyclone influence.

**2.4 Results and Discussion**

The final sample consisted of 34 trees ($n$ = 67 cores) sampled from the three study sites (Figure 4). L+ IADFs per sample ranged from 0–14, ($\sigma = 2.8$) during the common period of growth (1972–2017) indicating that certain trees are more effective at capturing L+ IADFs (Figure 4). During the common period of growth (i.e., the range of years in which $n$ = 67), BRF had the highest mean L+ events/year ($\bar{x} = 4.08$), followed by BRP ($\bar{x} = 2.95$), and NLO ($\bar{x} = 1.41$). The mean L+ IADFs per site are significantly different ($p$ = 0.003), with more L+ IADFs at BRF than NLO indicating that there are significant site-specific differences in the study region. In addition, I tested whether tree characteristics (i.e., age, diameter, height) are significantly different between sites and found that there are significant ($p < 0.001$) differences in both age and diameter between sites. BRP trees are significantly wider ($p < 0.05$) than BRF trees, which are significantly wider ($p < 0.05$) than NLO trees. In addition, I find that NLO trees are significantly older ($p < 0.05$) than BRF trees and find no significant difference in cambial age between BRF and BRP.

These finding that older and smaller diameter trees (NLO) have less L+ IADFs agree with previous work (Copenheaver et al. 2006; Vieira et al. 2009, 2010; Campelo et al. 2015; Zalloni et al. 2016) suggesting that IADF formation is similar across study regions. In addition, the role of land management should be accounted for when comparing site characteristics. Between these three study sites, the more maintained (i.e., more frequent prescribed fires) sites (BRP and BRF) have more L+ IADFs than the less frequently burned site (NLO), which indicates the potential influence of land management on IADF formation. The open-canopy environments produced by frequent prescribed fires limits confounding factors on radial growth, which could explain the higher sensitivity to L+ IADFs in these environments.

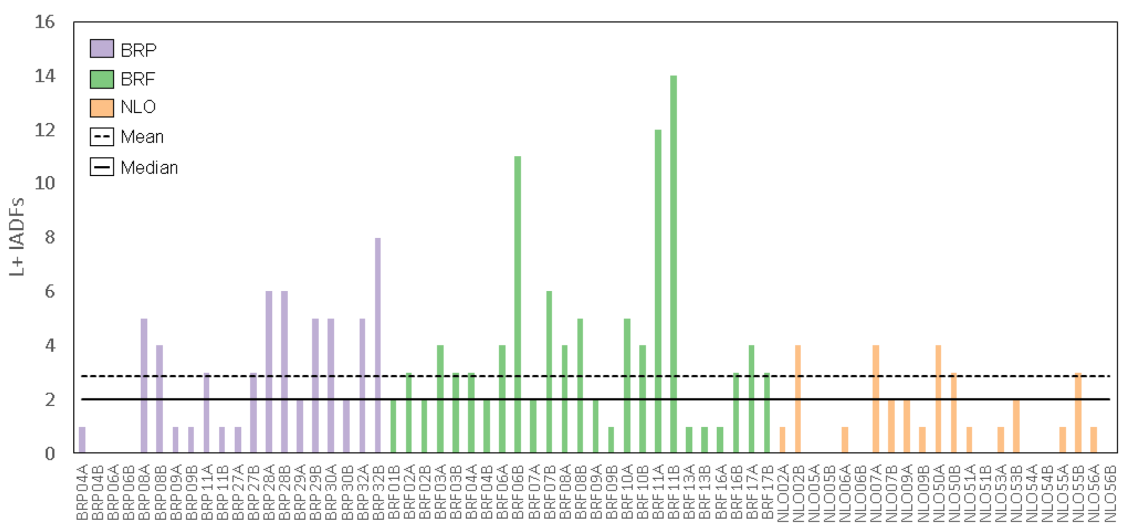


Figure 4. Raw Occurrence of L+ IADFs Per Sample at Each Site in The Common Period of Growth (1972–2017).

