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Dendrochronological studies have traditionally centered around the analysis of one tree species from either one location or from multiple locations. Recently, there has been an emergence of multiple species analysis from one location or more that seeks to establish a chronology that crosses the species boundary, as well as the hardwood and softwood divide. The goal of this research is to determine the dendroclimatic benefit of using of multiple, co-occurring tree species collected from a single site. This paper examines the correlation of climatic variables to multiple species of trees sampled from a 0.84 square kilometer mixed-growth forest in the Uwharrie Mountain foothills known as the Margaret J. Nichols Piedmont Longleaf Pine Preserve (hereafter Nichols Tract). Two species of softwood (*Pinus palustris* and *Pinus echinata*) were dendrochronologically sampled along with one species of hardwood (*Quercus stellata*). Using a sample size of $n = 90$ during the period 1935–2016, I evaluate the compatibility of these three species in analyzing climate trends to determine if there is an increase in climatic sensitivity when combining ring-width data from all species. I also address if climatic sensitivity is temporally dependent and why.

EXAMINING THE UTILITY OF USING MULTIPLE, CO-OCCURRING TREE
SPECIES TO INCREASE CLIMATE SENSITIVITY
IN DENDROCHRONOLOGY

by

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Approved by

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APPROVAL PAGE

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CHAPTER I
INTRODUCTION AND RESEARCH OBJECTIVES

Introduction

Dendrochronological studies have traditionally centered on the analysis of one tree species from either one location (e.g., Guyette and Dey 1997, Rubino and McCarthy 2000, Stambaugh and Guyette 2004, Harley et al. 2011, Knapp et al. 2016) or from multiple locations (Salzer and Hughes 2006, Salzer et al. 2009, LeBlanc and Terrell 2011, Knapp et al. 2014). Recently, several studies (e.g., Maxwell et al. 2011, Maxwell et al. 2014, LeBlanc and Stahle 2015, Maxwell and Harley 2017) have attempted to improve climate/radial growth relationships by using multiple–species combinations of hardwoods and softwoods (Estes 1970, García–Suárez et al. 2001, Fraver and White 2005). Collecting from multiple species is more labor intensive due to the need to create additional chronologies and meet the minimum statistical threshold of $n = 30$. Maxwell et al. (2014) successfully used multiple species to increase the sensitivity of the climate/growth relationship. This thesis examines several climactic indices and the correlation between those indices and radial growth for multiple species of trees sampled from an 83.8 ha stand of mixed coniferous/hardwood forest in the Uwharrie Mountain foothills known as the Nichols Tract. Two species of softwood— longleaf pine (*Pinus palustris* Mill.) and shortleaf pine (*Pinus echinata* Mill.) were dendrochronologically sampled along with one hardwood species, post oak (*Quercus stellata* Ashe). Here, I seek

to determine the viability of using these three species in analyzing climate trends to determine if there is an increase in climatic sensitivity when combining ring–width data from all species during 1935–2017. If an increase in climatic sensitivity is determined, I then address if this sensitivity is time dependent.

Hard Wood and Soft Wood

This study centers around two gymnosperm softwood trees, the longleaf pine (*Pinus palustris* Mill.) and shortleaf pine (*Pinus echinata* Mill.) and one angiosperm hardwood species, post oak (*Quercus stellata* Ashe). Gymnosperm trees have an internal wood structure that is simpler and homogenous in nature. Gymnosperms lack the vessels found in angiosperm trees and is non-porous. Unlike the angiosperms which transport water up the tree in vessels and are porous in nature.

Background on the Longleaf Pine

The historical longleaf pine range covered 33 million ha, extending principally along the Coastal Plains from eastern Texas, to southeastern Virginia (Way 2011). Extensive populations in the Piedmont region also existed including “montane” forests in the Ridge and Valley region of Georgia and Alabama and the Uwharrie Mountains of North Carolina (Landers et al. 1995, Davis 1996, Van Lear 2005, Patterson and Knapp 2016). Extensive anthropological disturbance, including logging, poor fire–management regimes, clear–cutting and domestic livestock overgrazing reduced the longleaf pine range to less than 4% of its previous habitat (Brockway and Outcalt, 1998, Jose et al. 2006).

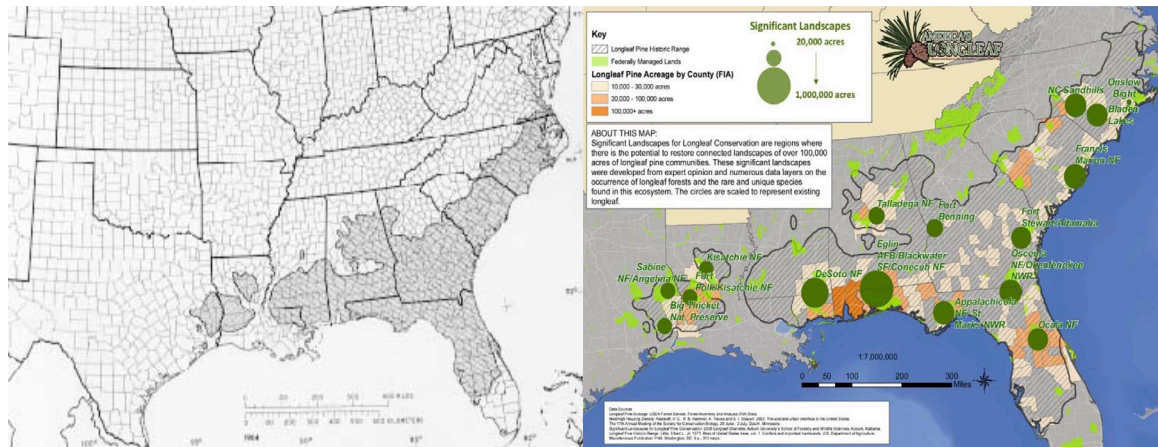


Figure 1. Historical Range (L) and Current Range (R) of the Longleaf Pine Ecosystem Including Areas where Restoration Activities are Occurring (Little 1971 and Scott et al. 1977).

Ecological Importance of Longleaf Pine

Longleaf pine is a keystone species currently providing habitat for over a 100 endangered species including the red cockaded woodpecker (*Leuconotopicus borealis*), the gopher tortoise (*Gopherus polyphemus*), the eastern indigo snake (*Drymarchon couperi*), fox squirrel (*Sciurus niger*), Bachman’s sparrow (*Aimophila aestivalis*), brown-headed nuthatch (*Sitta pusilla*), eastern diamondback rattlesnake (*Crotalus adamanteus*), and flatwoods salamander (*Ambystoma cingulatum*) (Kantola and Humphrey 1990, Engstrom 1993, Guyer and Bailey 1993, Crofton 2001, Brockway and Lewis 2003, Kirkman, et al. 2004). Pre-colonial longleaf pine savannas provided habitat for over 640 species endemic to longleaf pine-dominated ecosystems (Walker 1998).

Dendroclimatological Importance of the Longleaf Pine

Longleaf pine characteristics include high sensitivity to summer precipitation (Ginter et al. 1979, Ramsey et al. 2003, Henderson and Grissino-Mayer 2009, Knapp et

al. 2016) and great longevity (e.g., > 500 years, Brockway et al. 2005), which makes it an excellent species for dendroclimatic studies. Despite a significant reduction in geographic extent, several stands of old-growth longleaf exist (Frost 1993, Landers et al 1995, Brockway et al. 1998, Drew et al. 1998) with some trees exceeding > 400 years age. Old trees coupled with rainfall sensitivity provide an opportunity to establish an accurate precipitation dating to the time of Colonial America. Additionally, dendrochronologists have been able to extend longleaf pine chronologies by crossdating beams from pre-civil war historic buildings (Grissino-Mayer and van de Gevel, 2007), 19th-century crib dams (van de Gevel et al. 2009), 16th-century canoes (Pickard et al. 2010) and slabs obtained from remnant (i.e., > 100 years old) longleaf pine stumps (McBride 1983).

