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This study examined the influence of significant 21st-century warming on the radial growth patterns of shortleaf pine growing on adjacent north- and south-facing slopes (hereafter NS and SS), in the Uwharrie Mountains of North Carolina, USA. Using two chronologies developed from old-growth trees dating back to the 18th century, I compared raw radial growth rates (hereafter radial growth) associated with earlywood, latewood, and totalwood during 1935–2020. Both chronologies exhibited near identical (r = .951, p<0.001) age-related growth decreases through the 20th century. However, beginning in the 21st century both chronologies exhibited abrupt increases in radial growth with less fidelity (r = .86, p<0.001), which correlated with the onset of warming mean annual temperatures (r = 0.58, p < 0.01) and warming winter temperatures (r = .55, p<0.05). These results show that 1) shortleaf pine growing on both NS and SS have experienced significant radial growth increases since the early 21st century, 2) that aspect affected growth rates and 3) warming mean winter minimum temperatures have contributed to the age-related growth trend reversal. During 2002–2020, NS radial growth increased (mm per year) for the EW (0.128), LW (0.15), and TW (0.277) chronologies at a faster rate than the SS chronologies suggesting that the effects of warming are more beneficial for NS trees. I conclude that these data show that old-growth shortleaf pine trees retain climatic sensitivity to significant environmental changes associated with a warming climate, which can reverse age-related growth declines that are affected by aspect.

ASPECT AFFECTS RADIAL GROWTH RATES OF SHORTLEAF PINE (*PINUS ECHINATA*) UNDER 21ST CENTURY WARMING CONDITIONS: A CASE STUDY IN THE UWHARRIE MOUNTAINS, NORTH CAROLINA, USA

by

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Approved by

Dr. Paul Knapp
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APPROVAL PAGE

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TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

CHAPTER I: INTRODUCTION

Multiple environmental variables influence the radial growth patterns of a tree; however, the spatial location of the tree plays one of the most influential roles (Fritts 1976). Site-specific variables, such as topographic aspects, can determine the temperature, soil moisture, and humidity of a site which can then impact the growth of trees. While topographic aspect has been documented to influence the radial growth patterns of trees around the world (Peterson *et al.* 1994, Oberhuber and Kofler 2000, Fekedulegn *et al.* 2003, Kujansuu *et al*. 2007, Leonelli *et al.* 2009, Rozas *et al*. 2013, Salzer *et al.* 2014, Montpellier *et al.* 2018) little research has been conducted on the role aspect has on the growth of shortleaf pine (Stambaugh and Guyette, 2004). Populations of trees found at opposing aspects have been documented to display differences in radial growth patterns, with notable differences primarily occurring between the north- and south-facing slopes.

Climate change is projected to increase average temperatures and water stress in the southeastern United States (Costanza *et al.* 2016) and has been shown to decrease the health of forest ecosystems across the globe (Breshears *et al.* 2005, Hicke *et al.* 2006, Westerling *et al.* 2006, Raffa *et al.* 2008, van Mantgem *et al.* 2009, Carnicer *et al.* 2011, Kelsey *et al.* 2018). These influences can be mitigated or exacerbated by topographic aspect due to solar insolation (Peterson and Peterson 1994, Kelsey *et al.* 2018). This study seeks to examine the role that climate change plays between the radial growth patterns of two adjacent populations of shortleaf pine and how that has changed over time.

The purpose of this research was to 1) assess whether topographic aspect influences the radial growth patterns of shortleaf pine on two adjacent slopes in the Uwharrie Mountains, North Carolina, and 2) assess whether a changing climate is impacting the radial growth patterns of these two populations differently. If topographic aspect influences radial growth patterns of shortleaf pine significantly, this study will emphasize the importance of site selection for dendrochronological research.

CHAPTER II: ASPECT AFFECTS RADIAL GROWTH RATES OF SHORTLEAF PINE (*PINUS ECHINATA)* UNDER 21ST-CENTURY WARMING CONDITIONS: A CASE STUDY IN THE UWHARRIE MOUNTAINS, NORTH CAROLINA, USA

2.1 Abstract

This study examined the influence of significant 21st-century warming on the radial growth patterns of shortleaf pine growing on adjacent north- and south-facing slopes (hereafter NS and SS), in the Uwharrie Mountains of North Carolina, USA. Using two chronologies developed from old-growth trees dating back to the 18th century, I compared raw radial growth rates (hereafter radial growth) associated with earlywood, latewood, and totalwood during 1935–2020. Both chronologies exhibited near identical (r = .951, p<0.001) age-related growth decreases through the 20th century. However, beginning in the 21st century both chronologies exhibited abrupt increases in radial growth with less fidelity (r = .86, p<0.001), which correlated with the onset of warming mean annual temperatures (r = 0.58, p < 0.01*)* and warming winter temperatures (r = .55, p<0.05). These results show that shortleaf pine growing on both NS and SS have experienced significant radial growth increases since the early 21st century, but that aspect affected growth rates. During 2002–2020, NS radial growth increased (mm per year) for the EW (0.021), LW (0.017), and TW (0.038) chronologies at a faster rate than the SS EW (0.019), LW (0.006), and TW (0.026) chronologies suggesting that the effects of warming are more beneficial for NS trees. I conclude that these data show that old-growth shortleaf pine trees retain climatic sensitivity to significant environmental changes associated with a warming climate, which can reverse age-related growth declines that are affected by aspect.

2.2 Introduction

Shortleaf pine is a long-lived (>300 years, Earle 2014) species with an average height of 24–30 m (NC Forest Service 2016). Exhibiting the widest geographic range of any southeastern pine, shortleaf pine extends from southern New York and New Jersey into eastern Texas (Figure 1), (Lawson *et al* 1990, NC Forest Service 2016). Shortleaf pine grows at locations between 3–900 m and is commonly found in deep, well-draining soils (Lawson, *et al.* 1990). Shortleaf pine range and populations have declined due to fire suppression, logging, and disease (South *et al. 2003)*.

Figure 1. Range map of shortleaf pine (green). Data from Lawson et al. 1990.

Climatic influences on shortleaf pine radial growth are well understood (Byram and Doolittle 1950, Friend and Hafley 1989, Grissino-Mayer and Butler 1993, Stambaugh and Guyette 2004, Watkins *et al.* 2018, Adhikari, *et.al.* 2021) yet little research (e.g., Stambaugh and Guyette 2004) has addressed the potential role that topographic aspect has on shortleaf pine radial growth.

The radial growth patterns of shortleaf pine are influenced by variations in temperature and precipitation (Byram and Doolittle 1950, Friend and Hafley 1989, Grissino-Mayer and Butler 1993, Stambaugh and Guyette 2004, Adhikari, *et al.* 2021). Friend and Hafley (1989) found that high spring temperatures and high soil moisture levels provide a consistent positive influence on annual cambial growth, potentially due to an earlier onset of cambial activity in shortleaf pine. Similarly, Adhikari et al. (2021) found that regardless of either management practices or stand conditions, temperature, and precipitation affect radial growth patterns and that warm, dry summers were associated with decreased growth while warm falls increased the following years' growth.

A rare opportunity to examine the influence of topographic aspect on the radial growth of shortleaf pine exists in the Uwharrie Mountains of North Carolina, USA. Here, I evaluate radial growth patterns of two old-growth shortleaf pine populations growing on adjacent north- and south-facing slopes to address if: 1) radial growth patterns between adjacent north-and south-facing slopes have similar growth patterns, 2) climate/growth responses were similar between stands, and 3) the onset of warming average temperatures influenced the shortleaf pine populations.