I examined each core's relationship with climate to determine if the climate sensitivity of a tree contributes to a higher proportion of L+ IADFs. I standardized each core's growth and correlated each individually with September PDSI, and 23 of the 67 (34%) cores were significantly associated with PDSI 1950–2017. During the common growth period 73 of 192 (38%) L+ IADFs are associated with the most climatically sensitive trees (i.e., the cores that are significantly associated with PDSI). The groups of cores that are significant with climate ($n$ = 23, $\bar{x}$ = 3.2 L+) and those that are not ($n$ = 44, $\bar{x}$ = 2.7) are not significantly different regarding total L+ IADFs, suggesting that an individual tree's climate sensitivity may not impact the occurrence of an L+.

The stabilized frequency ($f$) of IADF Type L+ occurrence (Figure 5) is significantly associated ($p < 0.01$) with PDSI for the months June through October (Figure 6). This agrees with previous investigations (Rigling et al. 2002; Campelo et al. 2007; Vieira et al. 2009, 2010; de Luis et al. 2011a; Rozas et al. 2011; Zalloni et al. 2016), indicating that the causal mechanisms of IADFs are similar across study areas. The strongest relationships occur in September and October, indicating the potential influence of tropical cyclone-sourced precipitation on $f$.

The specific influence of tropical cyclone-sourced precipitation likely is the principal cause for the formation of IADF Type L+ in this region. During 1950–2017, 38 of the 68 years (56%) experienced a TC tracking within the study area. The type L+ $f$ value in years that have a TC track into the study area and the years that do not are significantly different ($p$ = 0.021), indicating the influence of TC passage into the study area on stabilized L+ frequency *(*i.e.,*"f")*. Further, of the 50 years with $f > 0$, 31 (62%)

were associated with TC passage while 19 (38%) were not, suggesting L+ events were an effective, but not an exclusive, marker of tropical cyclone passage in the study area (Figure 5). However, the majority (83%) of non-TC positives ($f > 0$, but no TC passage) occurred with $f < 0.25$. Conversely, for $f \geq 0.25$, 19 of the 23 years (83%) were associated with TC passage, while for $f \geq 0.50$, 7 of the 8 years (88%) were associated with TC passage indicating that IADF Type L+ may be an effective marker of historic TC passage when $f$ is greater than a certain threshold (i.e., 0.25).

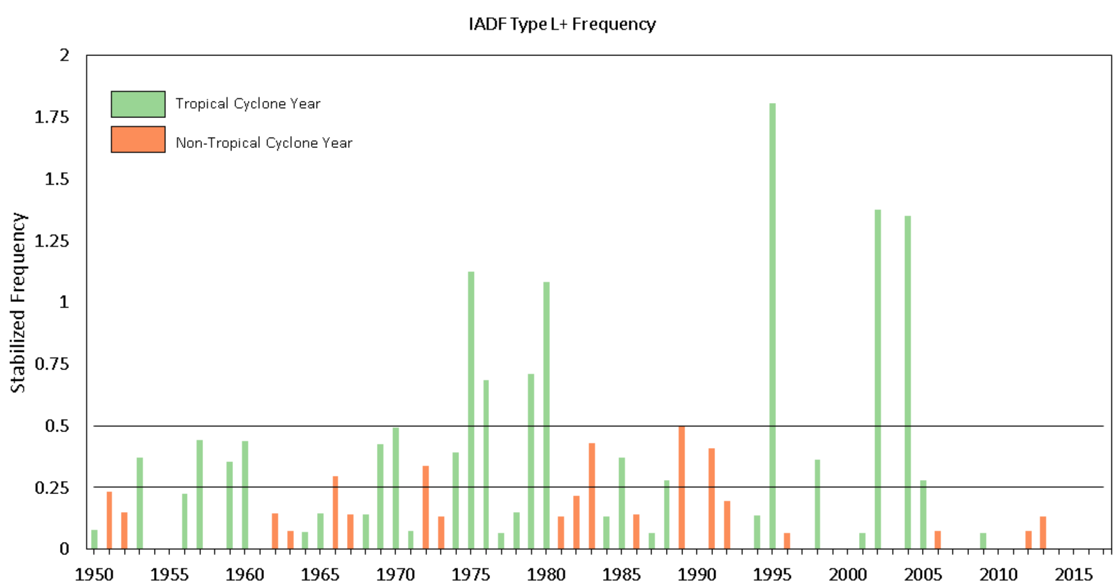


Figure 5. The Stabilized Frequency, $f$, of IADF Type L+ Occurrence. Green Bars Indicate Years ($n$ =31) Where a TC Tracked into The Study Area While Orange Bars Indicate Years ($n$ =19) That Did Not Have a TC Track into The Study Area. Seven of The Eight $f$ Values > 0.5 From 1950–2017 Correspond With a TC Tracking Into The Study Area During Either July, August, September, or October.

