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21st Century Warming, Site Aspect, and Reversal of Age-Related Growth Decline in Shortleaf Pine (*Pinus echinata*) in North Carolina, USA

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Abstract: We examined the influence of significant 21st century warming on the radial growth patterns of shortleaf pine growing on adjacent north/northeast- and south/southwest-facing slopes (hereafter NS and SS), in the Uwharrie Mountains of North Carolina, USA. Using two chronologies developed from old-growth trees dating to the 1700s, we compared raw radial growth rates (hereafter radial growth) associated with earlywood, latewood, and totalwood during 1935–2020. Both chronologies exhibited similar ($r = 0.951$, $p < 0.001$) age-related growth decreases through the 20th century. However, both chronologies experienced abrupt increases in radial growth with less fidelity ($r = 0.86$, $p < 0.001$), correlating with the onset of warming mean annual temperatures ($r = 0.58$, $p < 0.01$) and warming winter temperatures ($r = 0.55$, $p < 0.05$) in 2002. 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 significantly ($p < 0.05$) more than SS earlywood, latewood, and totalwood, indicating that the effects of warming were greater for NS trees. We conclude that old-growth shortleaf pine trees retain climatic sensitivity to significant environmental changes associated with a warming climate and can reverse age-related growth declines.

Keywords: topographic aspect; dendrochronology; southeastern USA; radial growth patterns; shortleaf pine

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1. Introduction

Shortleaf pine (*Pinus echinata* Mill.) has the widest distribution of any southeastern USA pine, ranging from southern New York to eastern Texas. Growing at elevations between 3 and 900 m and commonly found in deep, well-draining soils [1], the species is both ecologically and economically important [2]. Further, shortleaf pine is commonly used for dendrochronological studies (e.g., [3–6]) because it is a long-lived species exceeding 300 years [7] that exhibits climate sensitivity. Less is known about its responses to a warming climate [8,9] and how these changes may affect the species' use in dendrochronological research.

Radial growth patterns of shortleaf pine respond to variations in temperature and precipitation, particularly warm (−) or wet summers (+), above-average winter temperatures (+), and absence of extreme minimum temperatures (+) [9–12]. Correlations with Palmer Drought Severity Index (PDSI) [13], a measure of soil moisture, are positively associated with radial growth from early summer (May) to late summer (September) [11,12]. Further, Friend and Hafley (1989) [14] found that high spring temperatures and high soil moisture levels provided a consistent positive influence on annual cambial growth, potentially due to an earlier onset of cambial activity.

Other factors in concert with climate may influence the radial growth of temperate trees. Topographic aspect can impact site-specific environmental conditions [15] that in turn can affect radial growth [16]. The greatest impact of topographic aspect on microenvironmental features occurs in the mid-latitudes (30–60° north and south) [17,18] and is the result of differences between solar radiation receipt [15,19] that affects humidity, soil moisture, and temperature [15,20,21]. Further, site-specific variability of temperature regimes related to topographic aspect can impact the climatic sensitivity of trees [22] and may promote divergence (i.e., less correlation) between temperature and radial growth patterns. For example, Leonelli et al. (2009) [22] found that topographic aspect influences growth divergence patterns with south-facing slopes experiencing greater divergence from summer temperatures while north-facing slopes experienced stable relationships with summer temperatures. Microclimatic conditions between north- and south-facing slopes can affect the radial growth patterns of trees due to induced environmental stress associated with temperature and/or soil moisture [19,20,22–25].

Little research, however, has addressed the potential role that topographic aspect has on shortleaf pine radial growth [11]. Here, we address the interaction between radial growth, aspect, and 21st century warming conditions in the Uwharrie Mountains, North Carolina, USA. Despite extensive research on shortleaf pine, the interactive effects of aspect and changing climate on radial growth is less understood. We evaluate radial growth patterns of two old-growth shortleaf pine populations growing on adjacent north- and south-facing slopes in the Uwharrie Mountains. Specifically, we evaluate (1) radial growth patterns between adjacent north-and south-facing slopes, (2) climate/growth responses between stands, and (3) if the onset of warming average temperatures differentially affected radial growth rates.