2.2.1 Topographic Aspect

Topographic aspect can impact site-specific environmental conditions (Rosenberg *et al.* 1983) that in turn can affect radial growth (Oberhuber and Kofler 2000). The greatest impact of topographic aspect on microenvironmental features occurs in the mid-latitudes (30°–60° north and south) (Holland and Steyn 1975, Bilir *et al.* 2021) and is the result of differences between received solar radiation (Rosenberg *et al.* 1983, Peterson *et al.* 1994). Topographic aspect influences the solar budget due to the angle of a slope in comparison to the angle of the sun throughout the year which in turn has an impact on humidity, soil moisture, and temperature (Rosenberg *et al.* 1983, Fekedulegn *et al.* 2002).

Significant differences in temperature and soil moisture have been documented between adjacent north- and south-facing slopes (Bennie *et al.* 2008) and this can affect the radial growth patterns of trees due to induced environmental stress (Peterson *et al.* 1994, Oberhuber and Kofler 2000, Fekedulegn *et al.* 2003, Kujansuu *et al*. 2007, Leonelli *et al.* 2009, Rozas *et al.* 2013, Salzer *et al.* 2014, Montpellier *et al.* 2018). While the literature on the relationship between topographic aspect and shortleaf pine radial growth is limited (Stambaugh and Guyette 2004) results from similar studies with different species document a strong topographic influence (Peterson, et. al., 1999, Oberhuber and Kofler, 2000, Fekedulegn, *et al.* 2003, Kujansuu *et al.*, 2007, Leonelli, *et al*., 2009, Rozas *et al*., 2013, Salzer *et al.* 2014, Kelsey *et al.* 2018, Montpellier *et al.* 2018).

Microenvironmental features, such as topographic aspect, can pose a challenge for dendrochronologists when constructing chronologies due to the variability of radial growth patterns (Oberhuber and Kofler 2000). Site-specific variability of temperature regimes related to topographic aspect can impact the climatic sensitivity of trees (Leonelli *et al.* 2009). These site-specific differences can influence the divergence between temperature and radial growth patterns (Leonelli *et al.* 2009, Salzer *et al.* 2014, Montpellier *et al.* 2018). For example, Leonelli *et al*. (2009) found that topographic aspect influences growth divergence patterns and note that south-facing slopes were found to have a greater divergence from summer temperatures while north-facing slopes had a relatively stable relationship with summer temperatures.

Kelsey *et al.* (2018) examined the growth trends of *Abies lasiocarpa* and *Picea engelmannii* in San Juan National Forest, Colorado, USA, and included topographic aspect as one of their variables of interest. Kelsey *et al.* (2018) found that trees growing on east-, south-, and west-facing aspects had declines in growth trends while trees on north-facing slopes experienced a positive growth trend. The authors note that historically, trees found on south-facing slopes had greater growth trends than trees found on north-facing slopes but note that this trend has flipped correlating with increasing global temperatures (Kelsey *et al.* 2018). Conversely, the findings of Dearborn and Danby (2018) found that the raw tree ring widths measured from *Pinus glauca* in the southwest Yukon were significantly wider on south-facing slopes when compared to north-facing slopes, with south-facing slopes having raw ring widths 49% wider than north-facing slopes. Dearborn and Danby (2018) also found that there were significantly higher interseries correlations on south-facing slopes in comparison to the north-facing slopes. They suggest that the growth patterns are influenced by broad-scale climatic patterns more so on the south-facing slope and microsite conditions on the north-facing slope (Dearborn and Danby 2018). Both research areas consist of complex alpine environments, but the difference in findings suggests that topographic aspect influences tree ring width and is modified by microenvironmental conditions.

2.2.2 Climate Change

The impacts of Anthropogenic climate change on global and local populations have influenced biodiversity and ecosystem structures across the world (IPCC 2022). The change in climate has introduced pronounced physiological stress on forests (Kelsey *et al.* 2018). These physiological stressors include any unfavorable environmental conditions that might occur over a short- or long-term period. Kelsey *et al.* (2018) note that while climate change is a globally encompassing feature, local topographical features, such as aspect, can determine whether a population is experiencing physiological stressors.

While the primary concern of anthropogenic climate change is the negative impacts on global and local populations, some populations may experience a positive effect (Upadhyay and Tripathi 2019, EPA 2021). A warming of average temperatures can promote earlier growth in tree populations in colder environments (Rossi *et al.* 2016, Upadhyay and Tripathi 2019) thus lengthening the growing season (EPA, 2021). The EPA (2021) states that almost every state in the U.S. has experienced a lengthening of the growing season. On average, the growing season has increased by 2.2 days per decade since 1895 with most of the lengthening happening in the western portion of the country (EPA 2021).

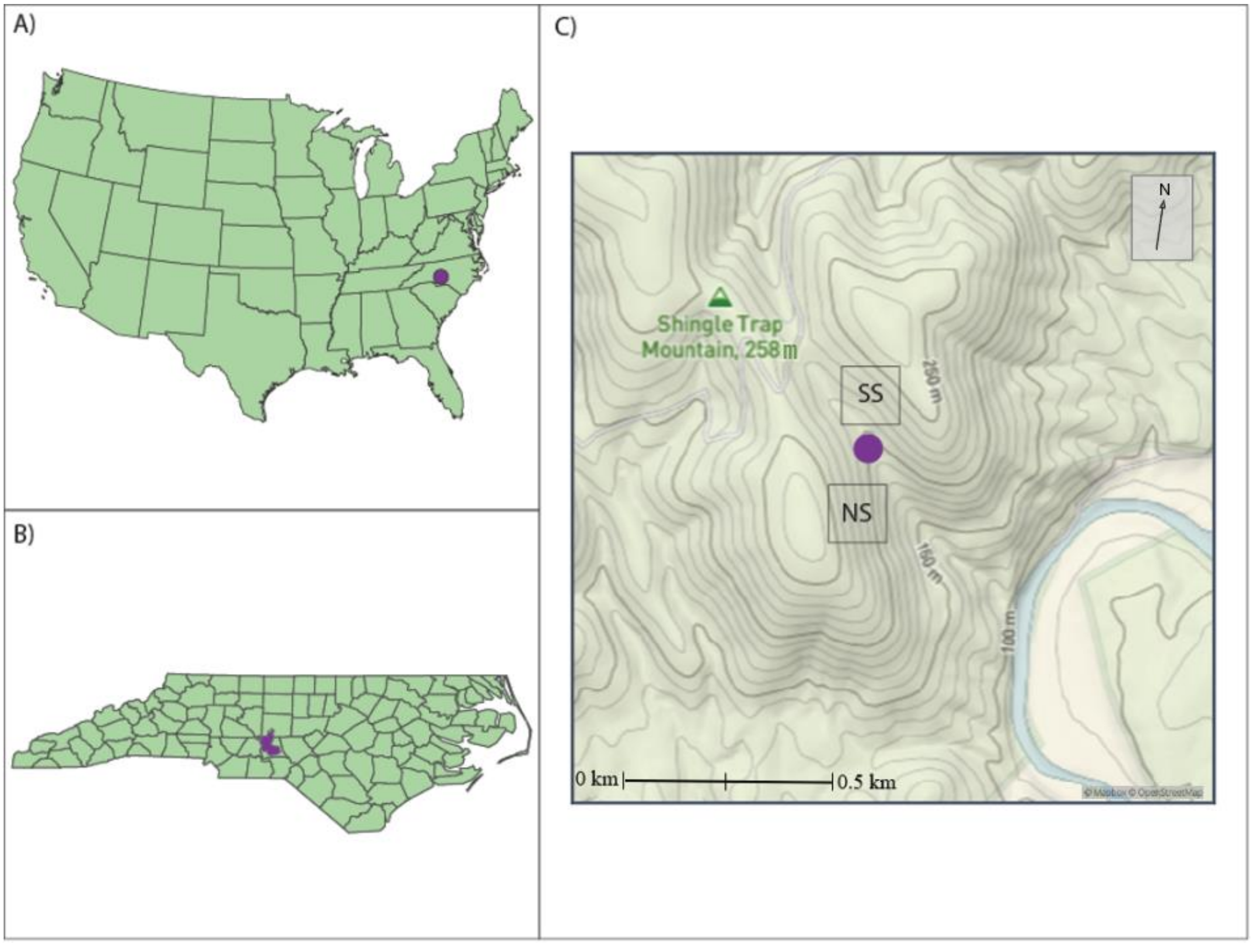
Increasing global temperatures can pose a significant implication on the analyses of tree ring data collected from high-latitude or -altitude sites (Wilmking *et al.* 2005, D’Arrigo *et al.* 2008, Montpellier *et al.* 2018). Divergence of radial growth trends potentially attributed to recent climatic warming has been identified by several (e.g., Wilmking *et al.* 2005, D’Arrigo *et al.* 2008, Montpellier *et al.* 2018). This divergence problem demonstrates a weakening in response to mean temperatures indicating a loss in climatic sensitivity during the last several decades of the record (D’Arrigo *et al.* 2008). While the divergence problem does not pose a threat to ecosystem health, it complicates climate reconstructions and dendrochronological analyses (Montpellier *et al.* 2018). The exact cause of the divergence problem is unknown yet demonstrates the necessity of analyzing sites at a small scale to uncover unique trends (Wilmking *et al.* 2005).

