CLIMATIC RESPONSE IN TREE RINGS OF LOBLOLLY PINE FROM NORTH GEORGIA

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Abstract: The relationship between climate and tree-growth for loblolly pine in north Georgia is investigated by: 1) determining during which months climate has its strongest impact on loblolly pine growth, and 2) specifically examining the relationship between loblolly pine growth and growing season precipitation. Response function analyses indicate that precipitation during the current May-August period has a positive effect on pine growth, while the previous growing season shows no significant effect on growth. Significant negative effects of temperature were found during the previous June and August, current April, and the current June-September period. A regression model predicting the May-September growing season rainfall total as a function of tree-ring indices was highly significant ($r^2 = 0.48$). These results indicate that loblolly pine is a useful species for investigating the impact of climate and other factors on the recent decline of pine growth in the southeastern United States. [Key words: Dendroclimatology, tree rings, loblolly pine, Georgia.]

Dendroclimatology is the science which extracts climatic information from the annual growth layers of woody plants, and assumes that these growth layers reflect the environmental conditions under which they were formed (Fritts, 1971; Hughes et al., 1982). Few dendroclimatic studies have been conducted in the southeastern United States, owing in part to the temperate, non-stressful climate of that region. Because of the many reports of growth reductions in commercially-important southern species (Sheffield et al., 1985; Sheffield and Cost, 1987; Dell, 1987; Lucier, 1988), tree-ring research may be employed to investigate the causes of these reductions.

The drought years experienced by the southeastern United States in the 1980s have focused attention on the effects of climatic variability upon the growth rates of southern pine species. Climate studies which utilize tree-ring data help determine whether climate is primarily responsible for recent growth reductions, or whether other factors, such as atmospheric deposition or tree pathogens, act together with climatic effects in a complex process to enhance these growth reductions. The purpose of this study is: (1) to determine during which months climate has its strongest impact on loblolly pine growth from a site in north Georgia, and (2) to examine the relationship between loblolly pine growth and growing season precipitation.

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PREVIOUS STUDIES

Several recent studies have utilized tree rings from species found in the southeastern United States to investigate climate/tree-growth relationships. Cleaveland (1975) reconstructed summer precipitation totals back to 1683 based on tree-ring data from shortleaf pine (*Pinus echinata*) in South Carolina. Phipps et al. (1979) analyzed tree rings of loblolly pine (*Pinus taeda*) from the great Dismal Swamp in Virginia and found that 72% of ring-width variability could be explained by climatic factors. Puckett (1981) reconstructed the Palmer Drought Severity Index (PDSI) for July back to 1745 based on tree rings of Eastern hemlock (*Tsuga canadensis*) from northern Virginia. Tainter et al. (1984) investigated the possible role of climatic effects in the growth decline of Northern red oak (*Quercus rubra*) in North Carolina. Zahner (1987a) suggested atmospheric deposition as a probable cause for the reduction in growth rates of loblolly pine from South Carolina after having adjusted for site and climatic effects. Grissino-Mayer and Butler (1988) should be consulted for references relevant to other regions.

TREE-RING AND CLIMATIC DATA

Twenty-seven loblolly pine were randomly chosen within a 20 km radius of the University of Georgia campus in Clarke and Oconee Counties, Georgia. All age classes were sampled as preference was given to those trees growing in what was believed to be a climatically-sensitive habitat (Schulman, 1937). No preference was given to longevity, because reconstruction of climate before historical periods of record was not the purpose of this study. Two increment cores were extracted at breast height on opposite sides of the tree parallel to the existing slope. The cores were then processed using standard dendrochronological techniques (Stokes and Smiley, 1968; Phipps, 1985).

Crossdating, which ensures a properly dated chronology (Douglass, 1941), indicated few missing rings in any cores. False rings were noted on most cores, but were easily identified by their diffuse termination into the larger earlywood cells (Cleaveland, 1980). However, cores from seven pine could not be accurately crossdated because of damage and were excluded from this study. Ring widths were then measured to the nearest 0.01 mm and automatically recorded in diskette files. Finally, ring widths from cores of the same tree were averaged to produce 20 individual series.

