Southeastern Geographer
Vol. XXXIII, No. 1, May 1993, pp. 65–81

EFFECTS OF CLIMATE ON GROWTH OF SHORTLEAF PINE (*Pinus echinata* Mill.) IN NORTHERN GEORGIA: A DENDROCLIMATIC STUDY[1]

Henri D. Grissino-Mayer and David R. Butler

Recent applications of dendroecological techniques in the southeastern United States have focused upon the analysis of forest health to assess the rate, timing, and magnitude of changes in recent (<30 years) growth rates of southern pine species. However, knowledge of the pine growth/climate relationship is necessary before such assessments can be made. We developed a tree-ring index chronology from shortleaf pine growing in north-central Georgia and investigated the pine/growth relationship using correlation and response function analyses and multiple regression techniques. We found that shortleaf pine have a significant positive response to above-normal precipitation and a significant negative response to above-normal temperature during the current growing season, especially from May to July. We also found a strong time-dependent response by shortleaf pine to climate during the period studied (1910–1986). A regression model using certain monthly climatic variables as predictors explained 46% of the variability in the index chronology. However, climate variables do not adequately model growth beginning in 1963 as the residuals from the climate/growth model show increased variability over the previous periods. This change in pine growth rates since 1963 must therefore be due to nonclimatic factors.

Previous applications of dendrochronology in the southeastern United States have focused on the identification of species that exhibit "sensitive" (i.e., variable) series of growth-rings and examining climate/tree growth relationships (Friend and Hafley, 1989; Grissino-Mayer et al., 1989; Jordan and Lockaby, 1990; Schulman, 1942). However, recent research in the Southeast has focused upon the analysis of forest health using dendroecological techniques to assess the rate, timing, and magnitude of changes in growth rates of southern coniferous species (Adams et al., 1985; Zahner et al., 1989). Many of these studies document a marked decrease in radial growth within the last 20 to 30 years (Cook, 1988; Sheffield et al., 1985) that may be due to anthropogenic effects,

---

Mr. Grissino-Mayer is a Graduate Research Associate at the Laboratory of Tree-Ring Research, University of Arizona, Tucson, AZ 85721, and Dr. Butler is Associate Professor of Geography at the University of North Carolina, Chapel Hill, NC 27599-3220.

such as acidic deposition (Pitelka and Raynal, 1989) or environmental effects, such as drought. Drought is a possible factor responsible for these reductions in growth because moisture stress in the southern pine species is believed to have been greater in the 1970s and 1980s than during previous decades (Sheffield et al., 1985, p. 33).

Differentiating between anthropogenic and environmental effects requires *a priori* knowledge on the effect each would have upon tree growth in the absence of the other. It is therefore critical to understand the climate/growth relationship for southern pine species in order to better identify factors causing the decline in southeastern pine growth. One approach that could use this relationship and help isolate factors that impact shortleaf pine growth is to first remove the physiological component of tree growth, i.e., the age trend, and then model the climate/tree growth relationship. The residual series can then be modeled with other possible candidate variables (e.g., acidic deposition). This method is possible because tree growth can be modeled using a linear combination of exogenous (originating from outside the stand), endogenous (originating from within the stand), and physiological (increasing tree age) factors (Cook, 1990). The residual series from such a model may contain information on other factors impacting growth of shortleaf pine not accounted for by the previous models.

Results of research from a single site, however, will not isolate impacts affecting an entire region. For this reason, it is necessary to develop a network of sites (Gholz, 1982; Graybill and Rose, 1989) throughout the Southeast and to investigate in detail the climate/pine growth relationship at each of these sites. This approach is necessary because topography, soils, disturbances, species composition, climate, and anthropogenic influences are not homogeneous throughout the Southeast. Each site therefore should exhibit subtle differences in the climate/pine growth relationship because of site heterogeneity. Only by incorporating such a network of sites and synthesizing results from research throughout the Southeast can we begin to isolate factors responsible for southeastern pine growth decline.

PURPOSE OF THE STUDY. We investigated the climate/pine growth relationship using a tree-ring series developed from shortleaf pine (*Pinus echinata* Mill.) growing at three sites in northern Georgia. The primary objectives of this research were to: (1) quantify the ring-width variability of shortleaf pine; (2) develop a tree-ring based annual chronology of growth indices; (3) compare the final chronology with others developed in the Southeast; (4) determine during which months climate exerts its strongest influence on shortleaf pine growth; and (5) develop an empirically derived mechanistic model of shortleaf pine growth using selected environmental variables. We will then discuss how knowledge of this climate/pine growth relationship can be used to help identify factors that may lead to a decrease in pine growth rates.

STUDY SITE. The study sites are located in Clarke County, Georgia (Fig. 1), in the north central NOAA climate division. The county is situated in the Piedmont physiographic province characterized by rolling hills overlying a granite/gneiss bedrock (Hodler and Schretter, 1986). The climate is broadly classified as humid subtropical with an average annual precipitation of 141 cm and mean annual temperature of 15°C (Hodler and Schretter, 1986). Vegetation is dominated by three genera: pine; oak (*Quercus* spp.); and hickory (*Carya* spp.), with oak-hickory being the dominant community type. Most vegetation communities in the Piedmont are secondary in origin, having developed from abandoned agricultural fields (Della-Bianca and Olson, 1961). However, we found three sites that contained shortleaf pine trees over 100 years old growing under similar topographic and soil conditions (Fig. 1).