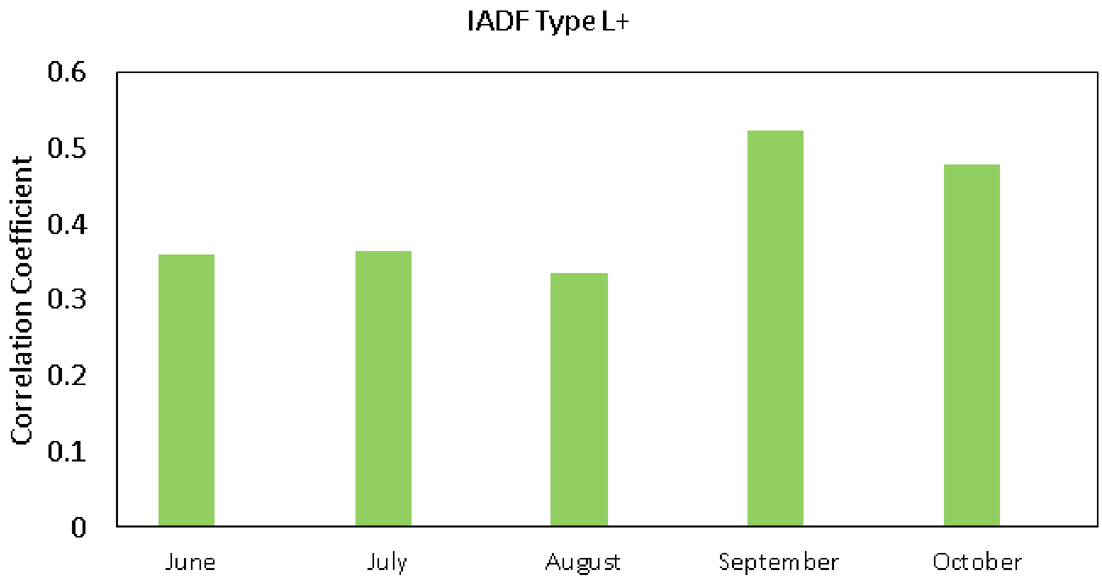


Figure 6. Stabilized Frequency of Type L+ IADF Occurrence, *f*, Is Significantly Associated ($p < 0.01$) With PDSI During Each Month June–October.

Eighteen of the 34 trees in the sample have non-TC positives (i.e., an L+ IADF in a year without TC influence) and there is a total of 55/387 (14%) incidents of non-TC positives. The groups of trees that have non-TC positives and trees without non-TC positives are significantly different ($p = 0.003$) in regard to each group's ability to capture a TC such that the group of trees with non-TC positives are also more effective at identifying TCs. Despite a near-equal distribution of El Niño ($n = 25$), La Niña ($n = 22$) and neutral ($n = 21$) phases of the El Niño Southern Oscillation (ENSO) during the study period, most (47 of 55, 85%) non-TC positives coincide with either the El Niño or neutral phase ENSO. However, I find no significant relationship between ENSO and non-TC positives, with the strongest relationship occurring during JJA ($r = 0.172$, $p = 0.161$). In addition, I find no significant difference between the number of non-TC positives in a year and whether it was an El Niño or neutral year suggesting that ENSO variability does not explain variations in non-TC positives. In addition, I find no significant relationship between June–October precipitation and non-TC positives, suggesting that non-TC positives are caused by non-moisture based variables.

The binary occurrence of a TC provides information regarding TC frequency while the magnitude of TCP could also explain variations in *f*. TCP and *f* are significantly associated ($p = 0.005$), yet the relationship explains only 15% of the total variance (Table 1). To examine the TCP and *f* relationship at a finer resolution, thresholds in the *f* value are defined to determine if TCP becomes a more important explanatory variable in higher *f* values.

