

LONG-TERM GROWTH AND CLIMATE RESPONSE OF SHORLEAF PINE AT THE MISSOURI OZARK FOREST ECOSYSTEM PROJECT

Michael C. Stambaugh and Richard P. Guyette[†]

ABSTRACT.—Shortleaf pine (*Pinus echinata*) is one of the most of important conifers in the Central Hardwood region both ecologically and economically. In the Ozark Highlands of Missouri and Arkansas, the presence of shortleaf pine provides an important conifer component in otherwise hardwood dominated forest types. Regional forest health issues such as oak decline and red oak borer as well as pine restoration efforts have increased interest in the species and the management of oak-pine forest types. The purpose of this paper is to provide information about the growth of shortleaf pine using one of the longest existing growth records available. Using tree-ring data collected at the Missouri Ozark Forest Ecosystem Project (MOFEP), we provide a long-term perspective of shortleaf pine growth, climate response, and regeneration. Tree-ring data from shortleaf pine remnants and cores of live trees illustrate the temporal variability in growth of shortleaf pine over the past 386 years. We developed a climate response function based on instrumental climate data from a 70 year period (1931-2001). Variation in shortleaf pine ring-width was most strongly correlated with growing year Palmer Drought Severity Index (PDSI) months, extreme minimum winter temperatures, and previous fall season PDSI ($r^2 = 0.43$, $p < 0.0001$). Further analysis of the relationship between tree-ring indices and PDSI suggest that the correlation was higher in the early half of the 20th century than the latter half. Late winter (January and February) may be becoming increasingly important in determining shortleaf pine growth. Spectral estimates of the tree-ring chronology suggest that shortleaf pine growth has a near 21 year periodic variation that is likely an influence of larger scale climatic cycles. Comparisons between growth of shortleaf pine in three age classes both pre- and post 1880 show that the species' growth rate was significantly greater during the 20th century than for the two prior centuries. Management implications for the long-term variations in shortleaf pine growth are discussed.

Shortleaf pine (*Pinus echinata*) is a valuable component of the Central Hardwoods region for notable reasons. Dendrochronologically, the species' high resistance to decay (Harborne 1994,) and successful regeneration on drought prone aspects (Parker 1982, Stambaugh 2001) makes it one of the best sources for studying the relationship between tree growth and climate in the Central Hardwoods region. Ecologically, the species provides diversity in a hardwood dominated forest region; in part because it is a conifer, its successful competition and occupation on xeric landscape positions (Guldin 1986, Murphy and Nowacki 1997, Stambaugh 2001) and its regenerative success during frequent disturbance (Keeley and Zedler 1998, Guyette and Spetich 2003). Economically, the species played a key role in the initial development of lumber industries in the Ozark Highlands of Missouri and Arkansas and remains an important commercial species today.

During the last century, many large-scale land management projects have been undertaken with objectives of promoting shortleaf pine success (USDA 2003, Bukenhofer and others 1994, Masters and others 1996, Rimer 2003). Interest in the management of shortleaf pine has increased because of the dramatic decrease in the acreage of the species since Euro-American settlement (Liming 1946, Hamilton 2003), including the decrease of pine savanna communities. Additionally, Ozark region forest health issues of red oak borer and oak decline have underlined the importance of maintaining a conifer forest component. In this paper we reconstruct the growth of shortleaf pine using one of the longest existing growth records available. Using tree-ring data collected at the Missouri Ozark Forest Ecosystem Project (MOFEP), we provide a long-term perspective of shortleaf pine growth, climate

[†]Senior Research Specialist (MCS), Missouri Tree-Ring Laboratory, Department of Forestry, 203 ABNR Bldg., University of Missouri-Columbia, Columbia, MO 65211; and Research Associate Professor (RPG, same address). MCS is corresponding author: call (573) 882-8841 or e-mail at stambaughm@missouri.edu.