All trees experience a decrease in radial growth with increasing age, which makes the growth series nonhomogenous about the mean (Fritts, 1976). The process of standardization effectively removes most of the growth trend, a major source of autocorrelation in the series, and ensures a consistent growth series with a mean of one. In this study, the traditional standardization method was employed by fitting the growth series of each tree to a linear, negative exponential, or low-order polynomial regression model with tree age as the independent variable. Ring-width indices for each tree for all years were then obtained by

$$I_t = R_t \,/\, \hat{Y}_t \tag{1}$$

where R_t is the actual ring width for year t, and $\hat{Y}_t$ is the predicted ring width (Graybill, 1982). Finally, indices for the 20 pine were averaged by year to produce a final master chronology extending back to 1911.

Monthly temperature and precipitation data (1895-1986) for north central Georgia were isolated from a master climate data tape obtained from the National Climatic Data Center in Asheville, North Carolina, and output to separate files. Regionally-averaged data were used because previous studies have shown that these data provide better results during regression analysis with tree-ring indices than single-station climate data (Lawson et al., 1980; Blasing et al., 1981). New variables for various monthly combinations (March to October), representing total growing season rainfall, were created and retained in the precipitation data file.

STATISTICAL ANALYSES

General univariate statistics were obtained to compare the climatic sensitivity of the loblolly chronology to other chronologies from the eastern United States (DeWitt and Ames, 1978). Primary statistics include standard deviation, first-order autocorrelation, and mean sensitivity. A high standard deviation is desirable and would indicate that loblolly pine is highly responsive to environmental factors. First-order autocorrelation is used to assess the influence of previous growth upon the current year's growth. Mean sensitivity, a measure of year-to-year variability, is calculated as

$$ms = \frac{1}{n-1} \sum_{t=1}^{n-1} \left| \frac{2\,(x_{t+1} - x_t)}{x_{t+1} + x_t} \right| \tag{2}$$

where x_t is the ring width for year t over n number of observations (Douglass, 1936). The effective range is from zero to two, representing a completely complacent and extremely sensitive growth series, respectively.

A rigorous assessment of the effects of climate upon tree growth is gained through response function analysis using the principal components of the normalized climate data set to reduce effects resulting from covariance among the independent variables. The weights of each response function represent the separate effects of temperature and precipitation upon tree growth on a monthly basis. The following methodology was used in this study, and is discussed in detail by Fritts (1976, 356–370).

Using lag functions, a new climate data set combining both temperature and precipitation data was created spanning previous May to current October.

Growth indices from the previous three years were also included to allow for effects resulting from biological persistence. Factor scores for each observation on each of the significant principal components of the normalized data set were used in a stepwise multiple regression to predict a new chronology, expressed in matrix notation by

$$_1\hat{Y}_n = {}_1R_pX_n \tag{3}$$

where $_1\mathbf{R}_p$ is the unknown row vector of coefficients for the significant number of p factor scores (X) retained.

The monthly weights of the response function were obtained by

$$_1\mathbf{T}_m = {}_1\mathbf{R}_p\mathbf{E}'_m \tag{4}$$

where $_p\mathbf{E}'_m$ is the transpose of the eigenvector matrix with m number of variables. Confidence limits for these weights were computed from the diagonal of the symmetric matrix

$$_m\mathbf{S}_m = {}_m\mathbf{E}_p\mathbf{U}_p\mathbf{U}_p\mathbf{E}'_m \tag{5}$$

where $_p\mathbf{U}_p$ is a matrix whose diagonal contains the standard errors of the coefficient row vector, $_1\mathbf{R}_p$. Any weight with a significant negative or positive departure from the standardized index indicates a month in which climate has a strong impact on pine growth.

Simple regression was used to model the growing season precipitation total as a function of loblolly pine growth. Because outliers adversely affect the estimated parameters of the regression model (Freund and Littell, 1986), each observation was evaluated as to whether or not it was poorly predicted (Graumlich, 1987). This evaluation was accomplished by inspection of studentized residuals, a diagnostic statistic obtained by dividing the residual $(Y_t - \hat{Y}_t)$ by its standard error. Because values of 2.5 or greater are rare in this distribution, any observation which exhibited a studentized residual of 2.5 or greater was deleted from the analysis, and a new model was generated.

Graumlich (1987) has pointed out that the final climatic reconstruction is always less variable than the original climate data used in the regression analysis. In this study, predicted values were rescaled to the original variance by first subtracting the mean of the series from each observation. Each centered observation was then multiplied by a scaling factor, k, defined as

$$k = s_x / s_p \tag{7}$$

where s_x and s_p are the standard deviations of the original and predicted values, respectively. Finally, the mean was then added back to each observation.