2. Materials and Methods

We collected tree-ring data from mature shortleaf pine on adjacent north/northeast- and south/southwest-facing slopes separated by 0.15 km in the Uwharrie Mountains (35.401467, −80.037806, Figure 1). The Uwharries are comprised of bouldery slopes with varying steepness (2–50%) and narrow ridge crests [26] with shallow A and B horizons [27]. We sampled shortleaf pine on steep (30–40%), extremely bouldery slopes comprising Georgeville silt loam [28] at elevations between 180–250 m. The slopes support a mixed hardwood–coniferous forest consisting of chestnut oaks (*Quercus prinus)*, shortleaf pine, Virginia pine (*Pinus virginiana*), and relict longleaf pine (*Pinus palustris*) [29,30].

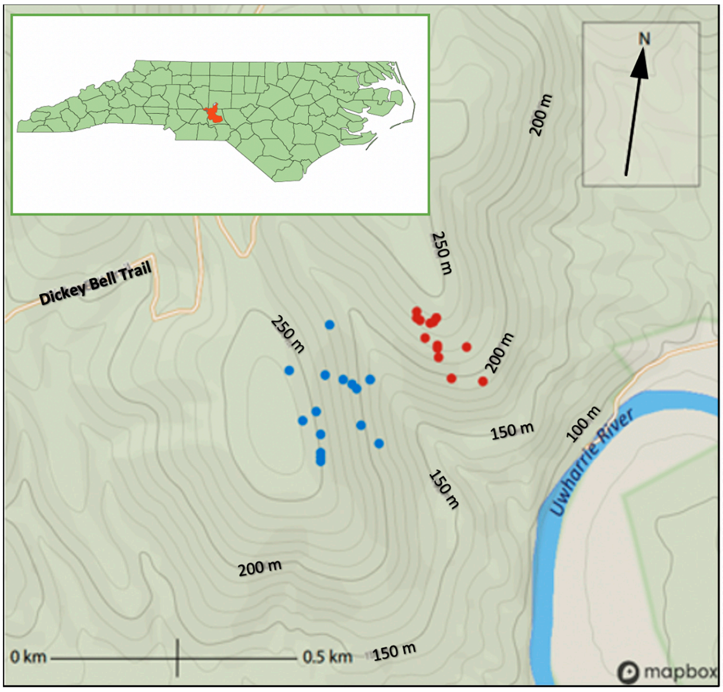

Figure 1. Map Inset: map of North Carolina with the Uwharrie National Forest shown in red. Map: 10 m elevation contour map displaying trees sampled on the NS (blue circles) and SS (red circles) sites. Map created using MapBox [31].

We collected shortleaf pine samples from 30 adult trees in December 2021 and June 2022 on the NS. Two 5.15 mm diameter increment cores were sampled from each tree on opposite sides at approximately 1.3 m height, and basal diameter, height, and GPS coordinates were recorded. We excluded trees with rot, fire damage, or missing tops from sampling. A previously constructed chronology from the SS comprising 33 samples and extending to 2020 [6,32] was used to compare the growth trends between the slopes.

The samples were dried and glued into wooden core mounts sanded with progressively finer grit (120–600 μm) until the growth rings were clearly visible and could be scanned at 1200 DPI resolution. We uploaded scans into WinDENDRO (Regent Instruments Inc., Québec City, QC, Canada 2013), measured ring widths at 0.001 mm precision [33] and verified cross-dating accuracy using COFECHA [34]. WinDENDRO compiles ring width data into three separate chronology files with measurements for earlywood, latewood, and totalwood (Guay 2012). ARSTAN [34] was used to standardize all chronologies using the negative exponential function as well as generating a raw ring width chronology. However, we elected to use raw ring widths (hereafter ring widths or radial growth) to avoid potential inflation of widths near the end of a record (“end effect”) caused by some standardization methods, particularly for older trees experiencing age-related narrowing [35]. Likewise, Soulé et al., 2019 [36] found that raw ring widths provided the strongest climate signal for trees old enough to where the age-related decline was less operative. We confirmed that the aggregated data were not affected by a few samples that expressed anomalous raw ring widths by examining individual cores to determine if radial growth was consistent among the samples.