Background on Shortleaf Pine

Shortleaf pine has the widest geographic range of any pine species in the southeastern United States (Lawson 1990). The current range covers approximately 114 million ha, across 22 states in the eastern U.S. (Figure 2). The current range is partially due to the economic value of the shortleaf pine as it is cultivated in part for a wide variety of commercial products including lumber, plywood and pulpwood.



Figure 2. Current Range of Shortleaf Pine (Source: Little 1971).

Ecological Importance of Shortleaf Pine

Because the current habitat ranges of the shortleaf pine and the historical range of longleaf pine overlap, many species have developed adaptations to live within the mixture of the two–pine species. Shortleaf pine seeds provide an alternate source of food for many of the birds and small animals (Hall 1977) and shortleaf pine boles provide a secondary refuge to the red cockaded woodpecker, though the red cockaded woodpecker needs a mature tree specimen that suffers from heart rot (Scott et al. 1977). Like the longleaf pine, shortleaf pines are also resistant to surface fires (Guyette and Dey 1993). The pine needles dropped contribute to low–intensity (i.e., “cool”) fires that help clear the local area of invasive species yet cause minimal damage to the tree bole and cambium (Sparks et al. 2002).

Dendroclimatological Importance of the Shortleaf Pine

Longleaf pine and shortleaf pine are genetically similar (Burns et al. 1990), thus shortleaf pine has similar responses to climatic responses as the longleaf pine and cross applications in dendrochronology exist (Schweingruber 1988). Studies of shortleaf pine have contributed to the dating of historic buildings (Stahle 1979, Wight 2004), fire chronologies (Guyette and Dey 1997) climate reconstructions that analyzed the climate/growth relationship (Schulman 1942, Estes 1970, Grissino-Mayer and Butler 1993) and response to anthropogenic disturbance (Watkins et al. 2018). Across all the studies cited, shortleaf pine was an excellent species regarding climate sensitivity. When examining master databases between shortleaf pine tree stands—some more than 500 km away—the climate signal persisted throughout both chronologies. Additionally, shortleaf pines that were growing in xeric (dry) habitats were more climatically responsive than samples taken from mesic (wet) habitats.

Background on Post Oak

The native range of the post oak occurs throughout the eastern two-thirds of the continental United States except for the New England states of Vermont, New Hampshire, and Maine and the North Central states of Wisconsin, Minnesota, North Dakota and South Dakota (Little 1971 (Figure 3)). The post oak has a variety of commercial applications due to its resistance to decay. Commercially classified as white oak, this tree is used for railroad ties, lathing, siding, planks, construction timbers, mine timbers, trim molding, stair risers and treads, flooring, fence posts, pulp, veneer, and

particle board (Guyette and Dey 1997). White oak bark also provides tannin, decorative and protective mulch for landscaping, and fuel (Guyette and Dey 1997).

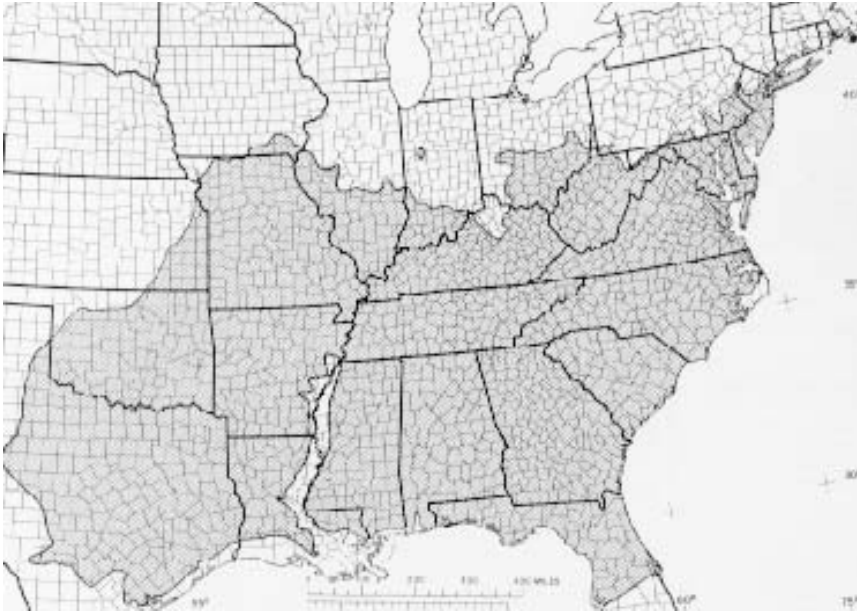


Figure 3. Native Range of Post Oak (Little 1971).

Ecological Importance of the Post Oak

Post oak is an integral contributor to wildlife stability in the southeastern United States. Post oak acorns provide an important food source for wild turkey, white-tailed deer, and squirrel as well as more than 100 other vertebrate species (Hall 1977). During the late fall and early winter more than 75 percent of a white-tailed deer diet is composed of acorns dropped by oak trees. The acorns dropped by the post oak have short hibernation periods and as a result are the main food source for local wildlife until late winter and early spring. The leaves provide nesting material for birds, squirrels and

raccoons and cavities within the tree provide nesting locations for a wider variety of other birds and animals (Martin 1951).

Dendroclimatological Importance of the Post Oak

Like longleaf pine and shortleaf pine, the climate sensitivity and non-commercial viability of post oak makes it an ideal dendrochronological species. (Rossen 1994, Therrell and Stahle 1998, and DeSantis 2010) The annual dormancy of the tree creates distinct annual markers, which results in this species lack of false rings occurrences and high correlation. These markers are absent in longleaf pine and shortleaf pine due to the year-round nature of their growth. Yearly growth of the post oak is measured from the outer bark growth to the boundary between large and small xylem conduits. Large xylem conduits indicate the beginning of growth as well as sufficient water availability. As the year progresses the xylem conduits shrink in diameter until there is a year boundary indicating hibernation for the winter (Sperry 1994). The geographical distribution of the post oak (*Quercus stellata* Ashe) makes it an excellent tool for creating expansive chronologies of a specific region or a large multi-state area (Stahle and Hehr 1984, Shumway et al. 2001, and White et al. 2011). Use of post oak chronologies have helped create timelines for prescribed burns (Guyette, R.P and Cutter 1991, DeSantis et al. 2010) and to date historical buildings such as Reynolds Homestead Research Center (Mann 2002). Post oak is a ring-porous species with larger pores forming in the early portion of the growing season (earlywood) and smaller pores during the latter portion of the growing season (latewood) creating a pattern that results in few observed missing or false rings (Sperry et al. 1994).

Research Objectives

The goal of this research is to determine the dendroclimatic benefit of using of multiple, co-occurring tree species collected from a single site. Specifically, I determine the climatic sensitivity of each species during the warm season (May–October) by examining latewood ring–width variability correlations with climate data. I also determine if combining tree–ring data from multiple species produces a stronger climate/growth signal than individual species chronologies, thereby improving the climatic reconstructions. By taking samples from three chosen tree species I seek to answer the following hypothesis:

- H₁ There is no difference in climatic sensitivity between co-occurring multiple species.
- H₂ There is no improvement in climate sensitivity using multiple species.
- H₃ Climatic sensitivity among the three species remains temporally consistent during the study period.

CHAPTER II
MANUSCRIPT

Introduction

Dendrochronological studies have traditionally centered on the analysis of one tree species from either one location (e.g., Guyette and Dey 1997, Rubino and McCarthy 2000, Stambaugh and Guyette 2004, Harley et al. 2011, Knapp et al. 2016) or from multiple locations (Salzer and Hughes 2006, Salzer et al. 2009, Knapp et al. 2014). Recently, several studies (e.g., Maxwell et al. 2011, Maxwell et al. 2014, LeBlanc and Stahle 2015, Maxwell and Harley 2017) have attempted to improve climate/radial growth relationships by using multiple–species chronologies comprised of hardwoods and softwoods (Estes 1970, García–Suárez et al. 2001, Fraver and White 2005). This study examines the benefit of using multiple species from a geographically limited location to determine the utility of using multiple co-occurring species in climatic reconstructions.