When *f* is restricted to a threshold of greater than or equal to 0.25, the relationship with TCP is insignificant, indicating that the initial correlation may be an artifact of sample size rather than influence (i.e., significance without meaningful explanatory power). However, when *f* is restricted to values greater than or equal to 0.50, these values are significantly associated with TCP ($p = 0.015$) (Table 1). TCP explains 65.6% of the variation in the $f \geq 0.50$ values. This indicates that type L+ IADFs may only be an adequate diagnostic metric for historic TCP when the *f* value exceeds a certain threshold (i.e., 0.50). Additionally, these results indicate that L+ IADFs may be an effective marker of TC passage, but an ineffective marker of the magnitude of TCP produced by a TC. It is likely that the width of L+ IADF may be a more effective marker of TCP, while the occurrence of an L+ IADF may be a more effective marker of TC frequency.

Table 1. Spearman-*r* Values Between *f* Values and TCP Totals During 1950–2017. ** Denotes $p < 0.01$, * Denotes $p < 0.05$.

| *f-value* Threshold | *N* | Correlation coefficient |
|---|---|---|
| None | 68 | 0.353 ** |
| $f \geq 0.25$ | 23 | 0.188 |
| $f \geq 0.50$ | 8 | 0.810 * |

These results indicate that L+ IADFs are an effective marker of historic tropical cyclone frequency for the period 1950–2017. Collecting more samples from older trees and/or remnant stumps has the potential to examine the proxy relationship further and potentially extend the record of historic tropical cyclone frequency beyond historic climate records. This method also has the potential to reconstruct historic tropical cyclone frequency throughout the southeastern United States, resulting in comparisons to previous work to address spatiotemporal patterns of tropical cyclone activity in the United States, which is based largely on tropical cyclone data from early 1900s to present (Keim et al. 2007).

**2.5 Conclusion**

These results indicate that while any large precipitation event in the late growing season can promote IADF L+ occurrence, higher stabilized frequency values of IADF Type L+ indicate an increased probability that a tropical cyclone tracked into the study area and reduces the odds of a non-TC positive (i.e., $f > 0$ but no TC passage). Positive *f* values below a certain threshold (i.e., $f \geq 0.50$), however, are less diagnostic of the magnitude of TCP in a given year. Despite these promising findings, data from more sites and older trees are needed to support these results. Further, via this relationship, reconstruction of specific environmental phenomena (e.g. tropical cyclone passage into a specific study area) is probable, which could allow for increased understanding of historic tropical cyclone activity prior to the historic climate record. Previous research (e.g., Miller et al., 2006, Knapp et al. 2016) show that longleaf pine trees record tropical cyclone precipitation in their latewood, and the method proposed in this work could act as an additional confirmatory metric of historic tropical cyclone passage and precipitation.

CHAPTER III

# CONCLUSION

Several findings emerge from these analyses. First, the stabilized frequency of intra-annual density fluctuations (IADFs) in longleaf pine latewood are significantly ($p < 0.01$) associated with June–October precipitation variability (indicated by the correlation with PDSI), indicating that the causal mechanisms of IADFs are similar across study areas with dissimilar climate. The strongest relationship between the stabilized frequency of IADFs and PDSI occurs during September and October, indicating the influence of tropical cyclone-sourced precipitation (TCP) on IADF formation. High IADF stabilized frequencies (i.e., > 0.50) nearly always (88%) coincide with a tropical cyclone tracking into the study area, and there is a significant ($p < 0.01$) relationship between TCP and the stabilized frequency of IADFs. Via these relationships, reconstruction of historic tropical cyclone frequency and precipitation is probable, which would allow for increased understanding of historic tropical cyclone activity prior to the historic climate record.

REFERENCES


Battipaglia, G., Campelo, F., Vieira, J., Grabner, M., De Micco, V., Nabais, C., Cherubini, P., Carrer, M., Bräuning, A., Čufar, K. and Di Filippo, A., 2016: Structure and function of intra–annual density fluctuations: Mind the gaps. *Frontiers in Plant Science*, **7**, 595.

Brockway, D. G., K. W. Outcalt, and W. D. Boyer, 2007: Longleaf pine regeneration ecology and methods. *The longleaf pine ecosystem*, Springer, 95–133.

Burns, R.M. and Honkala, B.H., 1990: Silvics of North America. Volume 1. Conifers. Agriculture Handbook (Washington), (654).

Campelo, F., C. Nabais, H. Freitas, and E. Gutiérrez, 2007: Climatic significance of tree-ring width and intra-annual density fluctuations in *Pinus pinea* from a dry Mediterranean area in Portugal. *Annals of Forest Science*, **64**, 229–238.