We plotted each chronology with the adjacent slope chronology (e.g., NS LW chronology plotted with SS LW chronology) to determine the radial growth differences. The slope, r values, and mean annual radial growth were recorded to compare trends during three periods: 1935–2001, when radial growth declined (early period); 2002–2020, when radial growth increased (late period); and 1935–2020 (full period). We collected climate data from NOAA’s National Centers for Environmental Information [37] for 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 (Palmers Drought Hydrologic Index), and PDSI from the Southern Piedmont Climate Division (CD5) of North Carolina. We selected data from 1935–2020 to avoid potential errors associated with statewide averaging of climate data prior to 1931 [38] and used bivariate correlation (SPSS 2021) to analyze climate–growth relationships using monthly and seasonal climate data.

3. Results and Discussion

The NS chronology contained 33 shortleaf pine cores from 20 trees and the SS chronology contained 32 cores from 20 trees. The median tree age on the NS was 120 years and 132 years on the SS. The age distribution of the NS and SS chronologies based on the innermost ring binned by decade ranged from 1790 to 1950 with the majority (65%) established prior to 1900. Series intercorrelations for NS and SS chronologies ranged from 0.41–0.60 while mean sensitivities ranged from 0.27 to 0.43 with the highest values for LW for both measures (Table 1).

Table 1. The 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	0.414	0.306
SS EW	32	0.487	0.277
NS LW	33	0.586	0.432
SS LW	32	0.602	0.416
NS TW	33	0.526	0.292
SS TW	32	0.588	0.270

Raw radial growth widths of EW (Figure 2A), LW (Figure 2B), and TW (Figure 2C) exhibited an expected age-related downward trend of growth [39] until the early 2000s, when growth began to increase through the end of the record in 2020. TW growth between the NS and SS chronologies are highly correlated ($r = 0.941$, $p < 0.001$) with a negative trend in the early period (i.e., 1935–2001) but a positive trend with reduced fidelity ($r = 0.86$, $p < 0.001$) during the late period (i.e., 2002–2020).