Table 1. Primary Descriptive Statistics Obtained for Loblolly Pine and the Average for Shortleaf Pine from Nine Previous Studies

Descriptive statistic	Average of previous studies (shortleaf pine)		Current study (loblolly pine)
Mean sensitivity	Upper 95%	0.293	
	Mean	0.202	0.134
	Lower 95%	0.112	
First-order auto-correlation	Upper 95%	0.796	
	Mean	0.533	0.429
	Lower 95%	0.270	
Standard deviation	Upper 95%	0.438	
	Mean	0.277	0.164
	Lower 95%	0.116	

RESULTS

Because little research has investigated loblolly pine tree-ring data, no previously published statistics are available for comparison. However, the average means and their 95 percent confidence limits from nine previous studies for shortleaf pine are included (DeWitt and Ames, 1978) for comparative purposes (Table 1).

Mean sensitivity for the loblolly chronology was low (0.134) but within

Table 2. Correlation Coefficients between Loblolly Pine Growth Indices and Various Yearly Periods Incremented by Decade[a]

Period	Coefficient
1961–1986	0.471
1951–1986	0.557
1941–1986	0.577
1931–1986	0.564
1921–1986	0.614
1911–1986	0.482

[a] All values are significant at the 0.01 level.

Table 3. Correlation Coefficients between Loblolly Pine Growth Indices and Regionally-Averaged Monthly Rainfall and Temperature (1921–1986)

Month	Rainfall	Temperature
January	−0.127	0.118
February	0.154	0.089
March	0.175	0.102
April	0.044	−0.306**
May	0.311**	0.010
June	0.357***	−0.283*
July	0.305***	−0.364***
August	0.277*	−0.340***
September	0.121	−0.428***
October	0.067	0.174
November	0.118	0.044
December	0.069	−0.029

*significant at the 0.05 level
**significant at the 0.01 level
***significant at the 0.005 level

the 95 percent confidence limits for shortleaf pine. This statistic may reflect a fast growth rate causing any narrow latewood produced during periods of moisture stress to exert less influence on total ring width. First-order autocorrelation for loblolly pine was slightly lower (0.429) than the average figure for shortleaf pine, but still indicated a strong dependence of current growth upon the previous years' growth. Standard deviation was much lower for loblolly pine (0.164) than for shortleaf pine, verifying the less variable nature of the former sampled for this study.

Correlation coefficients between loblolly pine growth indices and climate data were obtained for various periods to ensure the stability of the relationship over time (Table 2). Correlation between indices and climatic data during the period 1911-1986 (0.48) is much lower than the 1921-1986 period (0.61), possibly because only one pine extended from 1920 to 1911. This period was not considered in further analyses, and new correlation matrices between tree-ring and climate data provided a preliminary assessment of the strength of the climate/pine growth relationship (Tables 3 and 4).

Response function analysis of the effects of precipitation on loblolly growth indicated significant ($p < 0.05$) positive effects during the May-August period (Fig. 1), verified by the significant correlation coefficients (Table 3). However, monthly precipitation from the previous growing season showed

Table 4. Correlation Coefficients between Loblolly Pine Growth Indices and Various Combinations of Growing Season Precipitation Totals (1921–1986)

Interval	Coefficient*
March–August	0.513
March–September	0.520
March–October	0.519
April–August	0.508
April–September	0.534
April–October	0.537
May–August	0.567
May–September	0.614
May–October	0.607
June–August	0.482
June–September	0.543
June–October	0.541

*All coefficients significant at the 0.001 level.

no significant effects upon current loblolly pine growth. The temperature response function (Fig. 2) revealed significant negative effects during April and the June-September period, a sequence also revealed by the correlation coefficients (Table 3). In addition, significant negative weights were found in previous June and August values, while the only significant positive effect was found in the previous October value. Finally, only the previous growth from the most recent growing season was found to have a significant effect on the current year's growth.

The May-September interval of growing season rainfall was selected for regression analysis based on the correlation coefficient for this interval (0.614), and because model statistics generated using other intervals indicated poorer models. Outliers were detected during 1967 and 1979 and deleted from the final analysis. In final form, the model was expressed as

$$(\text{May-Sept PPT})_t = (20.261 * I_t) + 0.088 \qquad (6).$$

This model accounted for 48% of the variability of growing season rainfall. First-order autocorrelation of the residuals (0.040) was insignificant, and indicated that the assumption of random error in ordinary least squares