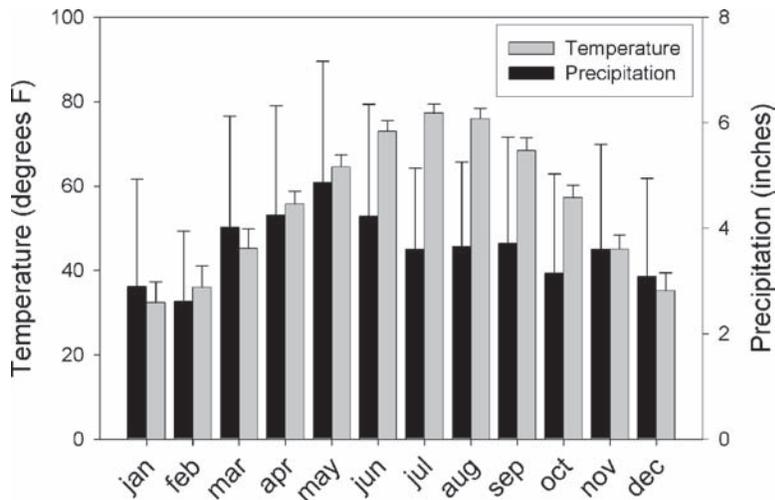


Figure 1.—Monthly averaged surface data for Missouri Climate Division 5 (NCDC 1994) for the period 1895 to 2002 with error bars equal to one standard deviation.

response, and regeneration. The information here provides managers a standard in long-term growth against which to compare current growth and measure future growth variability.

Study Areas

Shortleaf pine samples were collected from the southeastern portion of Missouri within site boundaries of the Missouri Ozark Forest Ecosystem Project (MOFEP)(approx. 91°4'9"W, 37°9'43" N). MOFEP is a landscape experiment comparing the effects of even-aged management, uneven-aged management, and no harvesting on multiple ecosystem components (Brookshire and others 1997a). Nine sites, each a minimum of 600 contiguous acres, comprise MOFEP. Sites are nearly entirely forested with approximately 9 percent of the total tree species importance values in shortleaf pine (Brookshire and others 1997b). Although shortleaf pine occurs on all MOFEP sites, its abundance is highly variable and attributed to competition with hardwoods, forest history, and topographic and soil properties (e.g., slope, aspect, parent material). Throughout the MOFEP study sites and the greater Ozark Highlands region ample remnant shortleaf pine wood (e.g., standing dead snags, stumps preserved from lumbering era (Hill 1949, Cunningham and Hauser 1989)) provides excellent opportunity for dendrochronological research and construction of long time series (Guyette and Dey 1997).

The climate and weather of the Ozark Highlands region is determined primarily by the mid-continent location in the middle latitudes and has been classified as humid-continental and humid subtropical (Rafferty 1980). The climatic patterns of the Ozark Highlands are consistent with those of the Central Plains, which infers that general circulation features dominate the local climate (Su 1997). Su (1997) found that the temperature and climate of the Ozark Highlands is significantly related to sea surface temperatures particularly of the north Pacific and tropical Pacific Ocean currents. In the region of MOFEP, mean monthly precipitation, primarily in the form of rain, is 3.64 inches (9.25 cm)(fig. 1).

Methods

During the years 1996 to 2002 over 200 shortleaf pine cross-sections were cut from remnant stumps and dead standing snags from all MOFEP sites. Over 150 increment cores from live trees were collected during the years 2002 and 2003 from MOFEP sites 1 through 7. Samples were collected non-randomly because of their limited quantity and tree-ring quality. Live trees were selected for sampling if 1) their age was likely greater than 50 years, 2) they had a live crown ratio greater than 30 percent and no signs of dieback, and 3) they occupied dominant and co-dominant canopy positions. Growth rate of the tree and the aspect and slope of the tree's geographic position were not considered in selection. Cross sections of remnants were collected from 15 to 100 cm above the ground and increment cores were collected from breast height (1.37 m). Cross sections and cores were prepared by sanding their surfaces with increasingly finer sandpaper down to 600 grit. All annual rings were measured to 0.01 millimeter precision. Tree-ring measurements of remnants were cross-dated using live

tree cores (i.e., known tree-ring dates) and a previously constructed shortleaf pine tree-ring chronology from Shannon County, Missouri (Guyette 1992). Cross-dating is a method whereby individual tree-rings are absolutely dated to calendar years by matching variation in ring-width patterns to those of known dates (Stokes and Smiley 1968, Baillie 1995). Crossdating identifies errors in measurement caused by missing or false rings. We used COFECHA software (Holmes and others 1986) for quality control of ring measurements and crossdating through inter-series correlations and t-tests.