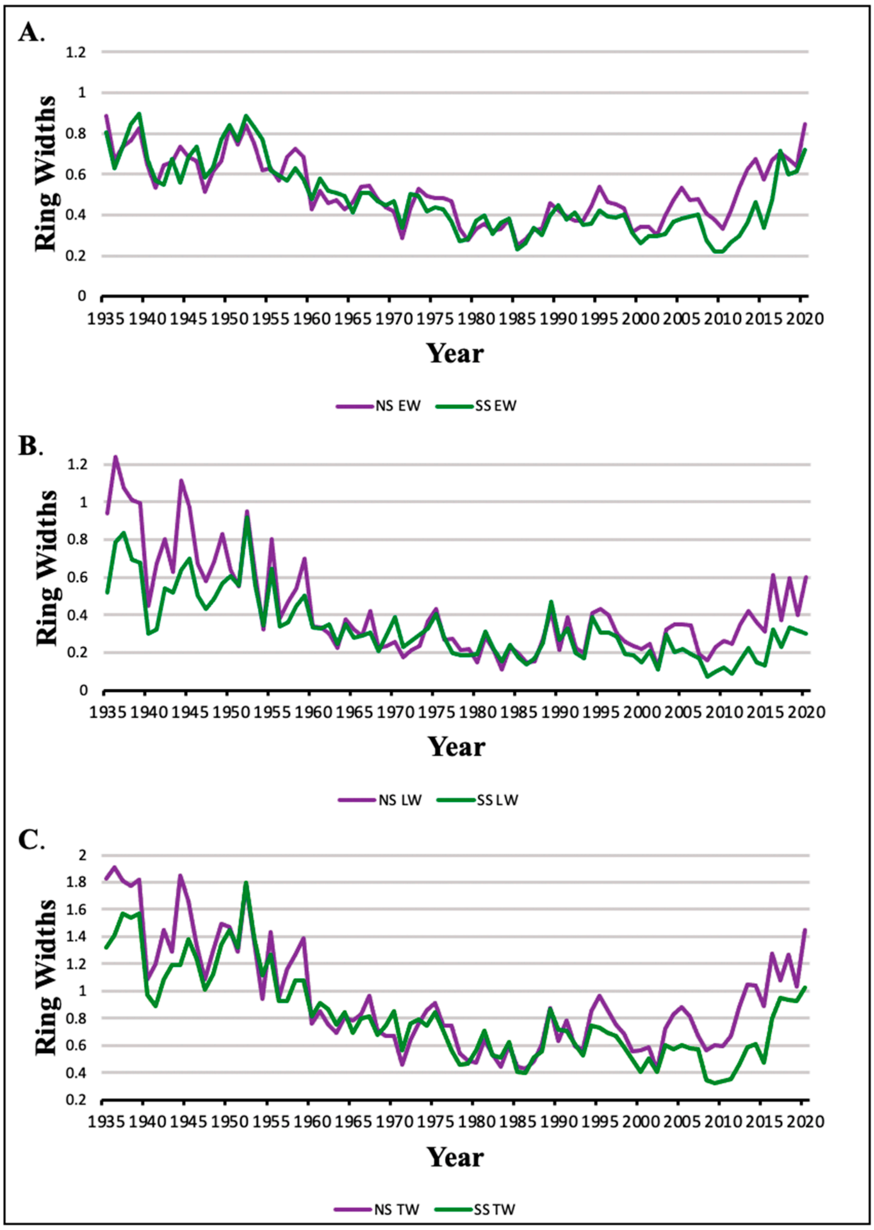

Figure 2. Raw ring widths for NS and SS during 1935–2020 showing EW (**A**), LW (**B**), TW (**C**).

The relationship between radial growth and monthly climate variables varied by period, aspect, and chronology. Average temperature was correlated ($p < 0.05$) with all periods but varied by aspect and chronology (Figure 3A–F). Likewise, minimum winter temperature was positively correlated with the late and full periods but varied by chronology for the full period (Figure 3C,F). Minimum winter temperature was not correlated with the early period (Figure 3A). Conversely, no significant correlations ($p > 0.05$) exist between the chronologies and maximum temperature, PDHI, PDSI, or precipitation during the early, late, and full periods.