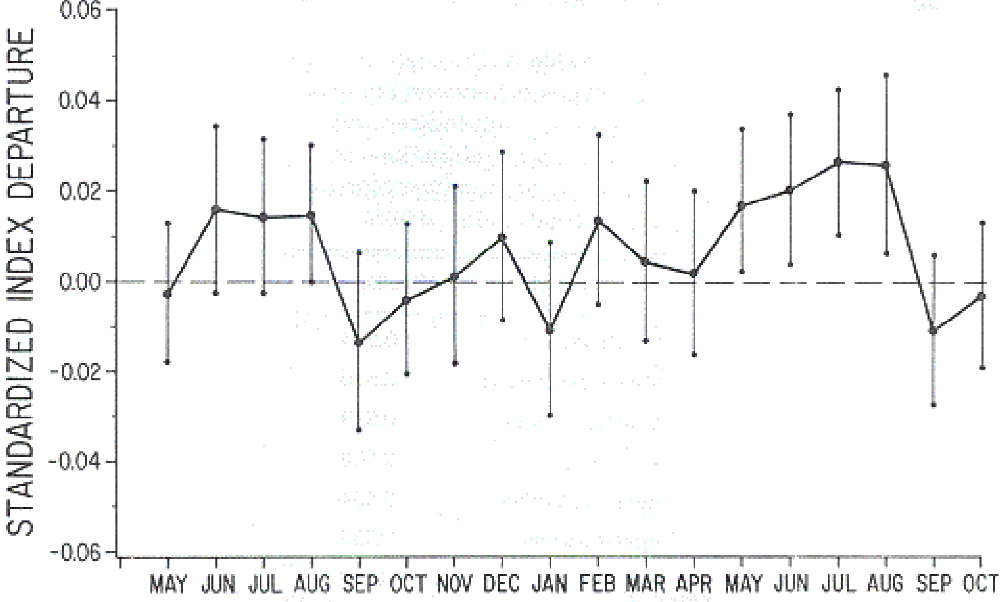

Fig. 1. Response function indicating months during the previous and current growing season in which precipitation has a strong impact on loblolly pine growth. Error bars indicate the 95% confidence limits.

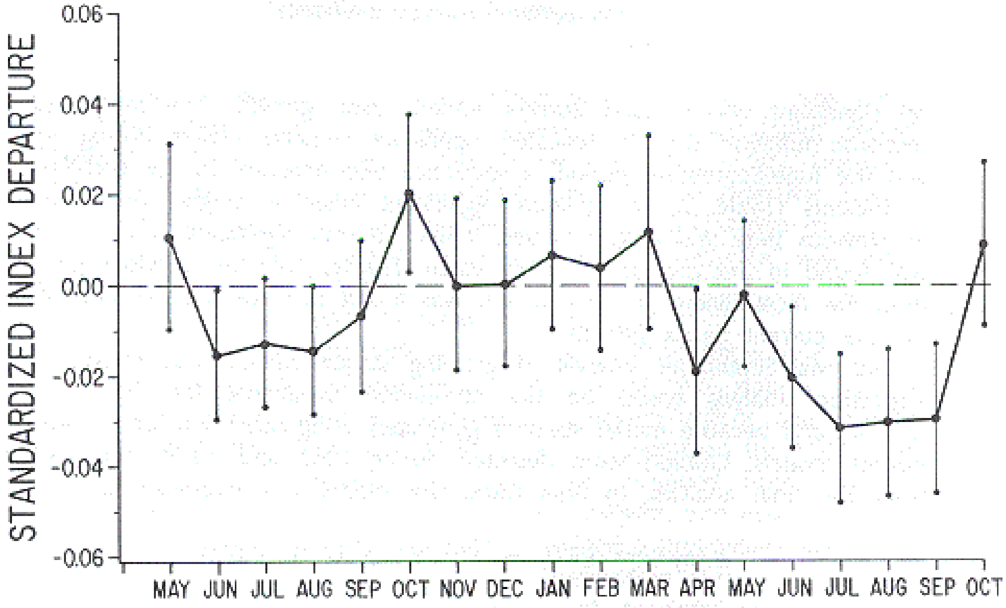

Fig. 2. Response function indicating months during the previous and current growing season in which temperature has a strong impact on loblolly pine growth.