2.3 Methods

2.3.1 Study Site

Tree-ring data were collected from mature shortleaf pine on adjacent north- and south-facing slopes (0.15 km distance mid-slope to mid-slope) in the Uwharrie Mountains, Uwharrie National Forest, North Carolina, USA [35.401467, -80.037806]. These mountains are comprised of bouldery slopes with varying steepness (2–50%) and narrow ridge crests (Daniel *et al.* 1996) that have shallow A and B horizons (N.C. Soil Survey, 1999) with sampled shortleaf pine on slopes ranging from 30–40%. The slope soil type is Georgeville silt loam and classified as extremely stony to extremely bouldery (Soil Survey Staff, USDA, Natural Resources Conservation Services, 2021). The trees were sampled between 180–250 m elevation and are part of a mixed hardwood-coniferous forest consisting of chestnut oaks (*Quercus prinus)*, shortleaf pine (*Pinus echinata*), Virginia pine (*Pinus virginiana*), and relict longleaf pine (*Pinus palustris*) (Wells, 1974). These sites were selected due to similar stand characteristics and their adjacency to one another.

Figure 2. A) Map of the lower 48 states, the Uwharrie National Forest is shown in purple. B) Map of North Carolina, the Uwharrie National Forest is shown in purple. C) 10 m contour map displaying the NS and SS. The purple circle is the midpoint [35.401467, -80.037806] between the slopes. Data from USGS and Mapbox OpenStreetMap.



2.3.2 Field Data

I collected shortleaf pine samples from 30 adult trees in December 2021 and June 2022. Two 5.15 mm increment cores were taken from each tree at breast height on opposite sides. The basal diameter, height, and GPS coordinates were recorded. Trees with rot, fire damage, or missing tops were not sampled. A previously constructed chronology for the adjacent south slope containing 33 samples from adult trees using the same sampling methodology was used to compare the growth trends between each slope (Cline, 2021, Mitchell and Knapp, 2022). This chronology extended to 2020.

The increment cores were dried and glued into wooden core mounts. These samples were sanded with a progressively finer grit (120–600 μm) until the growth rings were clearly visible and then scanned at 1200 DPI resolution. The scans were uploaded into WinDENDRO where they were measured at .001 mm precision (Guay 2012) and crossdating accuracy was verified using COFECHA (Holmes 1983). WinDENDRO compiles the data into three separate chronology files with measurements for totalwood, latewood, and earlywood ring widths (Guay 2012). ARSTAN was then used to standardize all chronologies using the negative exponential function as well as generating a raw ring-width chronology (Holmes 1983).

2.3.3 Climate Data

Climate data were collected from NOAA's National Centers for Environmental Information. Seasonal (Winter = D–F, Spring = M–M, Summer, J–A, Fall S–N) divisional time series for average, minimum, and maximum temperature as well as precipitation, PDHI, and PDSI were collected from the Southern Piedmont climate division (CD5) of North Carolina. Data were collected from 1935–2020 to examine the warming trend present in both the minimum and maximum temperature time series. Minimum and maximum temperatures as well as precipitation for January–December were collected and broken into four 3-month intervals to represent winter, spring, summer, and fall as well as broken into monthly time series. Climate data from 1935–2020 were used to avoid potential errors associated with statewide averaging of climate data prior to 1931 (Guttman and Quayle, 1996).

2.4 Analyses

2.4.1 Tree-ring Analyses

Ring widths were measured using WinDENDRO (Guay 2012) and compiled into raw ring-width chronologies. Raw ring widths (hereafter ring widths or radial growth) were used to avoid potential inflation of widths near the end of a record ("end effect") caused by some standardization methods particularly older trees experiencing age-related narrowing (Cook and Peters 1997). To determine the radial growth differences, each chronology was plotted with the adjacent slope chronology (e.g., NS LW chronology plotted with SS LW chronology) for trend analyses. The slope and *r* values were recorded to compare trends. The mean annual radial growth for each chronology was calculated by averaging the annual measurements to examine the annual growth rates and was based on the growth patterns of three periods: 1935–2020 (hereafter Full Period), 1935–2001 when radial growth declined (hereafter Early Period), 2002–2020 when radial growth increased (hereafter Late Period). Frequency charts were constructed to analyze the average age of the innermost ring for each slope by tallying the earliest ring in each sample and placing it into the corresponding decade.

The Mann-Whitney U test (Mann and Whitney 1947) was conducted for all chronologies using SPSS (2021) for the Full , Early, and Late Periods. The Mann-Whitney U test (Mann and Whitney, 1947) was used to test for significance between differences of medians between the chronologies of opposing slopes due to the ring widths being non-parametric.

2.4.2 Climate data

Climatic variables were chosen to analyze the influence of climate on the radial growth of the two populations. Mean annual temperature, minimum temperature, maximum temperature, PDHI, PDSI, and precipitation were used to analyze the significance or correlation between each variable and radial growth. The climatic variables were analyzed on a seasonal time scale and using SPSS (2021) were analyzed using bivariate correlation. SPSS (2021) was used with each chronology for the duration of the 1935–2020 period and for 2002–2020. To analyze on a seasonal scale, the mean temperatures for the 3-month period (defined in section 2.3.4) were calculated annually. To visualize the climatic trends of the southern Piedmont (CD5) climatic variables were plotted to examine visual trends and the slope and *r* values were recorded.