Long-term growth

Shortleaf pine chronologies were constructed for the purpose of quantifying the long-term growth of the species at MOFEP. Shortleaf pine remnants (n=70) and cores (n=38) used to construct the MOFEP shortleaf pine tree-ring chronology were chosen based on circuit uniformity, the lack of missing rings, and crossdating. We constructed an ARSTAN tree-ring chronology utilizing Turbo ARSTAN software (Cook 2002). ARSTAN derives a standardized chronology using a robust mean value function to reduce the effect of statistical outliers. Standardized chronologies are pre-whitened by reincorporating the derived pooled auto-regressive model to form the auto-regressive standardized (i.e., ARSTAN) chronology. ARSTAN chronologies are described in detail in Cook (1985) and Cook and Holmes (1984).

Tree-ring series were interactively detrended in two steps (Holmes and others 1986). First, a negative-exponential curve or linear regression line was fit to individual series to remove age related growth trend. Second, we interactively chose flexible spline curves (i.e., 20-50 yr length) to remove higher frequency variation in growth due to stand disturbances (e.g., mid-1940's logging event). All tree-ring series from remnant wood (i.e., outside ring date prior to 1880) were fit with 50-year spline curves as we had no knowledge of dates of prior stand disturbances. The stationary tree-ring chronology was analyzed for the purpose of identifying common high frequency (e.g., < 30 yrs) components or climate cycles influencing ring-width variation. Using SAS software, we tested for significant white noise components in the time series by Fisher's Kappa and Bartlett's Kolmogorov-Smirnov test statistics. SAS software uses a Fast Fourier Transform to generate periodograms. A centrally weighted Daniell filter (bandwidth = 5) was used to smooth the periodogram. It was taken into consideration that excessive smoothing can obscure the important spectral detail and insufficient smoothing leaves erratic unimportant detail in the spectrum. The power spectral density was estimated for the purpose of defining which periodic components likely contribute the most variation in the frequency of ring width (i.e., tree growth). The greater the power spectral density the more variation is accounted for by that period or climate (e.g., drought) cycle.

We analyzed the differences in growth rates of shortleaf pines that grew at MOFEP over approximately the past 386 years. Only cores and cross sections of remnants that had an estimated 15 or fewer rings missing (number of missing rings was estimated using methods of Duncan 1989) to the pith were used for the analysis. Near exact pith dates were necessary because we wished to separate and compare the growth rates of shortleaf pine both pre- and post-1880. Pith dates likely incorporate some error due to differences in sampling heights between cross sections and cores. We chose to compare the growth rate of shortleaf pine post- and pre-1880 because of the time period's association with increases in lumbering (Cunningham and Hauser 1989), decrease in fire frequency (Guyette and others 2002), and increases in human population (Stevens 1991) and agricultural land use (Jacobson and Primm 1997). From radial measurements of tree-rings we calculated tree diameter at 10, 30, and 50 years of age. Radial tree-ring measurements were converted to tree diameter by multiplying by two. We used t-tests to test for differences in the growth of shortleaf pine pre- and post-1880.

Climate response

Increment cores from live trees, ranging from 50 to over 200 years old, were used to analyze the climate response of shortleaf pine. Considering the land use history of MOFEP and larger Ozark region (Rafferty 1980, Stevens 1991), many trees likely developed following logging disturbance, grew under the influence of specific stand developmental processes (i.e., stem initiation, stem exclusion (Oliver and Larson 1996), and currently occur in closed canopy conditions. For the climate response analysis we chose sections of cores with the least amount of growth suppression and anomalous wood formation. For the purpose of maximizing the climate signal of the chronology, we chose the most highly inter-

correlated trees (n=38) growing during the period of divisional instrumental climate record (1895-2002). This resulted in a minimum of 28 trees represented in the indexed growth value for any year for the period 1895-2002.