TREE-RING DATA. We extracted 77 cores from 31 shortleaf pine trees at the three sites within the study area. We first crossdated all cores visually using the extreme-ring match-mismatch method (Phipps, 1985), then used program COFECHA to ensure the correctness of the crossdating once all series had been measured (Holmes, 1983). Because of the topographic homogeneity of the three sites, the similar ages of the trees growing at these sites, and the series intercorrelations which showed no major deviations from normal growth among trees growing at these sites, series from all three locations were pooled into one dataset. Using program ARSTAN, we then detrended all measured series by fitting a cubic smoothing spline with a 50% cutoff wavelength (Cook and Peters, 1981), than obtained dimensionless indices by dividing the actual ring measurement by the spline value. Program ARSTAN then averaged these indices by year from all series to develop a standard index chronology and also calculated the common descriptive statistics for the index chronology with which we may compare other shortleaf pine tree-ring chronologies (DeWitt and Ames, 1978).

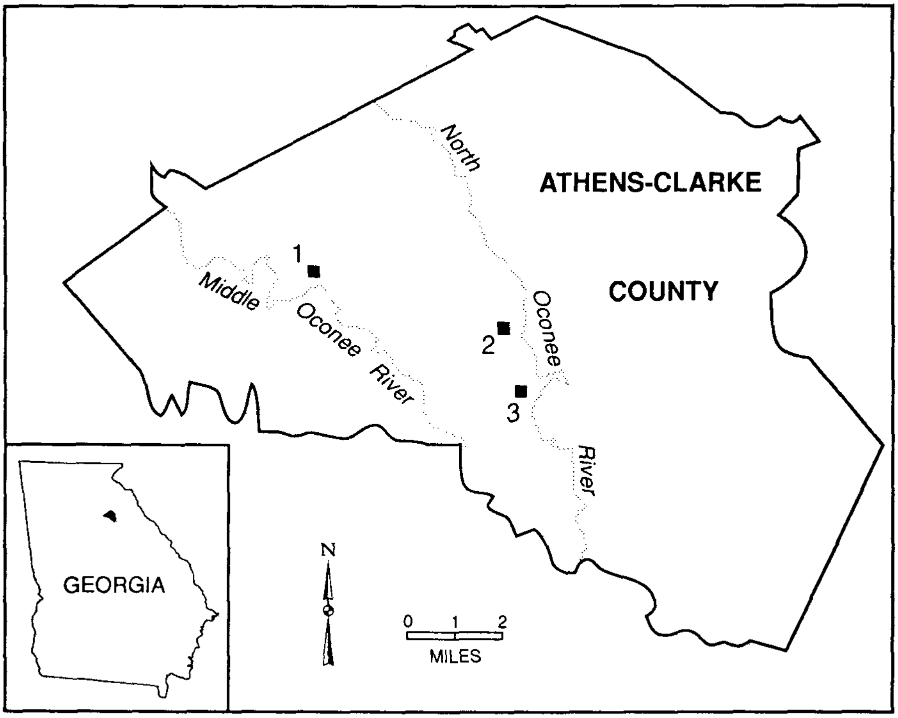

Fig. 1. Athens-Clarke County, Georgia, with locations of the three sites sampled: (1) the east bank of the Oconee River at Ben Burton Park; (2) a relict stand on the University of Georgia campus; (3) and in the Oconee Experimental Forest.

CLIMATIC DATA. We examined both local and regional monthly climatic data to determine which was more appropriate for these analyses. Local data are available from the nearby weather station in Athens back to 1910, while regional data are available for the north-central Georgia climate division back to 1895. Local data included both total monthly precipitation and average monthly temperature, while regional data analyzed include these data as well as the Palmer Drought Severity Index (PDSI) and the Palmer Hydrological Drought Index (PHDI). To assess the possible influence of climate over an entire growing season, we created new variables by adding monthly precipitation totals and averaging mean monthly temperatures over various intervals from March to October.

PHDI is a real-time calculation of PDSI and only changes sign when the ratio of moisture received to moisture required to end a dry or wet spell equals 100% (Karl and Knight, 1985). PHDI therefore responds more slowly to changes in weather regimes than does the PDSI, but more closely approximates true subsurface hydrologic characteristics. However, because index values from previous months are used to calculate current values, both indices exhibit high degrees of autocorrelation from one month to the next precluding the use of multiple regression techniques on these variables without additional treatment (e.g., prewhitening).

METHODS. We used three techniques to assess the climatic influence on growth of shortleaf pine. First, we performed correlation analyses between monthly and seasonalized precipitation and temperature and the shortleaf pine tree-ring index chronology. The climatic variables were also lagged to determine whether climate during the previous growing season, beginning in July, affects pine growth during the current growing season. The use of lagged variables is necessitated because tree growth during the current growing season is partially dependent on carbon uptake and production of photosynthates that occur during the previous growing season as well as during the dormant season (Fritts, 1976, pp. 25–27; Waring, 1983).