2.5 Results and Discussion

2.5.1 Sample size, series intercorrelation, and mean sensitivity

The NS chronology contained a total of 33 shortleaf pine cores from 20 trees while the SS chronology contained a total of 32 cores from 20 trees. The median tree age on the NS was 120 years and 132 years on the SS. Series intercorrelations for NS and SS chronologies were similar and ranged from .414–.602 (Table 1) with the highest values for LW for both chronologies. Series intercorrelations range from 0.0–1.0 where higher numbers indicate stronger agreement of annual ring widths between samples (Speer, 2010). Mean sensitivities, which are used to identify whether a core is responsive for climate and useful for crossdating purposes, ranged from .270–.432 between the NS and SS chronologies with the highest values for LW (Table 1).

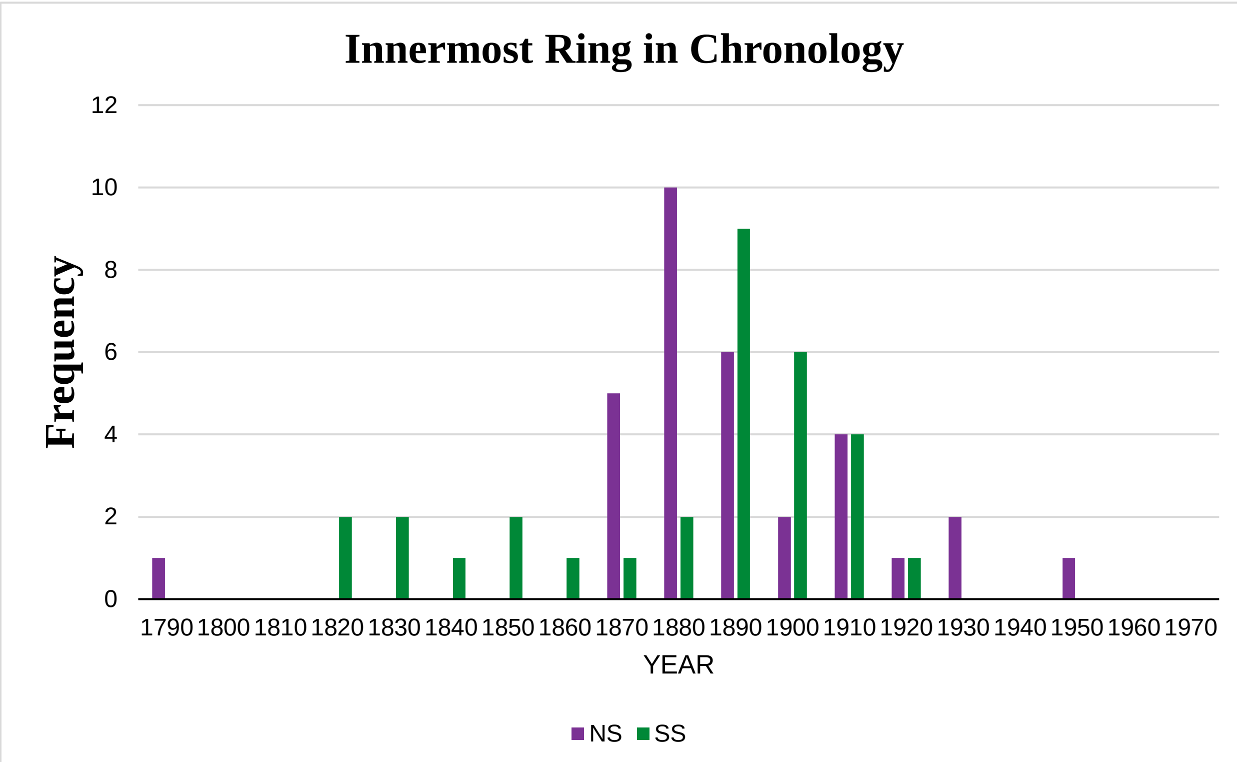
Series intercorrelations were higher in the SS chronologies while average mean sensitivities were higher for the NS chronologies. Similarly, to the findings of Dearborn and Danby (2018) who analyzed aspects influences on radial growth in the Yukon on *Picea glauca* and *Salix glauca*, SS chronologies had higher series intercorrelations in comparison to NS chronologies in the Yukon. They conjectured that these differences were an artifact of variability in soil moisture content and shallow active layers (Dearborn and Danby, 2018).

Table 1. Number of dated series, series intercorrelation, and mean sensitivity of the NS and SS chronologies for EW, LW, and TW.

Chronology	# Dated Series	Series Intercorrelation	Mean Sensitivity
NS EW	33	.414	.306
SS EW	32	.487	.277
NS LW	33	.586	.432
SS LW	32	.602	.416
NS TW	33	.526	.292
SS TW	32	.588	.270

The age distribution of the NS and SS chronologies based on the innermost ring binned by decade ranged from 1790–1950 with the majority establishing prior to 1900 (Figure 3). The most common (30% of samples) decade for the NS innermost rings was 1880 while the most common (28% of samples) decade for the SS innermost rings was 1890.

Figure 3. Inner-most ring for all sampled trees by decade. All cores displayed either curvature or pith.



2.5.2 Radial growth rates and increasing temperatures.

The raw radial growth widths of totalwood (Figure 4), earlywood (Figure 5), and latewood (Figure 6) exhibited an expected age-related downward trend of ring widths (e.g., Carrer and Urbinati, 2004) until the early 2000s when raw widths began to increase until the end of the record in 2020. TW growth between the NS and SS chronologies are highly correlated (r = .941, $p < 0.001$) with a negative trend in the Early Period (i.e., 1935–2001) but during the Late Period (i.e., 2002–2020) exhibited a positive trend with reduced fidelity (r = .86, p <0.001). This Late-Period trend correlated with the onset of warming mean annual temperatures (r = 0.58, p < 0.01) and warming winter (D–F) minimum temperatures (r = .55, $p < 0.05$). These results are consistent with the findings of Johnson and Abrams (2009), who documented an increase in the growth rates of old-growth *Populus*, *Quercus*, *Pinus*, *Tsuga*, and *Nyssa* in the eastern United States. Further, these results are inconsistent with the idea of age-related growth declines (Ryan and Yoder 1997). Johnson and Abrams (2009) propose that this is potentially related to a global change in climate caused by the historic trends in land use and various atmospheric factors such as increased CO_2 levels and warming temperatures. These Late-Period radial growth increases coincide with an increase in mean annual temperatures between 2002–2020 (Figure 7) by 0.12℃ per decade.

Figure 4. Totalwood raw ring widths for the north and south slope from 1935–2020. Ring widths are measured in mm.