Divisional climate data (1895-2002) from the National Climate Data Center (NCDC 1994), which included monthly precipitation, monthly temperature, and monthly Palmer Drought Severity Index (PDSI) values, were used for the climate response analysis. We also used individual station data (Salem, MO, 1931-2001) for the purpose of accounting for more localized weather events such as extreme minimum winter temperature. SAS (SAS/STAT, 2002) and DendroClim2002 software (Biondi 2002) were used to correlate climate data and tree-ring chronology indices and analyze and choose the response variables. Although climate response functions typically employ principal components regression, we used stepwise regression so to keep monthly variables distinctively defined. The stepwise regression may cause an inflation of the correlation coefficients when multi-colinearity exists. In model development, we chose climate variables (and their combinations), based on their biological relevance to shortleaf pine tree-growth. A multiple regression equation defined the response function with all variables significant ($\alpha = 0.1$).

Correlations were calculated between the ARSTAN chronology and monthly precipitation, temperature, and PDSI data for August of the year prior to growth through December of the year of growth. We calculated the mean correlation between the ARSTAN chronology and PDSI using moving intervals of 36 years on one year time steps (e.g., time step 1: 1895-1929; time step 2: 1896-1930; etc.) The length of moving interval (36 years) was chosen so to maximize the number of time steps compared, include an adequate number of years for correlation analysis, and because it is the minimal length allowed by DendroClim2002 software. Slight differences in correlation results likely occur as the length of the moving interval is adjusted by a few years, however too short of intervals may be unrelated to larger scale climate variability and too long of intervals decreases the number of comparisons between intervals.

Results

Long-term growth

We constructed a 386-year tree-ring chronology to demonstrate the long-term year to year changes in growth of shortleaf pine (fig. 2). For the 20th century some of the notable years and periods of relatively low growth were 1901, 1912-1913, 1930, 1936, 1952-1954, 1960, 1978, 1980, 1984; a total of 12 years. In retrospect, approximately 11 years of comparable low growth (ring-width index < -0.20) occurred in each of the 18th and 19th centuries. Calendar year 1936 had the lowest ring-width index value during the 20th century and from 1700 to 2001 only four years had a less or equal ring-width index value. Prior to 1700 the chronology is poorly replicated and changes in growth should be viewed with caution.

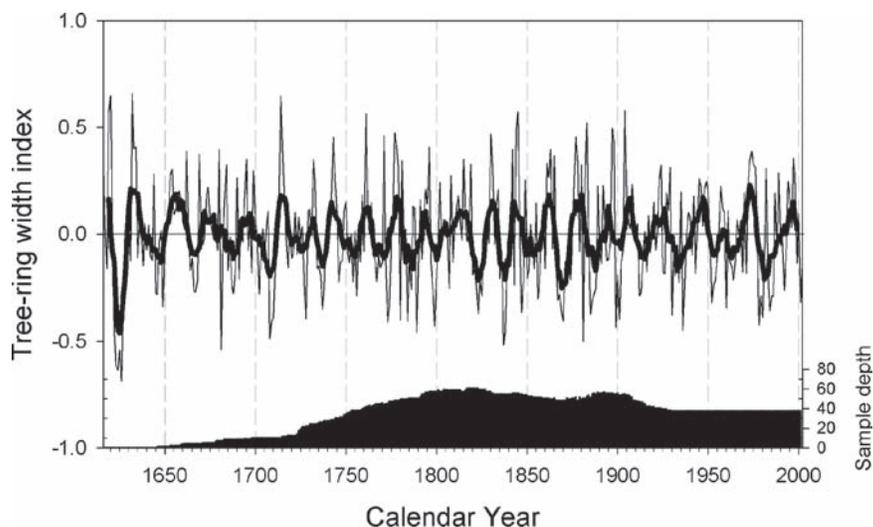


Figure 2.—A 386-year shortleaf pine tree ring chronology from the Missouri Ozark Forest Ecosystem Project (MOFEP) with the sample depth at calendar years plotted on the right y-axis. A 7-year moving average (bold line) demonstrates the lower frequency variation in the tree-ring indices. Variation in tree-ring indices were most highly correlated to mean summer (May through August) Palmer Drought Severity Indices (PDSI)(NCDC 1994).