Hardwood trees are angiosperm broad–leaved trees with most midlatitude species being deciduous. Softwoods are gymnosperms with most species being evergreen, coniferous trees. In many midlatitude locations, hardwoods and softwoods co–occur, thus providing a potential opportunity to develop a statistically relevant mixed species chronology with a strong climate/growth signature. Several of these studies (García–Suárez et al. 2001, Fraver and White 2005) examined the mechanisms by which both angiosperm and gymnosperm trees react to the precipitation changes throughout the year.

While the mechanisms that spur growth differ between angiosperms and gymnosperms, García-Suárez et al. (2001) showed that both tree groups show detectable reactions to anthropogenic climate change.

Here I examine the correlation between different climactic variables with multiple species of trees sampled from an 83.8 ha old-growth stand of mixed coniferous/hardwood forest in the Uwharrie Mountain foothills known as the Nichols Tract. Two softwood species— longleaf pine (*Pinus palustris* Mill.) and shortleaf pine (*Pinus echinata* Mill.) were dendrochronologically sampled along with one hardwood species, post oak (*Quercus stellata* Ashe). Each of the three species has been used extensively in dendrochronological studies, yet to my knowledge not as a combined dataset.

Analysis of population growth and decline is fundamental to the study of an ecology. (Cole 1954, and Slobodkin 1964) The longleaf pine and shortleaf pine are important resources in the southeastern United States and could be impacted by increasing changes to the global climate. (Iverson et al. 1999 and Bhuta et al. 2009) To understand the changing response of the trees that form the base of the ecology in the Nichols Tract, this study will examine change in the climate/growth relationship over time. Identifying the change in the climate/growth relationship over time can help identify changes in the local environment that can impact the ecology of the area. (Francis et al. 1998)

Given the potential value of working with multiple species to develop a better climate/radial growth response helpful for climatic reconstructions, in this research I

evaluate the viability of using these three species to determine: 1) which species has the best climatic sensitivity; 2) if climatic sensitivity increases when individual chronologies are combined; and, 3) if this climatic sensitivity is temporally variable over the study period of 1935–2017.

Methodology

Site Selection

Tree-ring data were collected from the Nichols Tract, (35.458126, -79.870586) in central North Carolina 11.91 km north of Troy (Figure 4). The Nichols Tract is .838 km² located in the Piedmont Province (Figure 5). Elevation of the site ranges between 175 m to 200 m. The site was selected based on the presence of native old-growth post oak, longleaf pine and shortleaf pine trees. The soil composition of the site is a mixture of Georgia silt loams (51.9%), Herndon silt loams (45.2%) and Biscoe-Secret complex (2.9%) (Soil Survey Staff 2018). The site is currently maintained by the North Carolina Zoo and has been undergone prescribed burns for the last 10 years. Prior to the North Carolina Zoo's conservatorship, the Nichols Tract was the homestead of the Nichols family, who maintained a farm on the land prior to the transfer of ownership to the North Carolina Zoo.

A minimum of fifteen trees for each species were selected based on older-age characteristics with two samples from each tree collected. These samples were combined with previous samples collected from this site. Collection indicates that tree age is species specific, with shortleaf pine trees not exceeding 100 years due to selective logging. Due to this selective logging the shortleaf pine trees were sampled indiscriminately.

Conversely, approximately one-third (36%) of the post oak and longleaf pine individuals exceed 130 years. Samples were selected from between twenty to thirty visibly healthy trees. Trees that exhibited turpentine scars, visible rot or fire damage above sampling height were avoided. For each tree, basal diameter (cm) was taken at chest height using a DBH tape. Tree height (m) was measured with a laser range finder. Each tree's location was recorded using a handheld Global Positioning System. Two samples were taken from each tree where possible from the opposite sides. Cores were extracted using a 5.15-mm diameter Haglof increment borer (Figure 6). For results to be considered "significant" for this study the p -value for a correlation between growth/climate must have been less than 0.05.



Aerial Photo 1950

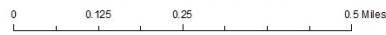


Figure 4. Nichols Tract (outlined in red) 1950. Source: North Carolina Zoo Collection.



Figure 5. Geographical Location of the Nichols Tract Forest.



Figure 6. Haglof Increment Borer Used to Collect Core Samples.

Processing

All samples were dried a minimum of 24 hours before mounted into wooden bases and sanded with progressively finer grit from 100 μm to 1000 μm sandpaper until cell structure became visible to assist with accurate measurements. Once samples were sanded, they were crossdated using the list method (Yamaguchi 1990) and compared with a local established chronology of the same species.

Following initial crossdating, the samples were scanned into WINDENDRO™, a program used to analyze annual tree-ring width, at a minimum resolution of 1,800 dpi (EPSON, Expression 10000XL) and digitally crossdated. Measurements of latewood obtained from WINDENDRO™ were then processed through the program COFECHA (Holmes 1983, Grissino-Mayer 2001) to verify crossdating accuracy. When COFECHA flagged cores indicating a potential crossdating errors, those samples were manually checked and adjusted as appropriate. COFECHA produces an interseries correlation

value that represents the extent of crossdating agreement between samples (i.e., cores), with higher values indicating higher agreement and a minimum acceptable interseries correlation of 0.50 (Schweingruber 1988). Each of the chronologies exceeded the minimum threshold and were individually standardized with ARSTAN before combined datasets were created for a total of seven raw ring-width chronologies (Table 1).

Table 1. Common Names, Binomial Abbreviation and Chronologies Used for Analysis.

| Common name | Chronology name | Groupings |
|-----------------------------------|--------------------|-----------|
| Longleaf pine | PIPA | PIPA |
| Shortleaf pine | PIEC | PIEC |
| Post oak | QUST | QUST |
| Longleaf and shortleaf | PIPA x PIEC | PINES |
| Longleaf and post oak | PIPA x QUST | PIPA_QUST |
| Shortleaf and post oak | PIEC x QUST | PIEC_QUST |
| Longleaf, shortleaf, and post oak | PIPA x PIEC x QUST | COMBO |

Standardizing and Statistical Analysis

In comparison to totalwood and earlywood, latewood (ring growth that is principally formed during June–August) is more sensitive to changes in seasonal climate and is increasingly utilized in dendroclimatic studies (Meko and Baisan 2001). Coile (1936), Devall et al. (1991), and Henderson and Grissino-Mayer (2009) found latewood to exhibit greater climate sensitivity. This analysis was used at the Nichols Tract, preliminary results, and later results confirmed that latewood crossdated better than earlywood or total wood. Thus, my analysis was based on latewood growth/climate responses during the warm season months, May–October. These months were chosen to

evaluate the impact on correlations between the growth/climate signal while using multiple co-occurring tree species outside the standard analysis timeframe.

To determine the most climate-sensitive chronologies, I examined three standardized versions of each chronologies, produced by ARSTAN, (STD, RES and ARS) as produced by five detrending options (Friedman's Super Smoother, Negative Exponential, Cubic Spline 33%, Cubic Spline 50% and Cubic Spline 66%). Each detrending option use slightly difference weighting procedures to produce a chronology that best reflects the local environmental characteristics such as tree density and disturbance frequency. Each of the three latewood chronologies generated by the five standardizing methods (n= 15) were then correlated (Pearson's r) against monthly PDSI, PHDI, and Palmer "Z" indices, monthly precipitation, and monthly minimum temperature and maximum temperature data from North Carolina Divisions 4 and 5 (NCDC 2018) as the Nichols Tract is located in climate division 5, but near climate division 4. The resulting three latewood chronologies (PIPA, PIEC, and QUST) used for further analysis were from the STD output generated using Cubic Spline 50%, detrending using PDSI data as the climate variable. This combination produced the strongest preliminary climactic correlations. Since PDSI is an index that measures the relative moisture content of the soil (Palmer 1965, Alley 1984) this study uses the PDSI index as a climate proxy.