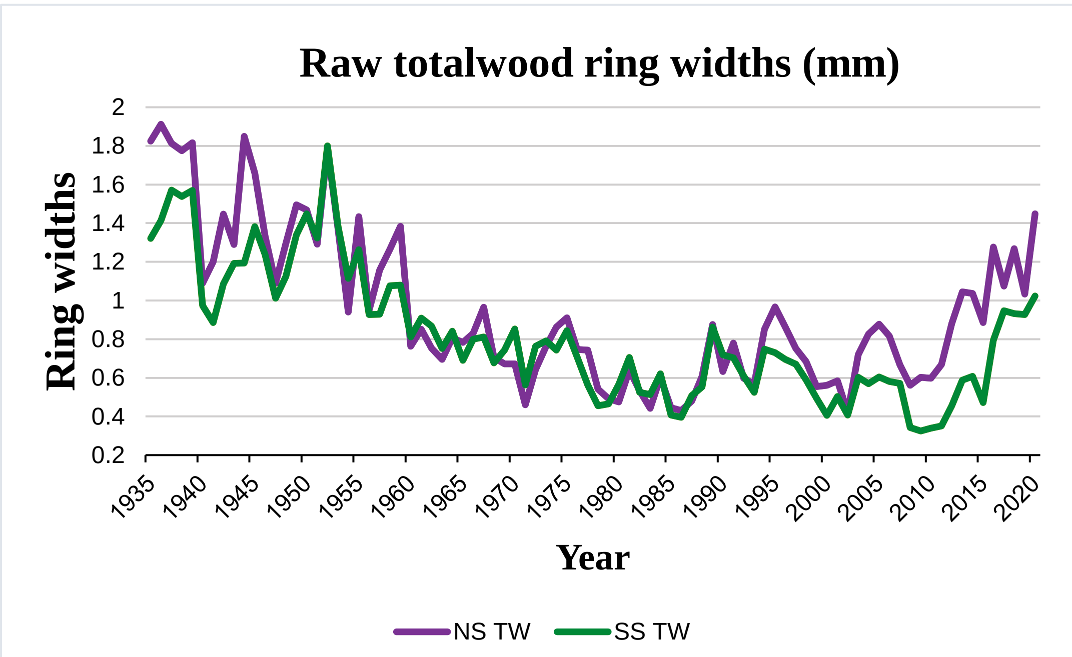


Figure 5. Earlywood raw ring widths for the north and south slopes from 1935–2020. Ring widths are measured in mm.

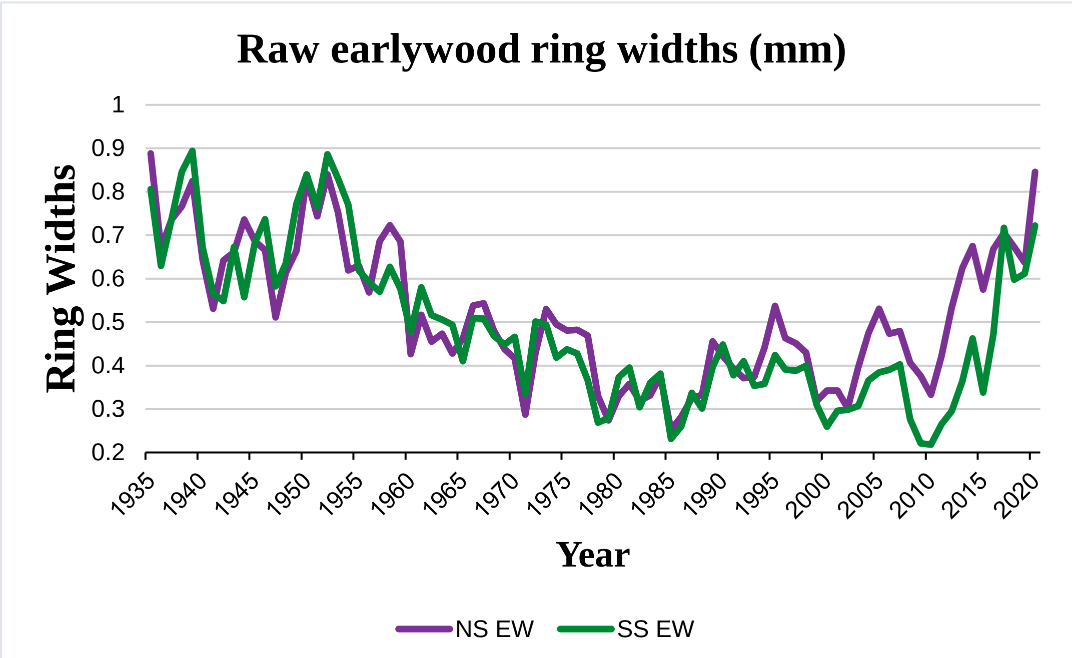


Figure 6. Latewood raw ring widths for the north and south slopes from 1935–2020. Ring widths are measured in mm.

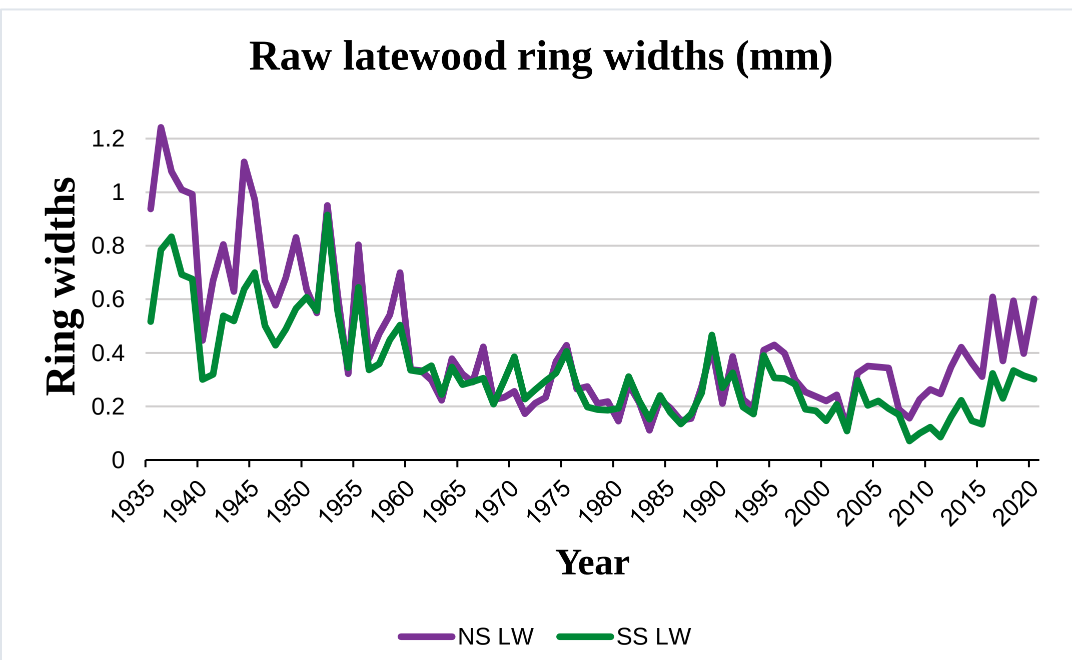


Figure 7. Mean Average Temperatures (°C) in the southern Piedmont (CD5) of North Carolina, USA for the total period (1935–2020). Trendline displayed in green. (r = .372, p < 0.001) Data from NOAA.