We arbitrarily chose and fit a 7-year moving average to the tree-ring width index in order to enhance the visibility of the lower frequency variation in shortleaf pine growth (fig. 2). A spectral analysis of the time series revealed peaks in variance at periods of 3.5, 9, and 21 years (fig. 3). The hypothesis that the

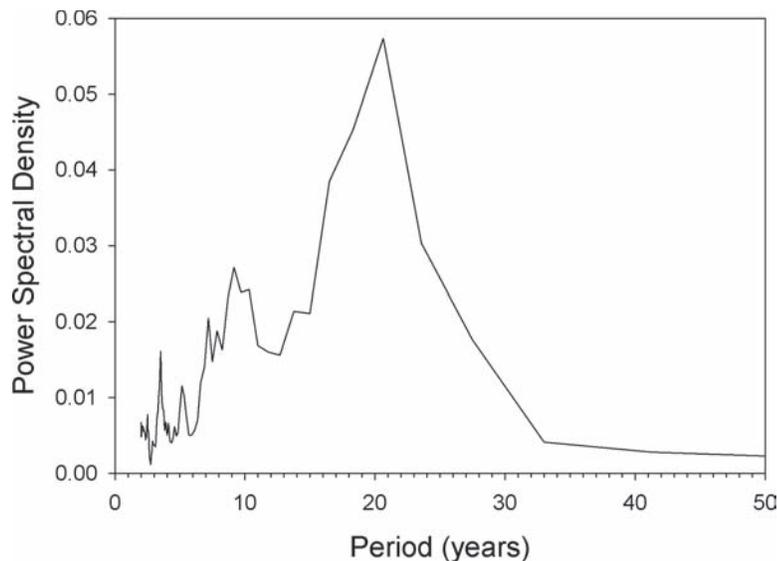


Figure 3.—A plot of the power spectral density of the 386-year tree-ring chronology with notable peaks in variance at periods of 3.5, 9, and 21 years. The tree-ring index time series was significantly different from white noise.

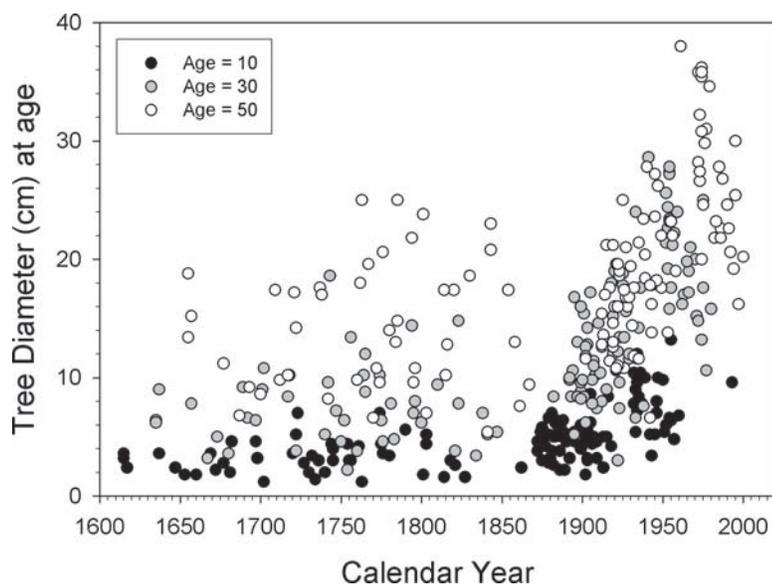


Figure 4.—A scatter plot of shortleaf tree diameter by calendar year. The plot shows the diameter and year of individual trees at ages 10, 30, and 50 years. On average, the growth at age of shortleaf pine trees currently growing at MOFEP have been unsurpassed in comparison to trees growing prior to 1880.