Campelo, F., Vieira, J. and Nabais, C., 2013: Tree-ring growth and intra-annual density fluctuations of *Pinus pinaster* responses to climate: Does size matter? *Trees*, **27**, 763–772.

Campelo, F., Vieira, J., Battipaglia, G., de Luis, M., Nabais, C., Freitas, H. and Cherubini, P., 2015: Which matters most for the formation of intra-annual density fluctuations in *Pinus pinaster*: Age or size? *Trees*, **29**, 237–245.

Chapman, H. H., 1932: Is the longleaf type a climax? *Ecology*, **13**, 328–334.

Coile, T., 1936: The effect of rainfall and temperature on the annual radial growth of pine in the southern United States. *Ecological Monographs*, **6**, 533–562.

Conner, R.N., Rudolph, D.C., Saenz, D. and Schaefer, R.R., 1994: Heartwood, sapwood, and fungal decay associated with red-cockaded woodpecker cavity trees. The Journal of Wildlife Management, **58**(4):728-734.

Copenheaver, C. A., E. A. Pokorski, J. E. Currie, and M. D. Abrams, 2006: Causation of false ring formation in *Pinus banksiana*: A comparison of age, canopy class, climate and growth rate. *Forest Ecology and Management*, **236**, 348–355.

de Luis, M., K. Novak, J. Raventós, J. Gričar, P. Prislan, and K. Čufar, 2011a: Climate factors promoting intra-annual density fluctuations in Aleppo pine (*Pinus halepensis*) from semiarid sites. *Dendrochronologia*, **29**, 163–169.

de Luis, M., Novak, K., Raventós, J., Gričar, J., Prislan, P. and Čufar, K., 2011b: Cambial activity, wood formation and sapling survival of *Pinus halepensis* exposed to different irrigation regimes. *Forest Ecology and Management*, **262**, 1630–1638

Devall, M. S., J. M. Grender, and J. Koretz, 1991: Dendroecological analysis of a longleaf pine *Pinus palustris* forest in Mississippi. *Vegetatio*, **93**, 1–8.

Edmondson, J. R., 2010: The meteorological significance of false rings in eastern redcedar (*Juniperus virginiana* L.) from the southern Great Plains, USA. *Tree-Ring Research*, **66**, 19–33.

Fritts, H., 1976: *Tree rings and climate*. Academic Press,

Frost, C., 2007: History and future of the longleaf pine ecosystem. *The longleaf pine ecosystem*, Springer, 9–48.

Frost, C. C., 1993: Four centuries of changing landscape patterns in the longleaf pine ecosystem. *Proceedings of the tall timbers fire ecology conference*, Vol. 18 of, 17–43.

Gaby, L.I., 1985: The southern pines, an American wood. FS–256. Washington, DC: US Department of Agriculture, Forest Service.

Glitzenstein, J. S., W. J. Platt, and D. R. Streng, 1995: Effects of fire regime and habitat on tree dynamics in north Florida longleaf pine savannas. *Ecological Monographs*, **65**, 441–476.

Harper, R. M., 1962: Historical notes on the relation of fires to forests. *Proceedings of the first tall timbers fire ecology conference, Tall Timbers Research Station, Tallahassee,* 43–52.

Henderson, J. P., and H. D. Grissino-Mayer, 2009: Climate–tree growth relationships of longleaf pine (*Pinus palustris* mill.) in the Southeastern Coastal Plain, USA. *Dendrochronologia*, **27**, 31–43.

Holmes, R. L., 1983: Computer-assisted quality control in tree-ring dating and measurement. *Tree-ring Bulletin*,

Guay R (2012) WinDENDRO 2012: User's Guide, Regent Instruments. Inc., Quebec, Canada.

Keim, B.D., Muller, R.A. and Stone, G.W., 2007: Spatiotemporal patterns and return periods of tropical storm and hurricane strikes from Texas to Maine. Journal of climate, **20**(14), 3498-3509.

Knapp, P.A., Soulé, P.T. and Grissino-Mayer, H.D., 2001. Post-drought growth responses of western Juniper (*Juniperus occidentals* var. *occidentalis*) in central Oregon. *Geophysical Research Letters*, **28**(13), 2657-2660.