Standardized values of each species chronology were also combined (Table 1) to determine if merged chronologies exhibited greater climate sensitivity than single chronologies. For this study I found stronger correlations using an average of

standardized values as established by Patterson (2011) and thus, analysis of climate/growth responses for the combined chronology followed this methodology, as opposed to than merging the raw data. I also evaluated the subsample single strength for each chronology, a measure of when sample size is sufficient to analyze (Wigley et al. 1984) for the three species. While both post oak and longleaf pine had longer periods of significant sample depth dating to the 1800s, most shortleaf pine trees did not exceed 100 years due to selective logging. The EPS values indicated sufficient correlations between climate and growth starting in the mid 1930's, thus, all analyses were based on the period 1935–2017.

Seven chronologies (Table 1) were evaluated to establish how the relationship between ring-width growth and PDSI has evolved through time, the standardized data were correlated in R, using the TreeCLIM package to create a 30-year moving window selecting the previous January through December PDSI data along with the current-year PDSI data. The 30-year window was selected to meet the minimum statistical threshold of $n = 30$ and was a compromise between creating a window that resulted in meaningful correlations and the ability to have a sufficient number of windows to illustrate any change detectable (Lloyd and Bunn 2007).

Results

Descriptive Statistics of Individual Species

Longleaf PINE (PIPA)

Latewood PIPA correlations with PDSI (Table 2) were significant ($p < 0.05$) for this site during August (0.270), September (0.245) and October (0.220) with p -values of

0.013, 0.026 and 0.045 respectively. The PIPA correlations measured by this paper paralleled other analysis done at this site (Patterson et al. 2016) and support notion that latewood growth is dependent on late–summer PDSI.

Table 2. Pearson Correlations and p-values of Single Species Climatic Response for PDSI.

| Trees | Analysis | MAY | JUN | JUL | AUG | SEP | OCT |
|-------|---------------------|---------|---------|---------|---------|--------|--------|
| PIPA | Pearson Correlation | 0.168 | 0.027 | 0.209 | *0.270 | *0.245 | *0.220 |
| | Sig. (2-tailed) | 0.129 | 0.809 | 0.058 | 0.013 | 0.026 | 0.045 |
| PIEC | Pearson Correlation | 0.174 | 0.071 | 0.197 | *0.273 | *0.261 | *0.260 |
| | Sig. (2-tailed) | 0.115 | 0.525 | 0.075 | 0.013 | 0.017 | 0.018 |
| QUST | Pearson Correlation | **0.369 | **0.539 | **0.512 | **0.436 | *0.275 | 0.118 |
| | Sig. (2-tailed) | 0.001 | 0 | 0 | 0 | 0.012 | 0.286 |

* Indicates confidence levels of $\leq 1\%$

** Indicates confidence levels of $\leq 1\%$

This chronology also supports the results of Henderson and Mayer (2009) in that both studies have similar interseries correlations, average mean sensitivity, and high correlations between longleaf pine growth and PDSI from same year spring and summer.

Shortleaf Pine (PIEC)

Shortleaf pine correlations (Table 2) were significant during August (0.273), September (0.261) and October (0.260) with p -values of 0.013, 0.017 and 0.018 respectively. The PIEC correlations measured by this paper reflect that latewood growth is dependent on summer PDSI similar to PIPA. Given the similarity of these two species, this result is expected. The results from this study are not consistent with the findings of

Grissino–Mayer and Butler (1993) who examined shortleaf pine climate reconstructions. Grissino–Mayer and Butler (1993) showed the strongest climate/growth correlations starting in May and ending in July. This study indicates that the climate/growth relationship is starting later, according to this study as late as August and extending into October.

Post Oak (QUST)

Latewood QUST correlations (Table 2) were statistically significant for this site during the warm months of May (0.369), June (0.539), July (0.512), August (0.436), and September (0.275) with p -values of 0.001, <0.001, <0.001, <0.001, and 0.012 respectively. The results of the individual species chronology QUST, supports the results by White et al. (2011). Preliminary analysis of this species for this project revealed a high interseries correlation ($r > 0.6$) on first dating indicating the sample trees all reflected the same environmental stresses. (Speer et al 2002, White et al. 2011) This formed the initial comparison database by which all other species were cross-referenced for dating accuracy.

Descriptive Statistics of Combined Species

The combined groupings, except for the PINES chronology, showed significant correlations during the months of May through October for the datasets evaluating PIPA with QUST and the three-species dataset (Table 3).

Table 3. Pearson Correlations of Combined Species Climatic Response PDSI.

| Trees | Analysis | MAY | JUN | JUL | AUG | SEP | OCT |
|-----------|---------------------|---------|--------|---------|---------|---------|--------|
| PINES | Pearson Correlation | 0.18 | 0.051 | 0.214 | **0.286 | *0.267 | *0.253 |
| | Sig. (2-tailed) | 0.103 | 0.646 | 0.052 | 0.009 | 0.015 | 0.021 |
| PIPA_QUST | Pearson Correlation | *0.277 | 0.199 | **0.362 | **0.396 | **0.320 | .246* |
| | Sig. (2-tailed) | 0.011 | 0.071 | 0.001 | 0 | 0.003 | 0.025 |
| PIEC_QUST | Pearson Correlation | **0.284 | *0.244 | **0.352 | **0.398 | **0.334 | .281* |
| | Sig. (2-tailed) | 0.009 | 0.026 | 0.001 | 0 | 0.002 | 0.01 |
| COMBO | Pearson Correlation | *0.243 | 0.147 | **0.302 | **0.359 | **0.311 | .269* |
| | Sig. (2-tailed) | 0.027 | 0.185 | 0.006 | 0.001 | 0.004 | 0.014 |

* Indicates confidence levels of $\leq 1\%$

** Indicates confidence levels of $\leq 1\%$

The PINES chronology achieved significance during the months of August (0.286), September (0.267) and October (0.253). with only October having a higher correlation value than the QUST chronology (Tables 3 and 4). The PIEC with QUST chronology achieved significance for the months of May through October 0.284, 0.244, 0.352, 0.398, 0.334, 0.281 respectively. Though only the months of May and October showed an increase in sensitivity above what could already be established by the QUST chronology alone (Table 3 and 4).

Longleaf Pine and Shortleaf Pine

The ability to for PIPA and PIEC to hybridize (Cotton et al. 1975) makes this combination intuitive. Richter et al. (1991) found that for pine species found in close proximity of each other can be treated as a single species. Throughout the year, the correlations for these species (Table 3) maintained a difference that no greater than .04, in

most months the correlations were the same value. When this study compared p -values of the PINES chronology to the p -values of the PIPA and PIEC chronologies the months where significant correlations were found, the p -values achieved in the combined chronology were smaller. This indicates a stronger dataset and a reduced chance that the correlations were spurious. The PINES chronology also performed better than either of the individual species (PIPA and PIEC) performed independently. Like Maxell et al. (2011) who found better correlations with similar species groupings, the combined groupings in this study found marginally higher correlation values with the combined PINES chronology as compared to the individual chronologies. The correlations in the PIPA or PIEC chronologies achieved significance starting in August, September and October, similar to the PINES chronology, but correlations were higher, and p -values were lower in the PINES chronology, indicating a better climate/growth signal.

Longleaf Pine and Post Oak

One of the combinations examined was PIPA and QUST (Table 3). The combined datasets (PIPA_QUIST) were analyzed and compared against the individual dataset correlations. For most of the year correlation values dropped; the exception being October (0.246). The correlations for the month of June dropped below the level considered to be significant. In contrast to the combined correlations for the year, the months of September and October show higher correlations than either the PIPA or the QUIST independently. This increased correlation occurs only during these two months and can help to extend the growth–climate relationship later into the year where it was not possible prior to grouping.