21-year peak was not significantly different from the white-noise spectrum was rejected (Fisher's Kappa = 10.46, $p < 0.01$; Bartlett's Kolmogorov-Smirnov test statistic = 0.29, $p < 0.0001$).

We quantified tree diameter at ages 10, 30, and 50 years for all tree-ring series with estimated pith dates. Series were divided into two periods; pre- and post-1880. T-tests showed that the growth of trees between the two periods is significantly different for all tree age classes (table 1). Trees post-1880 grew faster than those grown pre-1880 (fig. 4).

Climate response

We used a highly replicated tree-ring chronology that spanned the instrumental climate record of 1895–2002 to analyze climate response variables. The highest correlations between the 107-year tree-ring index and a single monthly climate variable was for July PDSI ($r = 0.51$, $p < 0.0001$). All individual growing season (May through July) PDSI variables were significantly correlated ($r = 0.43$ to 0.51 , $p < 0.0001$) with the tree-ring index. Mean PDSI variables for a growth year (January through July) and

Table 1.—Important changes in forest history occurred circa 1880 for the study site region (see text). A comparison of shortleaf pine mean tree diameters at age between the pre- and post-1880 periods. We hypothesized that there is no significant difference in growth at ages 10, 30, and 50 years between the two periods. The null hypothesis was rejected for each of the age comparisons.

Tree age	Period	n	Mean		t-stat	p
			diameter (cm)	Variance		
10	Pre-1880	72	3.77	2.37	-7.34	<0.0001
	Post-1880	57	6.75	7.49		
30	Pre-1880	72	8.79	13.12	-9.04	<0.0001
	Post-1880	56	16.97	35.63		
50	Pre-1880	72	14.96	23.7	-6.95	<0.0001
	Post-1880	56	23.15	59.42		

mean annual PDSI values also yielded significant correlations ($p < 0.0001$). Although several individual months of precipitation and temperature (e.g., June precipitation, $r = 0.40$, $p < 0.0001$; July temperature, $r = -0.44$, $p < 0.0001$) were significantly correlated to the tree-ring index, combinations of these variables (e.g., PDSI) can better represent the climatological influence on growth. Extreme minimum winter temperature (February and March, 1931-2001) was also significantly related to the ring-width index.

The independent variables predicting the tree-ring index were growth year PDSI values, extreme minimum winter temperature, and previous year fall PDSI. Because of the inclusion of extreme minimum winter temperature, our response function was developed from data taken during the period 1931-2001. The response function was defined as:

$$\text{TRI} = 0.92 + 0.07*(\text{PDSI}_G) + 0.01*(\text{ExT}_W) - 0.02*(\text{PDSI}_F)$$

where: TRI = tree-ring chronology index

PDSI_G = mean of growth year PDSI values (January through July),

ExT_W = extreme minimum temperature (February and March), and

PDSI_F = mean PDSI values of previous year fall season (October through December)
(model $r^2 = 0.43$, $p < 0.0001$)

Correlations between monthly PDSI and the tree-ring index using 36-year moving intervals were also greatest for June PDSI, particularly during the periods with moving interval end dates between 1954 (i.e., 1918-1954) and 1967 (i.e., 1931-1967) (fig. 5). The individual months May, June, and July PDSI were generally highly correlated to tree-ring indices for all 36-year intervals, except those intervals with end dates after 1987 (i.e., 1951-1987). Correlations between monthly PDSI and the tree-ring index for months prior to the growing season (i.e., prior to May) were less correlated with PDSI than growing season summer months (May through August). Pre-growing season months (January to April) had the greatest portion of significant correlations around the period of approximately 1909 to 1970, suggesting that, at least during some years of growth, conditions prior to the period of cambial expansion are important for current year growth. This result, coupled with a potential trend towards higher correlations between ring-width indices during months prior to the growing season (e.g., January and February) and the lack of correlation late in the growing season (e.g., July and August) may point to changes in climate. Six of the last eight moving intervals (i.e., 1994-2002) had significant correlations during growing season January. No significant correlations existed between PDSI of growing season months and the tree-ring index after the interval with end date 1985 (i.e., 1949-1985).