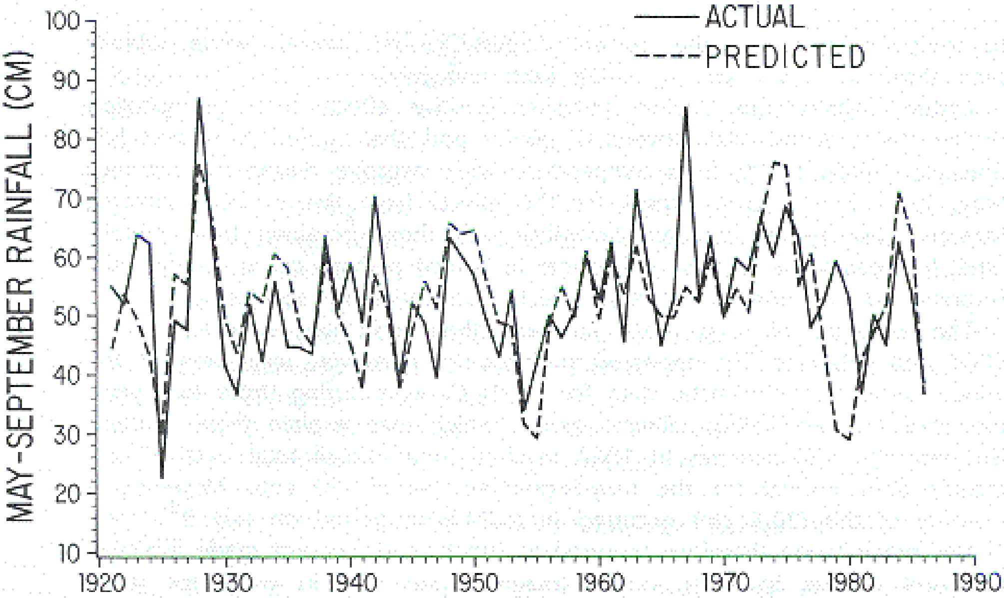

Fig. 3. Reconstructed growing season rainfall predicted from tree-ring data of loblolly pine showing the high degree of correlation between precipitation and tree growth.

regression had not been violated. After applying the scaling factor, predicted values indicate a high degree of correlation with the observed values (Fig. 3).

DISCUSSION

Growth indices for loblolly pine from a site in north Georgia, derived using dendroclimatological techniques, are significantly correlated with regionally-averaged monthly precipitation and temperature. Growth response to precipitation effects is strongest during the current May-August period, but no effect from rainfall of the previous growing season is detected. Response to monthly temperature was found to be strongest during the previous June-August period, current April, and the current June-September period, with the only positive response occurring in the previous October. No explanation for the exclusion of the current May temperature from this analysis can be offered until further studies verify this exclusion.

Few studies conducted in the southeast United States have provided results for the timing and response of southern species to monthly climatic factors using orthogonally-transformed data. Cleaveland (1975) found positive effects from precipitation upon the annual growth of shortleaf pine during the previous October-December and current July-October periods, and negative effects during the current January and March. However, loblolly pine shows no effects from the previous growing season, and no negative effects. Shortleaf pine annual growth was also found to be inversely related to temperature during the current August-October period, while loblolly pine show additional effects during June and July.

Eastern hemlock in Virginia indicates positive effects from precipitation during the previous May-November period and the current May and July (Puckett, 1981). Effects from temperature were negative during the previous May, June, and August. Except for the effects from the previous growing season, these results compare favorably with those obtained from loblolly pine. It appears that regional differences in habitat perhaps cause a differential response to environmental factors which also varies by species.

The existence of rings much narrower than what was expected during 1967 and 1979 at first appeared problematic. However, inspection of the annual summary of climatic data for north Georgia during these two years indicated two anomalous climatic events which may explain these outliers. An unusually wet summer in 1967 resulted in a rainfall total over 35 cm greater than normal for the May-September period (50 cm). However, a majority of this (22.5 cm) occurred in a 24-hour period on July 9th. Most of this precipitation therefore occurred as runoff, and was not made available for plant uptake. In 1979, north Georgia experienced its worst ice storm in 50 years, which resulted in extensive damage to most trees, especially pine. The relationship between ring width of loblolly pine and ice storms is currently being investigated (Travis et al., 1989).

Future studies will concentrate on creating a larger and longer tree-ring data base which should further enhance the climatic signal found in the tree-ring data. Other species from the Georgia piedmont region, such as shortleaf pine and white oak (*Quercus alba*), will also be considered for analysis because of the longer chronologies possible from these species. Finally, techniques have been described which investigate effects of atmospheric deposition upon growth rates of eastern species (Phillips et al., 1977; McLaughlin and Bräker, 1985; Cook et al., 1987), and should be applied jointly with dendroclimatic analyses to investigate in detail the possible causes of recent pine growth reduction in the southeast.

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