Knapp, K.R., Kruk, M.C., Levinson, D.H., Diamond, H.J. and Neumann, C.J., 2010: The international best track archive for climate stewardship (IBTrACS) unifying tropical cyclone data. *Bulletin of the American Meteorological Society*, **91**(3), 363-376.

Knapp, P.A., Maxwell, J.T. and Soulé, P.T., 2016: Tropical cyclone rainfall variability in coastal North Carolina derived from longleaf pine (*Pinus palustris* Mill.): AD 1771–2014. *Climatic Change* 135:311–323.

Labotka, D.M., Grissino-Mayer, H.D., Mora, C.I. and Johnson, E.J., 2016: Patterns of moisture source and climate variability in the southeastern United States: a four-century seasonally resolved tree-ring oxygen-isotope record. *Climate dynamics*, **46**(7-8), 2145-2154.

Lewis, D.B., Finkelstein, D.B., Grissino-Mayer, H.D., Mora, C.I. and 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. Journal of Geophysical Research: *Biogeosciences*, **116**(G2).

Li, L., Li, W., Barros, A.P., 2013: Atmospheric moisture budget and its regulation of the summer precipitation variability over the Southeastern United States. *Climate Dynamics*, **41**, 613–631. https://doi.org/10.1007/s00382-013-1697-9

Lodewick, J. E., 1930: Effect of certain climatic factors on the diameter growth of longleaf pine in western Florida. *Journal of Agricultural Research*, **41**, 349–363.

Marchand, N., and L. Filion, 2011: False rings in the white pine (*Pinus strobus*) of the Outaouais Hills, Quebec (Canada), as indicators of water stress. *Canadian Journal of Forest Research*, **42**, 12–22.

Matyas, C.J., 2010. Associations between the size of hurricane rain fields at landfall and their surrounding environments. *Meteorology and atmospheric physics*, ***106***(3-4), 135-148.

McIntyre, R.K., Guldin, J.M., Ettel, T., Ware, C. and Jones, K., 2018: Restoration of longleaf pine in the southern United States: a status report. Proceedings of the 19th biennial southern silvicultural research conference; 2017 March 14-16; Blacksburg, VA. e-Gen. Tech. Rep. SRS-234. Asheville, NC: U.S. Department of Agriculture, Forest Service, Southern Research Station: 297-302.

Meldahl, R., N. Pederson, J. Kush, and J. Varner, 1999: Dendrochronological investigations of climate and competitive effects on longleaf pine growth. *Tree Ring Analysis: Biological, Methodological and Environmental Aspects. CABI Publishing, Wallingford, UK*, 265–285.

Miller, Dana L., Claudia I. Mora, Henri D. Grissino-Mayer, Cary J. Mock, Maria E. Uhle, and Zachary Sharp. "Tree-ring isotope records of tropical cyclone activity." *Proceedings of the National Academy of Sciences* 103, no. 39 (2006): 14294-14297.

Mitchell, R.J., Hiers, J.K., O'Brien, J.J., Jack, S.B. and Engstrom, R.T., 2006: Silviculture that sustains: the nexus between silviculture, frequent prescribed fire, and conservation of biodiversity in longleaf pine forests of the southeastern United States. *Canadian Journal of Forest Research*, **36**(11):2724-2736.

Mitchell, T.J., Patterson, T.W. & Knapp, P.A., 2019: Comparison of climate–growth responses of montane and piedmont longleaf pine (*Pinus palustris* Mill.) chronologies in North Carolina. *Trees,* https://doi.org/10.1007/s00468-019-01823-8.

Mo, K.C., Schemm, J.E., 2008: Relationships between ENSO and drought over the southeastern United States. *Geophysical Research Letters* 35. https://doi.org/10.1029/2008GL034656

Molina, M. J., R. P. Timmer, and J. T. Allen, 2016: Importance of the Gulf of Mexico as a climate driver for US severe thunderstorm activity. *Geophysical Research Letters,* 43.23.

Novak, K., M. A. S. Sánchez, K. Čufar, J. Raventós, and M. de Luis, 2013: Age, climate and intra-annual density fluctuations in *Pinus halepensis* in Spain. *IAWA Journal*, **34**, 459–474.