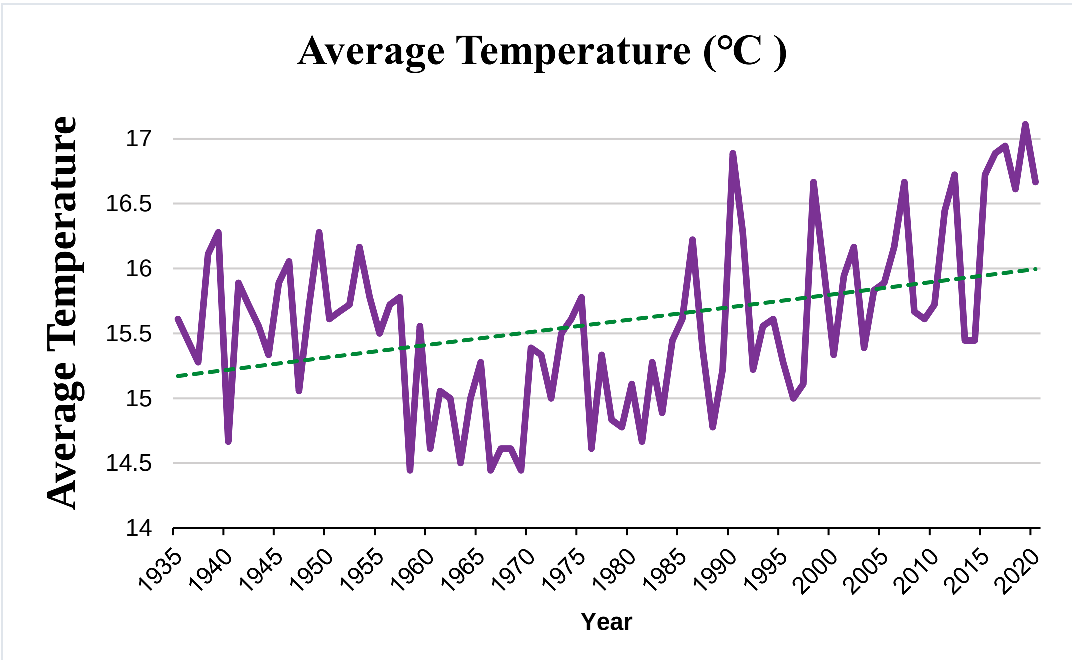


Figure 8. Mean Average Temperatures (°C) in the southern Piedmont (CD5) of North Carolina, USA for the Late Period (2002–2020). Trendline displayed in green. (r= .582, p < 0.01) Data from NOAA.

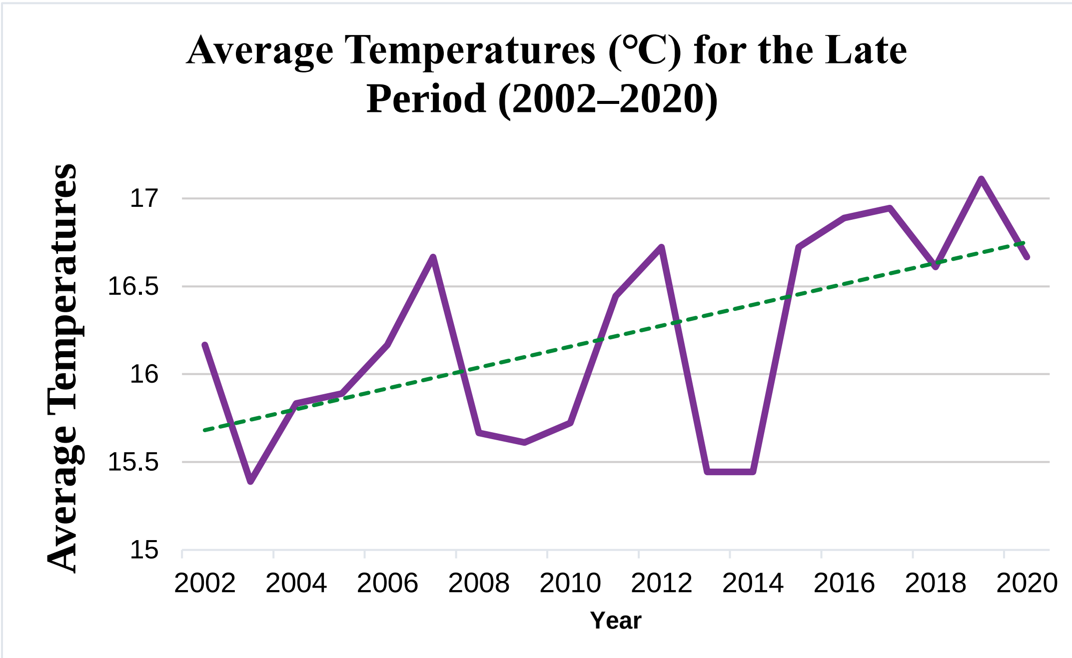


Figure 9. Mean minimum winter (D–F) temperatures (°C) for the southern Piedmont (CD5) of North Carolina, USA for the total period. Trendline displayed in green (r = .264, $p < 0.05$). Data from NOAA.