Table 4. Correlations and *p*-values.

| Tree | Correlations | | p-values | |
|-----------------|----------------|---------------|--------------|-------------|
| | SEP | OCT | SEP | OCT |
| PIPA | 0.245* | 0.220* | 0.026 | 0.045 |
| PIEC | 0.261* | 0.260* | 0.017 | 0.018 |
| SPO | 0.275* | 0.118 | 0.012 | 0.286 |
| PINES | 0.267* | 0.253* | 0.015 | 0.021 |
| PIPA_SPO | 0.320** | 0.246* | 0.003 | 0.025 |
| PIEC_SPO | 0.334** | 0.281* | 0.002 | 0.01 |
| COMBINED | 0.311** | 0.269* | 0.004 | 0.014 |

* Indicates confidence levels of $\leq 1\%$

** Indicates confidence levels of $\leq 1\%$

Evaluating *p*-values for the combined dataset against the *p*-values for the independent species, the confidence only improves for the months of September and October (Table 4). The combined *p*-values for September was 0.003, compared to a PIPA *p*-value of 0.026 and a QUST *p*-value of 0.012. October *p*-values offer better confidence in climate-growth correlations, as the QUST had a *p*-value of 0.286, outside the point at which correlations are considered significant. The PIPA *p*-value for October was 0.220 and is significant. When the combined dataset is evaluated the *p*-value for October is 0.025 which shows that combining PIPA and QUST can not only help evaluate PDSI related growth during these months but also to increase the confidence level in those results.

Shortleaf Pine and Post Oak

When the combination of PIEC with QUST was analyzed (Table 3) a similar trend was found as the combination of PIPA and QUST. The only relevant months that

showed an increase in correlations and confidence were September and October (Table 4). Correlation measurements for PIEC for September and October were 0.261 and 0.260 respectively. The QUST correlations for September and October were 0.275 and 0.118. Combined correlations for September and October were 0.334 and 0.281.

P-values for these months (Table 4) also reflect a higher confidence level when compared against individual species *p*-values. Comparing the PIEC *p*-values of 0.017 and 0.018 for September and October and the QUST *p*-values of .012 and .0286 against the combined dataset showed *p*-values for September and October of 0.002 and 0.01. This indicates a higher confidence for the later months correlations between growth and PDSI.

Longleaf Pine, Shortleaf Pine and Post Oak

When the combination of PIPA, PIEC and QUST were analyzed (Table 3), a similar trend was found as the two previous combinations of PIPA and QUST, PIEC, and QUST. The only relevant months that showed an increase in correlations and confidence were September and October (Table 4). Correlations measurements for the combined dataset for September and October were 0.311 and 0.269, compared with the PIPA chronology correlations of September and October of 0.245 and 0.220, the PIEC chronology correlations 0.261 and 0.260 and the QUST chronology correlations of 0.275 and 0.118. This is in keeping with García-Suárez et al. (2009) who found that when comparing combined chronologies there was an overall reduction in correlation with PDSI for the months August–November as compared with the single species chronology, the only notable exceptions being September and October. The correlations in this study

are similar to the correlations found in that study until the early 1990s, however, the study window for García–Suárez ended in 1992, this study shows a reduction in the climate/growth relationship after this time period.

P–values for these months also reflect a higher confidence level when compared against individual species *p*–values (Table 4). Comparing September and October PIPA chronology *p*–values of 0.025 and 0.045, PIEC chronology *p*–values of 0.017 and 0.018 and QUST chronology *p*–values of .012 and .0286 against the COMBO chronology showed *p*–values for September and October of 0.004 and 0.014. This supports the indication that a higher confidence for the later month’s correlations between growth and PDSI is observed.

Descriptive Statistics of Temporally Consistency Analysis

To examine the changing nature of each species sensitivity to climate trends over time, each species chronology was run through a thirty–year moving window using the statistical package TreeCLIM within R. Starting at 1935, the starting year for this study, correlations were analyzed in thirty–year segments moving forward each year until 2017, the last year of the study. The correlation values were illustrated in a chromatic moving window that allows for visual interpretation of the change over time. Correlations that meet the minimal confidence level ($p < 0.05$) are notated with an asterisk.

Longleaf Pine

The analysis of the PIPA series in the 30–year moving (Figure 7) window shows correlations between PDSI and latewood growth. Growth and Climate correlations from

the first window, 1935–1965, show different responsiveness to seasonal growth as compared to the last window, 1988–2017 (Table 5).

Table 5. Net Change of Climate/Growth Relationship Over Time: Positive, No Change or Negative.

| | PIPA |
|-----------|----------|
| May | Positive |
| June | NC |
| July | NC |
| August | NC |
| September | Negative |
| October | Negative |

Though most months showed no significant changes over the span of the analysis, only September and October had values that were significant at the early period and lost that significance by the late period. September and October correlations with PDSI started positive and ended lower, resulting in an overall negative trend. There is an observable trend, starting in the 1960's, that shows correlations increasing over time, these correlations do not reach the level needed to be considered significant, and the trend of stronger correlations fades over the second half of the timespan.

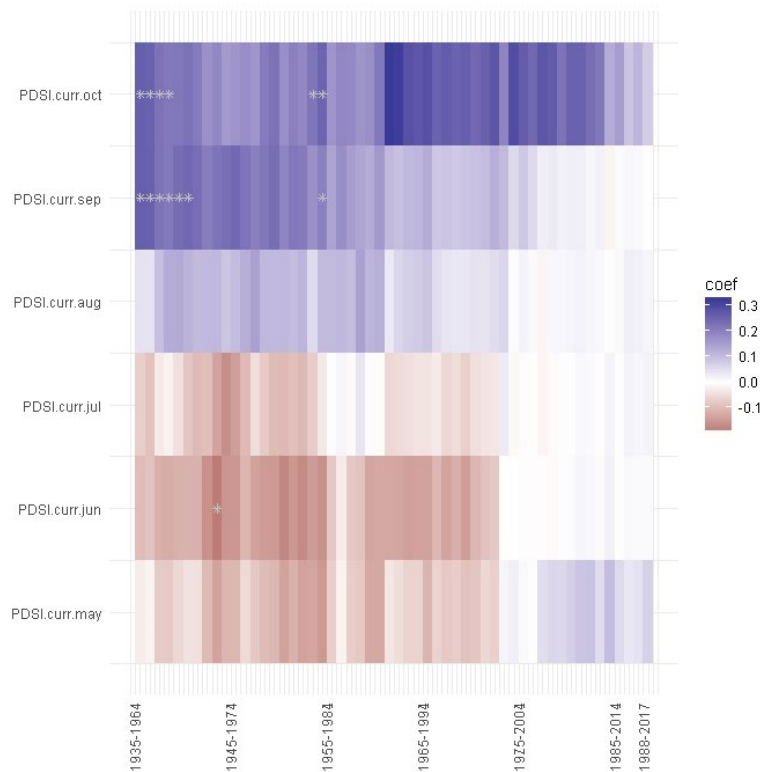


Figure 7. 30-year Running Window for the Longleaf Pine. The initial period is 1935–1964 and the last period is 1988–2017 (n=53). “PDSI-curr.” indicates current year PDSI values of the month mentioned.

This indicates that the growth climate relationship is malleable and becoming weaker over the length of this study for this species, this supports the García–Suárez et al. (2009) study which took place in Ireland. Like that study these changes reflect possible changes in sample size variations, changing climate patterns, or changing CO₂ levels, though further studies will be needed to confirm the impacts of these factors. This analysis only examined current year PDSI impacts.

Shortleaf Pine

Correlations across time (Figure 8) for the PIEC were stronger than the PIPA. The analysis of the PIEC series in the 30-year moving window show a series wide positive correlation between PDSI and latewood growth during the months of September, and October when correlated with PDSI. Though most months showed changes over the span of the analysis, only September and October had values that were significant at the early periods (1935-1964) and lost that significance by the late periods (1988-2017). (Table 6) September and October correlations started positive and ended lower, resulting in a net negative trend.

Table 6. Net Change of Climate/Growth Relationship Over Time: Positive, No Change or Negative.

| | SLP |
|-----------|----------|
| May | NC |
| June | NC |
| July | NC |
| August | NC |
| September | Negative |
| October | Negative |

Like the PIPA this indicates that the climate/growth relationship is weakening. This also supports the García-Suárez et al. (2009) study who found similar results in scots pine (*Pinus sylvestris*).