Osborn, T.J., Biffa, K.R. and Jones, P.D., 1997: Adjusting variance for sample-size in tree-ring chronologies and other regional-mean timeseries. *Dendrochronologia*, ***15***, 89-99.

Oswalt, C. M., J. A. Cooper, D. G. Brockway, H. W. Brooks, J. L. Walker, K. F. Connor, S. N. Oswalt, and R. C. Conner, 2012: History and current condition of longleaf pine in the southern United States. *Gen. Tech. Rep. SRS–166. Asheville, NC: US Department of Agriculture Forest Service, Southern Research Station. 51 p.*, **166**, 1–51.

Palakit, K., S. Siripattanadilok, and K. Duangsathaporn, 2012: False ring occurrences and their identification in teak (*Tectona grandis*) in north-eastern Thailand. *Journal of Tropical Forest Science*, 387–398.

Patterson, T.W., Cummings, L.W. and Knapp, P.A, 2016: Longleaf pine (*Pinus palustris* Mill.) morphology and climate/growth responses along a physiographic gradient in North Carolina. *The Professional Geographer* 68:238–248.

Provencher, L., Litt, A.R., Gordon, D.R., LeRoy Rodgers, H., Herring, B.J., Galley, K.E., McAdoo, J.P., McAdoo, S.J., Gobris, N.M. and Hardesty, J.L., 2001: Restoration fire and hurricanes in longleaf pine sandhills. *Ecological Restoration*, **19**(2), 92-98.

Rajagopalan, B., Cook, E., Lall, U., Ray, B.K., 2000: Spatiotemporal Variability of ENSO and SST Teleconnections to Summer Drought over the United States during the Twentieth Century. *Journal of Climate* **13**, 4244–4255. https://doi.org/10.1175/1520-0442(2000)013<4244:SVOEAS>2.0.CO;2

Rigling, A., O. Bräker, G. Schneiter, and F. Schweingruber, 2002: Intra-annual tree-ring parameters indicating differences in drought stress of *Pinus sylvestris* forests within the Erico-Pinion in the Valais (Switzerland). *Plant Ecology*, **163**, 105–121.

Rozas, V., I. García-González, and R. Zas, 2011: Climatic control of intra-annual wood density fluctuations of *Pinus pinaster* in NW Spain. *Trees*, **25**, 443–453.

Schulman, E., 1938: Classification of false annual rings in Monterey pine. *Tree-Ring Bulletin*,

Schumacher, F. X., and B. B. Day, 1939: The influence of precipitation upon the width of annual rings of certain timber trees. *Ecological Monographs*, **9**, 387–429.

Stokes, M.A., 1996: An introduction to tree-ring dating. *University of Arizona Press*.

Van Lear, D. H., W. Carroll, P. Kapeluck, and R. Johnson, 2005: History and restoration of the longleaf pine-grassland ecosystem: Implications for species at risk. *Forest Ecology and Management*, **211**, 150–165.

Varner, J. M., and J. S. Kush, 2004: Remnant old-growth longleaf pine (*Pinus palustris* Mill.) savannas and forests of the southeastern USA: Status and threats. *Natural Areas Journal, **24** (2): 141-149,*

Vieira, J., F. Campelo, and C. Nabais, 2009: Age-dependent responses of tree-ring growth and intra-annual density fluctuations of *Pinus pinaster* to Mediterranean climate. *Trees*, **23**, 257–265.

Vieira, J., Campelo, F. and Nabais, C., 2010: Intra-annual density fluctuations of *Pinus pinaster* are a record of climatic changes in the western Mediterranean region. *Canadian Journal of Forest Research*, **40**, 1567–1575.

Wang, H., Fu, R., Kumar, A., Li, W., 2010: Intensification of Summer Rainfall Variability in the Southeastern United States during Recent Decades. *Journal of Hydrometeorology*, **11**, 1007–1018. https://doi.org/10.1175/2010JHM1229.1

Wells, B. W., 1942: Ecological problems of the southeastern United States coastal plain. *The Botanical Review*, **8**, 533.

Zalloni, E., de Luis, M., Campelo, F., Novak, K., De Micco, V., Di Filippo, A., Vieira, J., Nabais, C., Rozas, V. and Battipaglia, G., 2016: Climatic signals from intra-annual density fluctuation frequency in Mediterranean pines at a regional scale. *Frontiers in Plant Science*, **7**, 579.