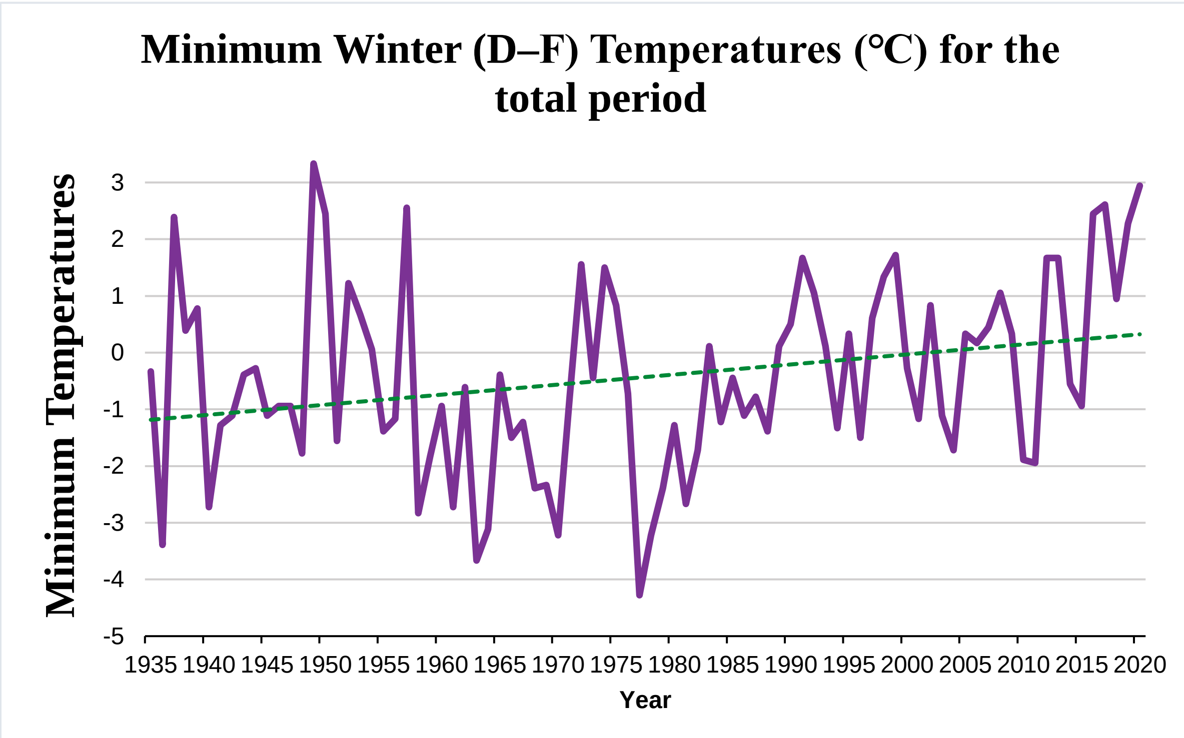
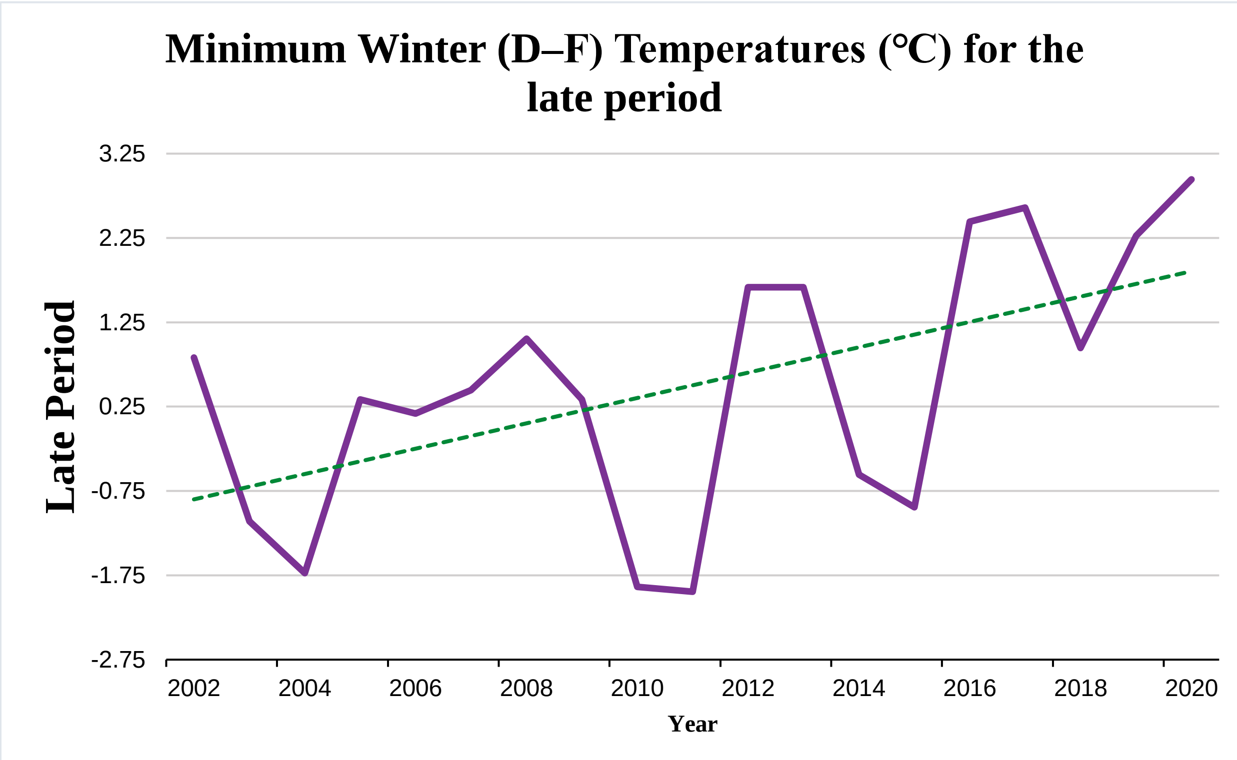


Figure 10. Mean minimum winter (D–F) temperatures (in °C) for the southern Piedmont (CD5) of North Carolina, USA for the Late Period. Trendline displayed in green (r = .545, p < 0.05). Data from NOAA.



2.5.3 Influence of Aspect

2.5.3.1 Full Period

Mean annual radial growth of NS TW was .127 mm (Table 2) greater ($p < 0.05$, Table 6) than the SS for the Full Period. Likewise, NS LW mean annual radial growth was significantly ($p < 0.05$) greater (0.093 mm) than SS. No significant ($p > .05$) differences were documented for the EW radial growth between the NS and SS.

2.5.3.2 Early Period

Mean annual radial growth for NS TW was not significantly different ($p = 0.21$, Table 5) than the SS for the Early Period. Similarly, there were no significant ($p > 0.05$) differences between the annual radial growth rates of each slope for EW (.006 mm) and LW (.078 mm) during this period suggesting similar growth trends.

2.5.3.3 Late Period

Mean annual radial growth of NS TW was .277 mm (Table 4) greater ($p < 0.05$, Table 5) than the SS for the Late Period. Likewise, NS EW (.128 mm, $p < 0.05$) and NS LW (.15 mm, $p < 0.001$) mean annual radial growth were significantly different from the SS. The significance of growth difference in the Full Period for TW and LW is driven by the significance in the Late Period.

2.5.3.4 Influence of Climate on Slope

All chronologies were tested to evaluate any correlations that exist between the climatic variables on monthly, seasonal, and annual scales.

2.5.3.4.1 Full Period

Average annual temperatures correlated with the NS TW ($p<0.05$) and EW ($p<0.05$) but was not significant (p>0.05) for all SS chronologies and NS LW. NS TW ($r=.51$, $p<0.05$) and EW ($r=.54$, $p< 0.01$) chronologies correlated significantly with winter (D–F) minimum temperatures while the SS TW ($r=.54$, $p<.01$), EW ($r=.56$, $p<.01$), and LW (r=.51, p<0.05) chronologies correlated significantly with January minimum temperature. No significant correlations exist between the chronologies with maximum temperatures, PDHI, PDSI, or precipitation.

2.5.3.4.2 Early Period

Average temperatures ($p<0.05$) and maximum temperatures ($p<.01$) correlated with all chronologies for the NS and SS during the Early Period. Minimum temperatures did not correlate significantly ($p>0.05$) with any chronology. No significant correlations exist between the chronologies and PDHI, PDSI or precipitation.

2.5.3.4.3 Late Period

Average temperatures correlated ($p < 0.05$) with NS EW, SS TW, and SS EW during the late period. Maximum temperatures did not correlate with any chronologies during the late period. Minimum temperatures correlated significantly ($p < 0.01$) for all chronologies during this period. No significant correlations exist between the chronologies and PDSI or precipitation.

2.5.3.4.4 Temperature and Radial Growth Trends

During the Full Period, average annual temperatures increased 0.012℃ per year ($p < 0.01$) while during the Late Period, there was a significant upward trend (Figure 8) resulting in temperatures increasing 0.061℃ per year ($p < 0.05$). Similarly, minimum temperatures have seen a warming trend of 0.016℃ per year for the Full Period and a significant ($p < 0.05$) upward trend has occurred during the Late Period resulting in minimum winter temperatures increasing .15℃ per year. While it makes sense that warming winter temperatures would accelerate growth rates due to an earlier onset in cambial growth, the Late Period represents the first period of significant divergence between the two chronologies for TW, EW, and LW. The Late Period coincides with the onset of a warming trend that is principally remarkable for the lack of extreme cold years. Specifically, during the Early Period the average minimum winter temperature was -0.74℃ with 33% of the years being above 0℃ while the average minimum winter temperature during the Late Period was 0.5℃ with 69% of the years being above 0℃.