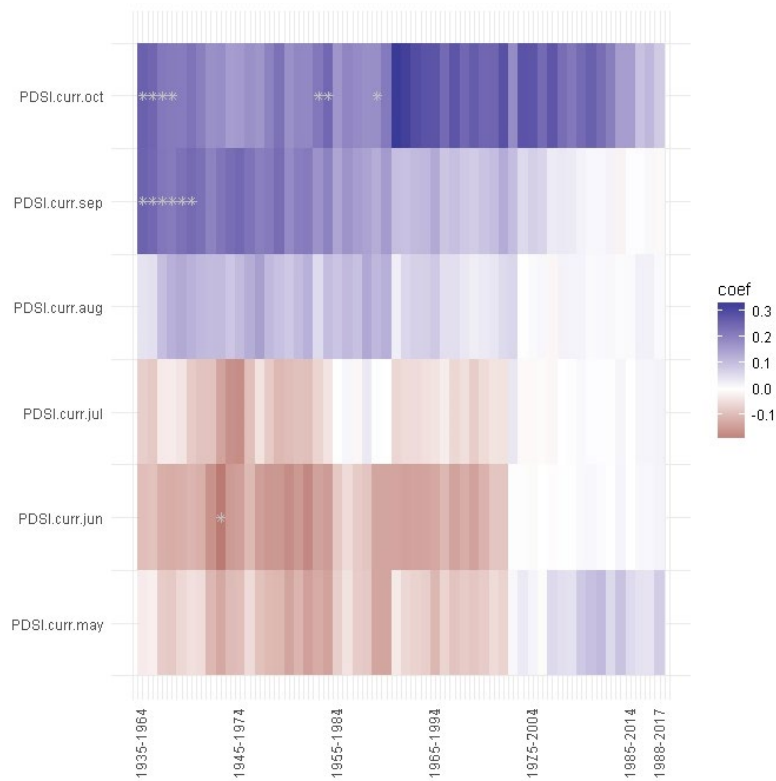


Figure 8. 30-year Running Window for the Shortleaf Pine. The initial period is 1935–1964 and the last period is 1988–2017 (n=53).

Post Oak

In contrast to the PIPA and PIEC chronologies, the QUST chronology showed time-related correlations with significance throughout many of the 30-year windows (Figure 9). Correlations for QUST were the highest among the single species analyzed. Significance occurred for this series during May, June, July and September. Though most months showed changes over the span of the analysis July, September and October had values that were significant at the early time period and lost that significance by the late time period (Table 7). July QUST correlations started positive and ended lower, resulting

in an overall negative trend. September and October in contrast started out with significant negative correlations and lost that significance, resulting in a positive trend. August had early correlations that lacked significance that became significant in the later period. The QUST chronology indicates that the post oak is the most sensitive to the climate/growth relationship as established by the PDSI values in this study. From early to late this study found that August has gained sensitivity in the later period and September and October lost sensitivity, indicating a longer growing season for the QUST. This contrasts with what Rubino and McCarthy (2000) found. This could be due to either the selection of 30 years for analysis of the moving window, or due to correlations for this species occurring in the timeframe after the Rubino and McCarthy (2000) study.

Table 7. Net Change of Climate/Growth Relationship Over Time: Positive, No Change or Negative.

| | SPO |
|-----------|----------|
| May | NC |
| June | NC |
| July | Negative |
| August | NC |
| September | Positive |
| October | Positive |

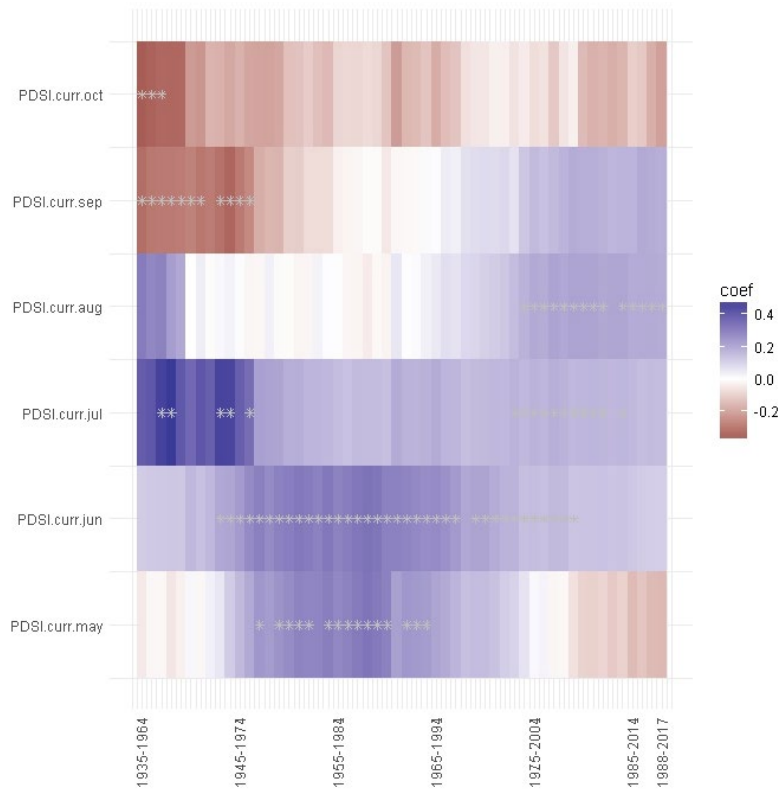


Figure 9. 30-year Running Window for the Post Oak Series. The initial period is 1935–1964 and the last period is 1988–2017 (n=53).

Longleaf Pine and Shortleaf Pine

Correlations for the PIPA and PIEC combined datasets (Figure 10) were the better than either of the single species analyzed independently. Significance occurred for this series during July and August. Early time frames for August had no significance and later gained significance resulting in a net positive trend in correlations for the month of August. (Table 8) The PINES chronology reflected a similar trend as is found in the QUST chronology in that sensitivity is gained in August when multiple species are

combined, which supports the conclusion that adding multiple species can increase the sensitivity in establishing a climate/growth relationship.

Table 8. Net Change of Climate/Growth Relationship Over Time: Positive, No Change or Negative.

| | PINES |
|-----------|-------|
| May | NC |
| June | NC |
| July | NC |
| August | NC |
| September | NC |
| October | NC |

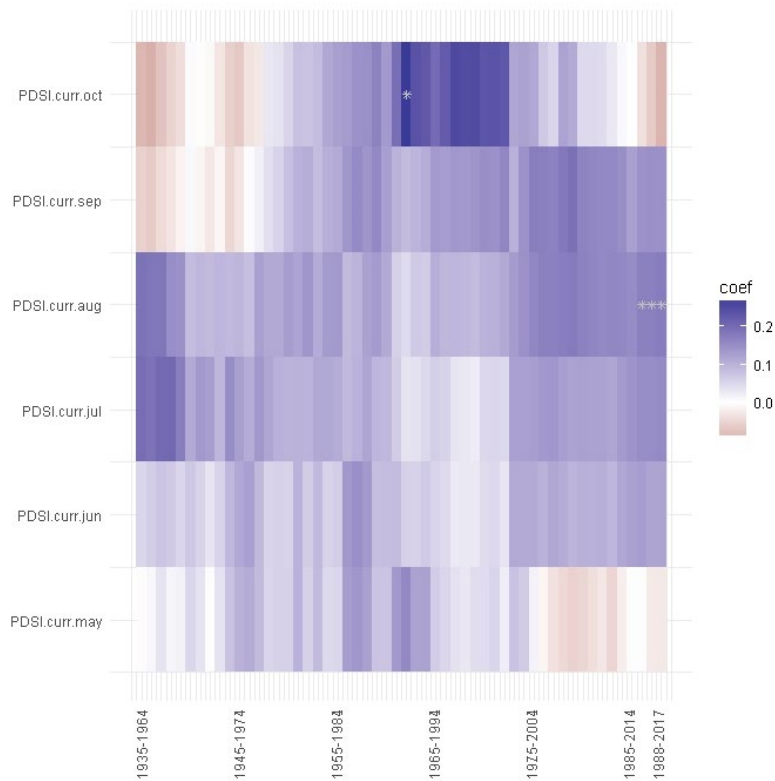


Figure 10. 30-year Running Window for the PINES Series. The initial period is 1935–1964 and the last period is 1988–2017 (n=53).