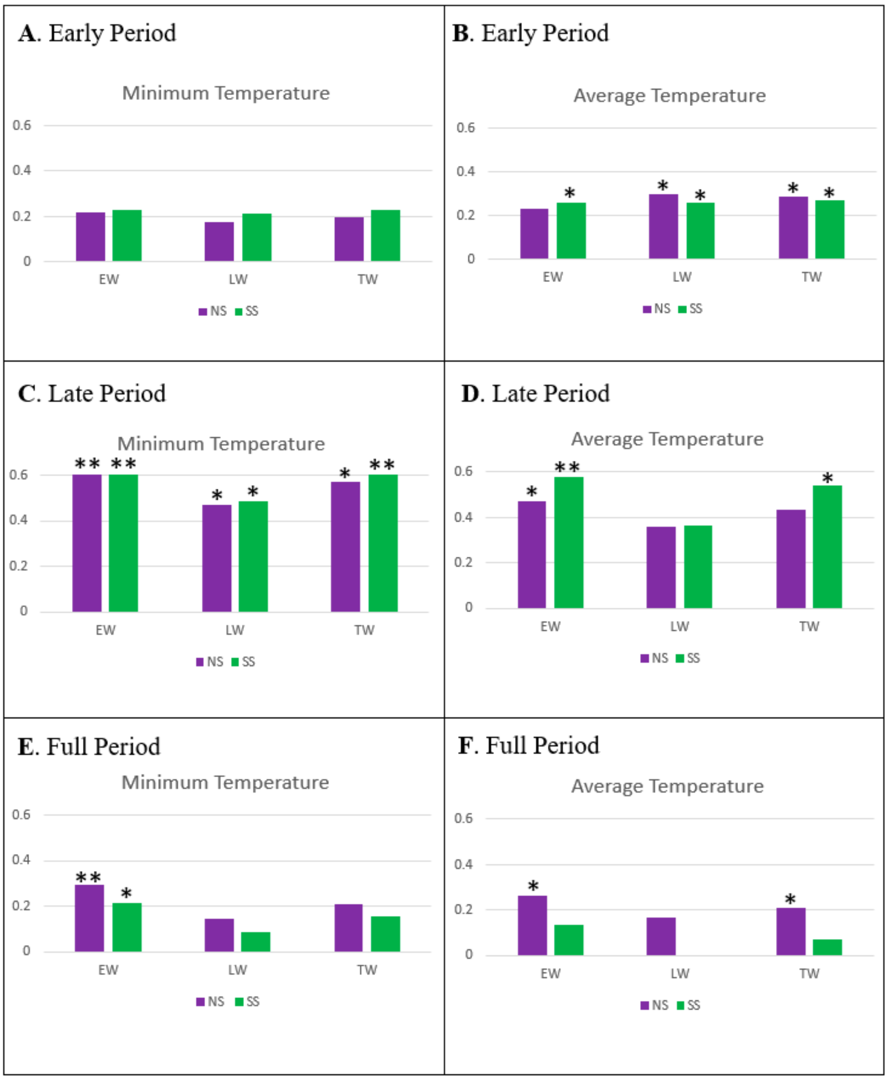

Figure 3. Correlation between raw ring widths and minimum winter temperature (**A**,**C**,**E**) and mean annual temperature (**B**,**D**,**F**) during the early, late, and full periods for north and south aspects. Significance is marked by ** ($p < 0.01$) and * ($p < 0.05$). SS LW r-value for the full period (-0.003) does not appear in the figure.

The late period trend correlated with the onset of warming mean annual temperatures ($r = 0.58$, $p < 0.01$) and warming winter (Figure 3D–F) minimum temperatures ($r = 0.55$, $p < 0.05$) (Figure 4). These results are consistent with the findings of Johnson and Abrams (2009) [40], who documented an increase in the growth rates of old-growth Populus, Quercus, Pinus, Tsuga, and Nyssa in the eastern United States and counter to typical age-related radial growth decline [41]. Johnson and Abrams (2009) [40] proposed that growth increases in older trees may be related to either warming temperatures and/or land use changes, while others have identified an atmospheric CO_2 fertilization effect for some pine species (e.g., [42,43]). Here, radial growth increases were significantly associated with warming temperatures but not rising atmospheric CO_2, nor were growth changes coincident with land use modifications, suggesting that temperatures were the primary driver of change. Mean annual radial growth for NS, EW, LW, and TW was greater than SS, EW, LW, and TW for the early and full periods, and significantly greater ($p < 0.05$) during the full and late periods. Further, the growth differences for LW and TW in the full period were driven by the significance (i.e., magnitude of correlation coefficient) in the late period (Figure 4 and Table 2).