The comparison between the Early and Late Periods are distinguished by significantly (-0.74℃ verses 0.5℃, $p < 0.01$) warmer minimum winter temperatures. I posit that it is more likely that accelerated growth is not principally an artifact of mean warmer temperatures but the lack of freezing temperatures. Friend and Hafley (1989) note that shortleaf pine cambial growth occurs earlier in the growing season than other *Pinus* species and therefore is more sensitive to early spring temperatures. While significant correlations did not exist between spring temperatures and the chronologies, warming winter minimum temperatures can trigger the start of an earlier growing season (EPA 2021). With the increase in frequency of above 0℃ average winter minimum temperatures, the threat of damage related to cold temperatures is reduced and therefore the trees on both slopes can begin cambial growth earlier in the season. Using the 0℃ threshold, Robeson (2002) found that the growing season length in Illinois has increased by roughly one week from 1906–1997 with warming occurring earlier in the spring thus allowing growth to occur earlier. The elongation of the growing season due to climate change is a well-documented phenomenon (Robeson 2002, Wuebbles and Hayhoe 2004, Linderholm 2006, Christiansen *et al.* 2011, Rossi *et al.* 2016, Upadhyay and Tripathi 2019, EPA 2021, Feng *et al.* 2022) that has implications for dendrochronologists (Prislan, *et al.* 2019). Growing-season lengths have been used as a climatic indicator to examine seasonality through time (Robeson, 2002) and is an important feature for dendrochronologists to consider as cambial growth can begin earlier in the growing season and increase average ring widths (Rossi *et al.* 2016, Upadhyay and Tripathi 2019, Prislan *et al.* 2019).

2.5.3.4.5 Alternative Causes for Radial Growth Increases

It is unlikely that other external factors contributed to the radial growth increases. Atmospheric CO2 fertilization has been documented for several tree species (e.g., Knapp *et al.*

2001, Soulé & Knapp 2006) where increased water-use efficiency has benefited trees growing in semi-arid environments whereas others have found no or limited effects where soil moisture is not a limiting feature (e.g., Giradin *et al.* 2016, Reed *et al.* 2018). Additionally, precipitation amounts during the Full Period either annually or during the summer growing season exhibited no trend ($p>0.05$). No direct anthropogenic disturbances including cutting or fire suppression were documented, and the open woodland-like forest with a rocky understory is not conducive to fire spread.

Table 2. Mean annual raw radial growth (mm) for the Full Period (1935–2020) for earlywood, latewood, and totalwood by slope.

	Earlywood	**Latewood**	**Totalwood**
North slope	.519	.425	.944
South slope	.485	.332	.817
Difference	.034	.093	.127

Table 3. Mean annual raw radial growth (mm) for the Early Period (1935–2001) for earlywood, latewood, and totalwood by slope.

	Earlywood	**Latewood**	**Totalwood**
North slope	.515	.448	.963
South slope	.509	.370	.879
Difference	.006	.078	.084

Table 4. Mean annual raw radial growth (mm) for the Late Period (2002–2020) for earlywood, latewood, and totalwood by slope. It is important to note that TW values are larger in Table 3 than in Table 5 due to Table 3 including the innermost ring measurements. The innermost rings, due to age-related growth trends, are typically wider than rings found near bark (Fritts, 1976).

	Earlywood	Latewood	Totalwood
North slope	.533	.346	.879
South slope	.405	.196	.602
Difference	.128	.15	.277

Table 5. Mann-Whitney U test calculated for each chronology by aspect for the Full Period (1935–2020), Early Period (1935–2001), and Late Period (2002–2020) and the significance of difference. The Mann-Whitney U test was used due to the ring widths being nonparametric.

Full Period		
Chronology	**Difference of Means**	**Significance (*p*-value)**
TW	0.12	**<0.05**
EW	0.03	0.12
LW	0.09	**<0.05**
Early Period		
TW	0.08	0.4
EW	0.01	0.73
LW	0.07	.29
Late Period		
TW	0.28	**<0.05**
EW	0.13	**<0.05**
LW	0.15	**<0.001**

Table 6. Mean annual radial growth (in mm) for the Full Period (below or above 0 degrees Celsius) and the significance of difference between those medians of the same chronology.

Chronology	Mean radial growth <0°C	Mean Radial growth >0°C	*p*-value
NS TW	0.909	.996	.32
SS TW	0.792	.856	.38
NS EW	.494	.556	.07
SS EW	.464	.518	.16
NS LW	.415	.440	.67
SS LW	.328	.338	.79

Table 7. Difference of medians between opposing slope chronologies for years above or below 0°C for the Late Period. Significance values of <0.05 are bolded.

Chronology	**< 0°C (*p*-value)**	**> 0°C (*p*-value)**
TW	.08	.15
EW	.3	.39
LW	**<0.05**	.08

2.6 Conclusions

The primary objective of this study was to determine if topographic aspect influences populations of trees differently within the Uwharrie Mountains. These results show that the radial growth patterns of old-growth shortleaf pine in the Uwharrie Mountains of North Carolina, USA are affected by aspect and warming minimum temperatures. Here I found that at the beginning of the 21st century, radial growth rates of adjacent NS and SS shortleaf pine began increasing, reversing decades of age-related decline. Further, growth rates diverged between slopes during the last two decades. These radial growth rates during the past 20 years run counter to the general principle of the physiological growth processes of age-related decline following an initial period of rapid growth (Kaufmann 1996, Ryan and Yoder 1997). These growth increases are coincident with significant warming beginning in the 21st century where mean annual winter temperatures remain above 0°C. Further, I posit that the influence of this warming is more influential for trees on the NS where there is less daily insolation, which likely promoted an earlier start to cambial growth.

These results show that aspect influences radial growth rates differently and a warming climate can reverse age-related radial growth declines which has implications for tree physiology and dendrochronology. The growth trends found in this study illustrate the influence that increasing temperatures have on tree physiology and how it has changed over time. The results of this study also show the importance of site selection when chronology building as the growth rates differ significantly. A chronology built solely from south-facing trees may exhibit different growth rates from trees sampled from other slopes thus potentially affecting climate-growth relations used for reconstructions.

Future studies further examining topographic aspect and radial growth patterns should be conducted. This study focused on north- and south-facing aspects, but the inclusion of east- and west-facing aspects would be beneficial to further understand the role of aspect on radial growth. The age-related growth trends mentioned in this study might also be further analyzed by the inclusion of different *Pinus* species found on the adjacent slopes as well as sampling younger trees to compare growth rates between younger and older trees during similar ages. Utilizing trees that express differences in the start of cambial growth would also prove useful in understanding how a potential elongation of the growing season will impact the growth of species differently.

CHAPTER III: CONCLUSIONS

Several key findings emerged from these results. First, topographic aspect can affect radial growth patterns of shortleaf pine in the Uwharrie Mountains of North Carolina, USA but the effect is likely modulated by temperature. Both the NS and SS chronologies exhibited near identical (r = 0.951, p< 0.001) growth-related declines during the 20th century but then displayed abrupt increases in radial growth with less fidelity (r = 0.86, p<0.001) during the 21st century. The upward growth trend correlated with warming winter minimum (r= .55, p<0.05*)* temperatures that were associated with the decreased frequency of winters with a mean below 0℃. Further, radial growth rates (mm per year) for the Late Period increased significantly (p<0.05) more for NS EW (0.021), LW (0.017), and TW (0.038) than that of SS EW (0.019), LW (0.006), and TW (0.026) widths. These results suggest increased mean winter minimum temperatures have: 1) contributed to the reversal of age-related growth trends for both populations likely due to a growing season elongation resulting in an earlier start to cambial formation, and 2) had a greater positive effect on NS trees. These results demonstrate the importance of 1) aspect in site selection, 2) potential age-related decline reversals under favorable environmental conditions, and 3) differential responses to warming temperatures.

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