Discussion

In the last few decades advances in tree-ring research, its methodology, and computer technology have contributed significantly to our understanding of the relationship between tree-growth, climate, and anthropogenic and natural disturbances in the Midwestern U.S. (Meko and others 1985, Cleaveland and Stahle 1989, Cook and Cole 1991, Cleaveland 1995, LeBlanc 1998, Woodhouse and Overpeck 1998, Guyette and others 2002, Hughes 2002, Fye and others 2003). The 386-year tree-ring chronology described here provides important information about long-term variability in shortleaf pine tree growth and the influence of climate at one of the largest landscape scale ecosystem projects in the country. MOFEP, an ecosystem project with an expected 100-year duration, can not only utilize the information here to gain a historical perspective of the growth of their current shortleaf pine forests, but also to apply the long-term variations recorded by tree-rings to the long-term variation in other ecosystem components. Relative to other MOFEP ecosystem components, trees are likely the best resource for quantifying and identifying long-term temporal climate and other environmental changes because trees are relatively long-lived, stationary in geographic location, relatively abundant, contain inter- and intra-annual growth information, and extensively studied thus comparable to many other locations.

Our results suggest that shortleaf pine growth at MOFEP is influenced by continental scale atmospheric general circulation patterns as suggested by Su (1997). The 21-year drought cycle is very similar in length to the 22-year drought cycle that has been found to influence tree-growth across the other parts of western (Mitchell and others 1979, Ammons and others 1983) and Midwestern United States (Meko and others 1985). In more detailed studies (Mitchell and others 1979, Stockton and others 1983) attributed the near 22 yr period (i.e., drought cycle) to the Hale solar cycle and commented about its somewhat imprecise rhythm. Guyette (1981) also found shorter periodicities represented in variance of tree-rings of white oak (*Quercus alba*) and eastern redcedar (*Juniperus virginiana*) growing in the Ozark region. In a qualitative sense, a near 22-year drought cycle fits many of the notable droughts of Missouri during the 20th century from 1911, 1912 to the 1930's dust bowl droughts to 1952-1954 to 1978 to 2000-2002. Most of these years had tree-ring index values < -0.20 (fig. 2). If the 21-year cycle continues as it has over the last 300 or more years, shortleaf pine indexed growth at MOFEP is expected to be entering a negative phase (fig. 2).

The correlation between the tree-ring index and individual monthly PDSI values using moving interval techniques showed that the strength of the correlation over the past century has important characteristics for understanding tree-climate response. One explanation for the high correlation between the tree-ring index and PDSI during the early half of the 20th century is that this was a period of abundant drought years, thus a growth-limiting factor common among all trees. In comparison, the latter half of the twentieth century has few intervals with significant correlation to PDSI which, at least in part, explains the low variance explained in the response function. During relatively wet periods, as was the case throughout much of the 1960s and through the 1990s, growth is not limited by moisture therefore, tree-rings, particularly shortleaf pine on xeric aspects, can be poor predictors of climate conditions.