As stated in the García–Suárez et al. (2009) this could be due to several factors, though due to the similarities between the two species in this study the most likely reason in this study is larger sample size.

Longleaf Pine and Post Oak

Correlations for the PIPA and QUST combined datasets had lower correlations than the individually analyzed QUST for most of the year. Significance never occurred for this series. Since this chronology lacked correlations in the early time frame as well as in the late period all net changes over time were not significant (Table 9, Figure 11).

Table 9. Net Change of Climate/Growth Relationship Over Time: Positive, No Change or Negative.

| | LLP | SPO |
|-----------|-----|-----|
| May | | NC |
| June | | NC |
| July | | NC |
| August | | NC |
| September | | NC |
| October | | NC |

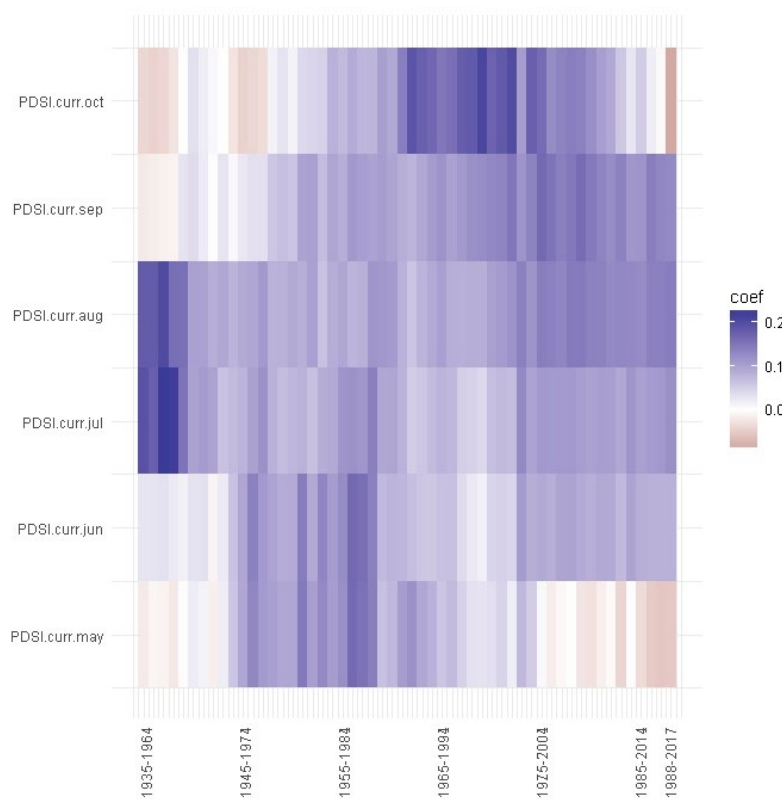


Figure 11. 30-year Running Window for the Longleaf Pine and Post Oak Series. The initial period is 1935–1964 and the last period is 1988–2017 (n=53).

Shortleaf Pine and Post Oak

Correlations for the PIEC and QUST combined datasets (Figure 12) had higher correlations than the PIPA and QUST for most of the year. PDSI showed growth and climate correlations with significance occurring for this series during August and October. Early timeframes for August had no significance and later gained significance. Thus, this chronology showed a net positive trend in correlations for the month of August. (Table 10) The PIEC_QUIST chronology and the PINES chronology reflect similar changes in sensitivity across the timespan of this study; these changes are not found in the PIPA_QUIST chronology. This indicates that the increase in sensitivity found in combining chronologies is due to the addition of the PIEC species.

Table 10. Net Change of Climate/Growth Relationship Over Time: Positive, No Change or Negative.

| | 4SLP | SPO |
|-----------|------|----------|
| May | | NC |
| June | | NC |
| July | | NC |
| August | | Positive |
| September | | NC |
| October | | NC |

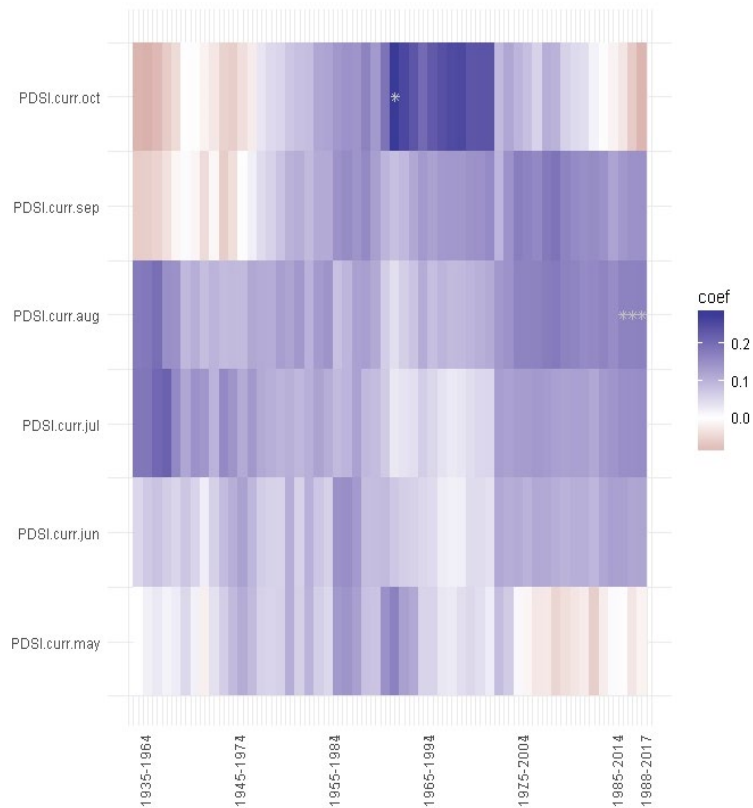


Figure 12. 30-year Running Window for the Shortleaf Pine and Post Oak Series. The initial period is 1935–1964 and the last period is 1988–2017 (n=53).

Longleaf Pine, Shortleaf Pine and Post Oak

The analysis of the COMBO series in the thirty-year moving window shows correlations between latewood growth and PDSI (Figure 12). However, the only correlations showing significance were September and October. The correlations for the COMBO chronology were smaller than correlations produced by the PIEC_QUEST chronology. Growth and climate correlations from the first window, 1935–1965, show different responsiveness to seasonal growth as compared to the last window, 1988–2017. Early timeframes for September and October had correlations with significance and later

lost that significance. Thus, this chronology showed a net negative trend in correlations for the months of September and October. (Table 11) This indicates that the COMBO chronology reflects overall losses in sensitivity in the climate/growth relationship.