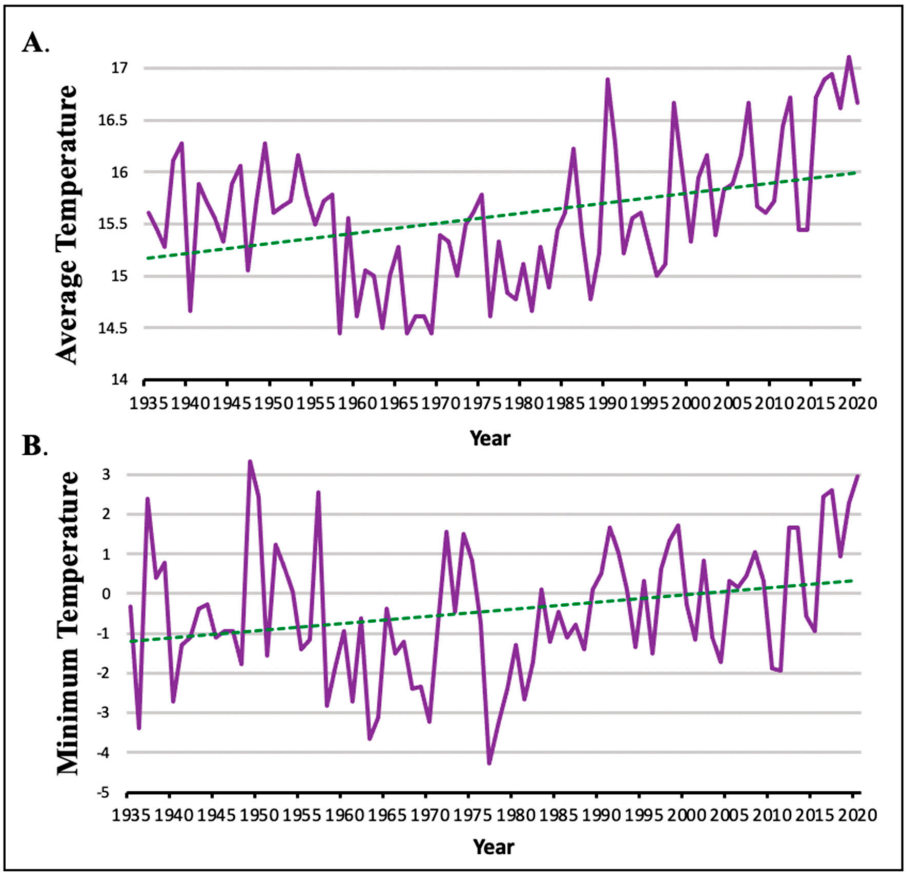

Figure 4. Average annual temperature (**A**) and minimum winter temperature (**B**) for the full period. The trend line (dashed line) is not significant at $p > 0.05$.

Table 2. Mann–Whitney U test calculated for each chronology by aspect for the early (1935–2001), late (2002–2020), and full (1935–2020) periods, and the significance of difference. Significant *p*-values bolded.

	Early Period	
Chronology	**Difference of Means**	**Significance**
EW	0.01	0.73
LW	0.07	0.29
TW	0.08	0.4
	Late Period	
EW	0.13	**<0.05**
LW	0.15	**<0.001**
TW	0.28	**<0.05**
	Full Period	
EW	0.03	0.12
LW	0.09	**<0.05**
TW	0.12	**<0.05**

We suggest that warming winter temperatures have increased radial growth rates due to an earlier onset of cambial growth, thus extending the growing season. The late period, characterized by a warming trend and a significant ($p < 0.05$) reduction in colder winters (<0 °C average), coincided with a significant ($p < 0.05$) growth divergence between the two chronologies (Figure 2, Table 2). Conversely, there were no significant ($p > 0.05$) differences between the two chronologies during the early period (Figure 2, Table 2). Specifically, during the early period, the average minimum winter temperature was −0.74 °C with 33%

of the years being above 0 °C while the average minimum winter temperature during the late period was 0.5 °C with 69% of the years being above 0 °C. Further, comparison between the early and late periods are distinguished by significantly (−0.74 °C verses 0.5 °C, $p < 0.01$) warmer minimum winter temperatures suggesting that accelerated growth is an artifact of the lack of freezing temperatures, concurring with Kosiba et al., 2018 [44]. Growing season elongation due to climate change is well documented (e.g., [45–50]). Specifically, these findings are consistent with cambial growth characteristics of shortleaf pine that develops earlier in the spring than other southeastern U.S. *Pinus* species [14] and thus may be more sensitive to early spring temperatures.

It is unlikely that other external factors contributed to the radial growth increases. Atmospheric CO_2 fertilization has been documented for several tree species (e.g., [51–53]) where increased water use efficiency has benefited trees growing in semiarid environments, whereas others have found no or limited effects where soil moisture is not a limiting feature (e.g., [54,55]), or that fertilization effect diminishes with tree age [42]. Further, neither annual nor summer precipitation amounts during the full period significantly ($p > 0.05$) changed, suggesting this variable was not a driver of growth increases. Lastly, no direct anthropogenic disturbances such as logging were observed (no remnant stumps), and the open woodland-like forest with a rocky understory is not conducive to fire spread that would alter stand dynamics.

4. Conclusions

This study evaluated topographic aspect influences on radial growth patterns under warming conditions within the Uwharrie Mountains of North Carolina, USA. We found that ring widths of old-growth shortleaf pine were positively affected—regardless of aspect—by warming winter minimum temperatures that likely created conditions favorable for an earlier onset of cambial growth in the spring. However, climate–growth relationships were not temporally stable. Here, chronologies built from opposite, but adjacent (0.15 km) slopes expressed nearly identical growth rates during the 20th century but diverged significantly beginning in the 21st century when winter minimum temperatures began rapidly warming. An elongation of the growing season due to warming minimum temperatures suggests potential increased forest productivity in this environment, but may be species-specific, such as for shortleaf pine. These findings suggest that changes in tree physiology have implications regarding site selection for dendrochronological studies and emphasize the dynamic nature of tree growth under warming conditions.

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