An arguable explanation for a change in correlation between the tree-ring index and PDSI over the last century is that climate in the region is changing. Cleaveland and Stahle (1996), in a tree-ring reconstruction of Ozark hydrologic drought using oaks (*Quercus stellata*, *Quercus alba*), eastern redcedar (*Juniperus virginiana*), and baldcypress (*Taxodium distichum*), identified a marked decrease in Palmer Hydrologic Drought Index (PHDI) variance occurring in the mid 20th century. A notable feature of the correlation between the tree-ring index and PDSI is the increase in the number of significantly correlated intervals for months prior to the onset of growth (fig. 5). Our climate response function supports that PDSI and extreme minimum temperatures prior to the period of wood formation have important influence on growth occurring primarily May through July. Minimum monthly winter temperature data from the Ozark region shows a trend of continual small increases in mean minimum winter temperature. Increases in winter temperature could benefit the growth of shortleaf pine, particularly in Missouri where the species' range and growth potential may be limited by temperature

(Fletcher and McDermott 1957, Lawson 1990). Assuming minimum winter temperatures will continue to increase and that the growth of shortleaf pine will positively respond to further increases, management to promote the species would be of increased value. Furthermore, increased growth rates by shortleaf pine would likely increase the species' ability to compete with hardwoods. This is particularly important under conditions of small-scale forest disturbances (e.g., canopy gaps), where shortleaf pine success is very low (Stambaugh 2001, Stambaugh and others 2002).

Despite the limitations on growth by climatic factors, our analysis shows that shortleaf pines at MOFEP are growing faster than they have over the past 300 years. Significant land use changes circa 1880 were used to separate our two sets of growth data. Explanations for the result that trees prior to 1880 grew significantly slower than post-1880 are numerous. Likely the most important event was lumbering and its effect of releasing advanced shortleaf pine regeneration, reducing competition, and increasing available light. Despite the effects of lumbering on pine growth, the difference in fire disturbance regimes between the two periods have likely also been important. Because the effects of fire on tree-growth were likely different during each stage of the regional anthropogenic fire regime (Guyette and others 2002) it is difficult to measure the influence of repeated fire disturbances. Future studies of the effects of overstory removal and fire disturbances on pine growth would not only enhance our understanding for shortleaf pine management but also aid in interpreting historic changes in tree growth.

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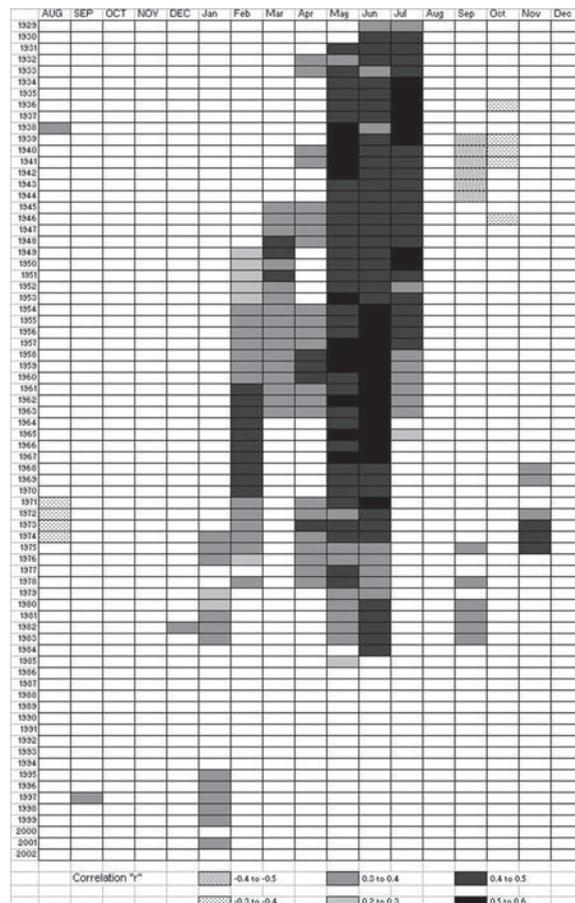


Figure 5.—Correlation matrix of ring-width index and monthly PDSI values. Months in capital letters are prior to the year of growth and smaller case months are during the year of growth. Each box represents a 36-year moving interval that ends on calendar year represented on the y-axis (e.g., 1950 represents the 36-year interval 1914 to 1950). Box shade represents the correlation coefficient between the ring-width index and PDSI values. Empty (white) boxes are intervals of no significant correlation ($p \geq 0.010$). See legend for correlation value ranges.

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