Table 11. Net Change of Climate/Growth Relationship Over Time: Positive, No Change or Negative.

| | COMBO |
|-----------|----------|
| May | NC |
| June | NC |
| July | NC |
| August | NC |
| September | Negative |
| October | Negative |

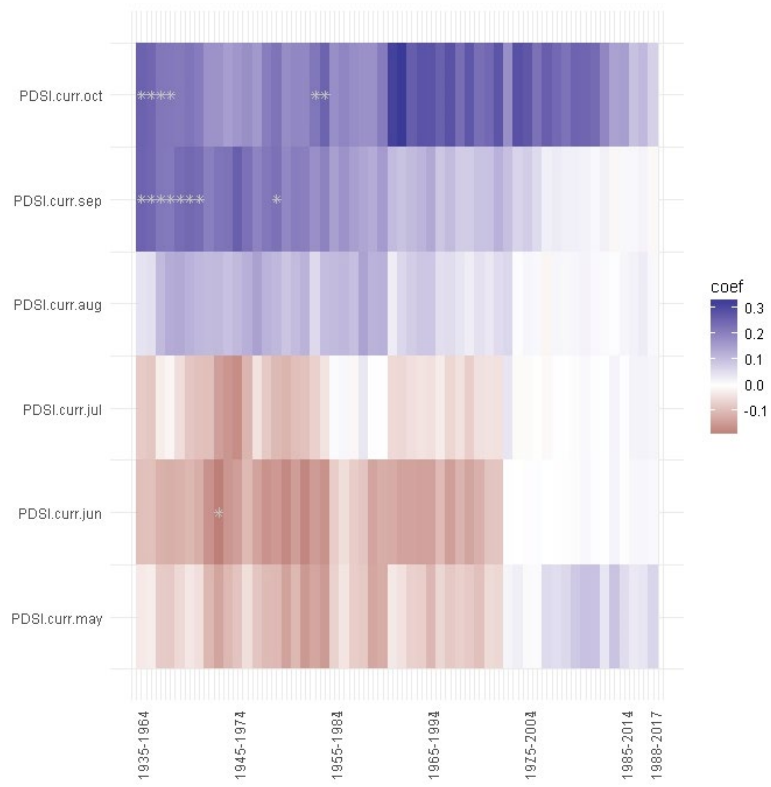


Figure 13. 30-year Running Window for the COMBO Series. The initial period is 1935–1964 and the last period is 1988–2017 (n=53).

CHAPTER III

DISCUSSION

This study evaluated the utility of using multiple co-occurring tree species to evaluate the impact of climate variables on the growth of latewood growth to expand the radial growth/climate relationship. This was accomplished by analyzing tree-ring growth against PDSI values. The three hypotheses put forward were:

- H1 *There is no difference in climatic sensitivity between co-occurring multiple species.*
- H2 *There is no significant improvement in climate sensitivity using multiple species.*
- H3 *Climatic sensitivity among the three species remains temporally consistent during the study period.*

This study examined the data and observed that during most of the year the combination of multiple tree species into one chronology is not a useful tool in examining the relationship between growth and climate. This does not hold true for the fall months of September and October when both the correlations and confidence increase above the individual component correlations and confidence levels.

Hypothesis 1

The first hypothesis tested in this study is to determine if there is a difference in climatic sensitivity between chronologies created from a single species of tree as compared to chronologies created from multiple co-occurring tree species. To evaluate differences between chronologies, this study considered months in which an individual species reflected no significant correlations for a given month in the climate/growth relationship as reflected in p -values and compared it against combined chronologies. If, in the combined chronology, stronger correlations were found, these months were considered to negate the hypothesis that there is no difference in climate sensitivity between co-occurring species. In evaluating individual species, the species that had the highest interseries correlations was post oak. When compared to longleaf pine and shortleaf pine, post oak interseries correlations were stronger overall. In addition to higher correlations post oak also had lower p -values, and fewer flagged cores during initial crossdating. The correlations for post oak thus became the baseline to determine if a higher correlation could be achieved by combining the species. Hypothesis 1 is determined to be false. For most of the warm season post oak correlations are higher than combined correlations, however, with the addition of shortleaf pine, sensitivity for the months of September and October increased, thus indicating that there is a difference in climate sensitivity when using multiple tree species to evaluate climate change. Both pine species reflected a higher growth/climate relationship when paired with the post oak, however the younger shortleaf pines increased the climate signal more than the older longleaf pines, this contrasts with Vieira et al. (2009), whom found that younger trees,

similar to the shortleaf pine trees that make up the PIEC chronology, tend to reflect climactic stresses in earlywood rather than latewood, as is observed by older trees. The results in this study support studies from that indicate it is the size of the tree, rather than age that is relevant (Mencuccini et al. 2005; Peñuelas 2005).

Maxwell et al (2015), found significant improvements when using multiple species to create a chronology for the area, this study also increases the climate signal when using multiple species in a single chronology. Maxwell et al (2015) used principal component analysis to combine datasets, while this study used the Patterson et al (2014) method of averaging standardized datasets. Though the increases in climate signal expands the window by adding September and October rather than increase the established years signal as found by Maxwell et al (2015). This is of limited utility as most studies focus on June, July and August precipitation values. This study expands that timeframe to include September and October.

Hypothesis 2

The second hypothesis tested in this study was that there is no improvement in climate sensitivity using multiple species. Richter et al (1991) found that pine species, located near each other, can be treated as a single species. The PINES chronology is composed of two pine species that fit this description. Increased interseries correlations are observed in all combination chronologies. However, when all three species are combined, stronger correlations are observed as compared to individual species only for the months of September and October. Comparisons made between the three species combined datasets (COMBO) against the two species datasets (PINES, PIPA_QUST

AND PIEC_QUIST) it is observed that the best correlations for a climate relationship occurred with the combination of shortleaf pine and post oak. Comparing climate growth correlations found in the PINES chronology (to account for sample size variation) to the climate growth correlations found in the PIEC_QUIST this combination indicates that hypothesis 2 is false as the combination of shortleaf pine and post oak proved not only to provide stronger correlations but confidence levels were also higher due to the lower p -values, furthermore the increased sensitivity can be attributed to the presence of the hardwood angiosperm post oak. Maxwell et al. (2015) used two species of oak, *Q. alba* and *Q. rubra*, and one species of tulip, *L. tulipifera*, to evaluate co-occurring tree species, this study used only one. For that species, confidence and correlation values are similar to Maxwell et al. (2015) until the species are combined. Maxwell et al. (2015) used principal component analysis to achieve better correlations, and according to Maxwell are due to the different species climate/growth responses being combined to give a better overall analysis of the climate signals. The departure in results occurs in September and October with the addition of either pine species, shortleaf pine being the preferred species. The use of principal component analysis by Maxwell et al. (2015) does provide a higher magnitude for correlations inherent in the climate/growth across the JJA timeframe, but the Patterson et al. (2014) method extends the climate/growth relationship laterally throughout the year, the JJASO timeframe.

Hypothesis 3

The change in the climate/growth relationship has been used for paleo-environmental studies and climate reconstructions, (Mann et al. 1998, Esper et al. 2002)

as well providing the initial guideline information to predict local ecological changing dynamics related to the climate change. (Rathgeber et al. 2000 and Beniston 2002) The third hypothesis tested was to determine if climatic sensitivity among the three species remains temporally consistent during the study period. All chronologies reflected a change in the climate/growth relationship, thus this hypothesis is null.

The longleaf pine chronology and the shortleaf pine chronology both showed similar responses across the period of September and October. Both species had significant correlations that were lost as the 30-year window moved through time. The post oak chronology showed three months where significance was lost moving from the early period to the late period, the months being July, September and October. The post oak also gained and lost statistically significant correlations in between the starting and ending period of this study. This chronology also gained significance moving from the early time frame to the later timeframe during the month of August. This chronology did show that there was a period during the moving window where significance was gained and then lost. The analysis of the data in this study negates the hypothesis that climatic sensitivity among the three-species studied remains temporally consistent. The reduction in temporal stability is consistent with what Maxwell et al. (2015) found.

CHAPTER IV

CONCLUSIONS

Several findings emerge from these analyses. First is that when available, post oak should be considered the primary source for late-season drought reconstruction studies in central North Carolina and potentially elsewhere. The post oak, across all datasets, showed the best correlations to PDSI in this study, when evaluating the entirety of the QUST chronology. Correlations of the post oak were only superseded with the addition either the longleaf pine or the shortleaf pine species, with shortleaf pine having the bigger impact on correlations and p -values and only during September and October. Second, stronger correlations were present during September and October. These months show declining correlations among the single species correlations, so for studies that wish to extend growth and climate correlations outside the summer season the use of a chronology with both post oak and shortleaf pine provide the best correlations and p -values. Third, combining multiple species to enhance climate/growth responses may not be an effective method in this mixed forest conditions of central NC.

Finally, caution must be placed on assuming climate/growth relationships remain temporally stable. My results suggest considerable fluctuations since 1935 suggesting that other exogeneous factors (e.g., fire, elevated atmospheric CO₂, selective logging)

also are critically important to the climate/growth relationship and that this relationship is changing over time similar to the findings of Rubino and McCarthy (2000).

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