Second, we used response function analysis (Fritts, 1976, pp. 376–405), a more robust analysis that minimizes effects due to multicollinearity among variables. In this analysis, climatic data spanning previous July to current October are first orthogonalized, then entered into a stepwise multiple regression with the standard index chronology as the dependent variable. Because the index chronology may be highly autocorrelated, three new variables representing growth from the three previous years are created by lagging the chronology, and were also included in the response function analysis (Fritts, 1976). Any principal component with an eigenvalue greater than one is added to the multiple regression equation (Daultrey, 1976; Guiot, 1990). The resulting regression equation contains the weights (coefficients) for each of the original climate variables. The standard error for each monthly coefficient is also calculated to determine the 95% (two standard error) confidence interval for each month in the response function. Any weight significantly different from zero indicates a month in which precipitation or temperature significantly affects pine growth.

For the final analysis, we modeled the shortleaf pine index chronology with the most influential climate variables using multiple regression. Only variables that entered significantly ($p < 0.05$) into a preliminary model using stepwise regression analysis were used. The dataset was first divided into two smaller half-subsets (1910–1948 and 1949–1986) and climate/growth models were generated. Both models were then verified using the independent data withheld from the calibration period. Verification statistics used included correlation coefficients between the actual and predicted data, the reduction of error statistic, and the chi-square test (Fritts, 1976, pp. 330–340). The model with the best verification statistics was chosen for the final multiple regression. Regression diagnostics in this final analysis included: (1) visually inspecting the graph of the residuals for autocorrelation and possible outliers in the data; (2) inspection of the studentized residual for each observation to monitor possible outliers; (3) inspecting values of Cook's *d* to detect observations adversely influencing the regression; and (4) inspecting the Durbin-Watson statistic for significant first-order autocorrelation in the regression residual series (Freund and Littell, 1986).

The use of these three methods represents a logical progression in dendroclimatic analysis. First, correlation analysis is a first step for investigating possible relationships between environmental variables and tree growth (Gholz, 1982, p. 469). However, no models are generated. Response function analysis is a second step because any multicollinearity among the variables that may exist is minimized, and therefore produces more robust results that represent the actual relationship between climate and tree growth. In addition, results from response function analysis can be used to corroborate results from correlation analyses. Multiple regression is a logical final step for modeling tree growth as a function of climate and is also more aesthetically pleasing because of its use of untransformed data, as opposed to response function analysis. The three methods are therefore complementary.

RESULTS. Three general descriptive statistics are used to characterize tree-ring chronologies: (1) mean sensitivity, a measure of year-to-year variability; (2) standard deviation, a measure of overall variability; and (3) first-order autocorrelation, a measure of interdependence between indices of successive years. Desirable characteristics include high values for mean sensitivity and standard deviation, and low values for first-order autocorrelation (DeWitt and Ames, 1978). The mean sensitivity for the shortleaf pine standard index chronology developed in this study is slightly lower than the mean for this species (Table 1) but well within

TABLE 1
STATISTICS[1] FOR THE SHORTLEAF PINE STANDARD CHRONOLOGY VERSUS THOSE LISTED IN DEWITT AND AMES (1978)

Study Site	Length	ms	sd	r_1
This Study	1822–1986	0.17	0.27	0.73
Clemson, SC	1694–1973	0.17	0.26	0.65
Norris R., TN	1681–1972	0.19	0.24	0.56
Montgomery Co., AR	1666–1939	0.20	0.20	0.26
Piney Cr., IL	1806–1972	0.29	0.40	0.58
Average[2]		0.20	0.28	0.53

[1] ms = mean sensitivity, sd = standard deviation, r_1 = first-order autocorrelation.
[2] average of all nine listed chronologies.

the range of expected values. The standard deviation is also comparable to the mean for this species. However, the first-order autocorrelation is much higher than values for other chronologies, but comparable to that value obtained for a nearby site in Clemson, South Carolina.

Preliminary correlation analysis showed that the relationship between the growth index chronology and local precipitation data is more highly significant than the relationship using regional precipitation data. The relationship between the pine growth indices and regional temperature data was, however, far superior to that obtained using local temperature data. No explanations for this weak relationship with local temperature are possible without further in-depth analysis of the temperature data. However, the temperature dataset had 10 missing monthly values between 1910 and 1942 which had to be interpolated, possibly weakening the relationship. The remainder of these analyses will therefore use local data for precipitation and regional data for the other three variables.

The correlation analysis between monthly climate and shortleaf pine growth shows significant positive relationships between pine growth and precipitation during May, June, and July (Fig. 2A), the three months in which approximately 61% of total annual growth occurs for southern pines in this region (Zahner and Grier, 1990). Weaker, nonsignificant effects are evident during the previous winter months. Significant negative relationships are shown between pine growth and temperature during April, June, July, August, and September (Fig. 3A). Increasingly significant correlations are evident between pine growth and PDSI and PHDI beginning in May (PDSI $r = 0.31$, $p < 0.01$; PHDI $r = 0.21$, $p <$

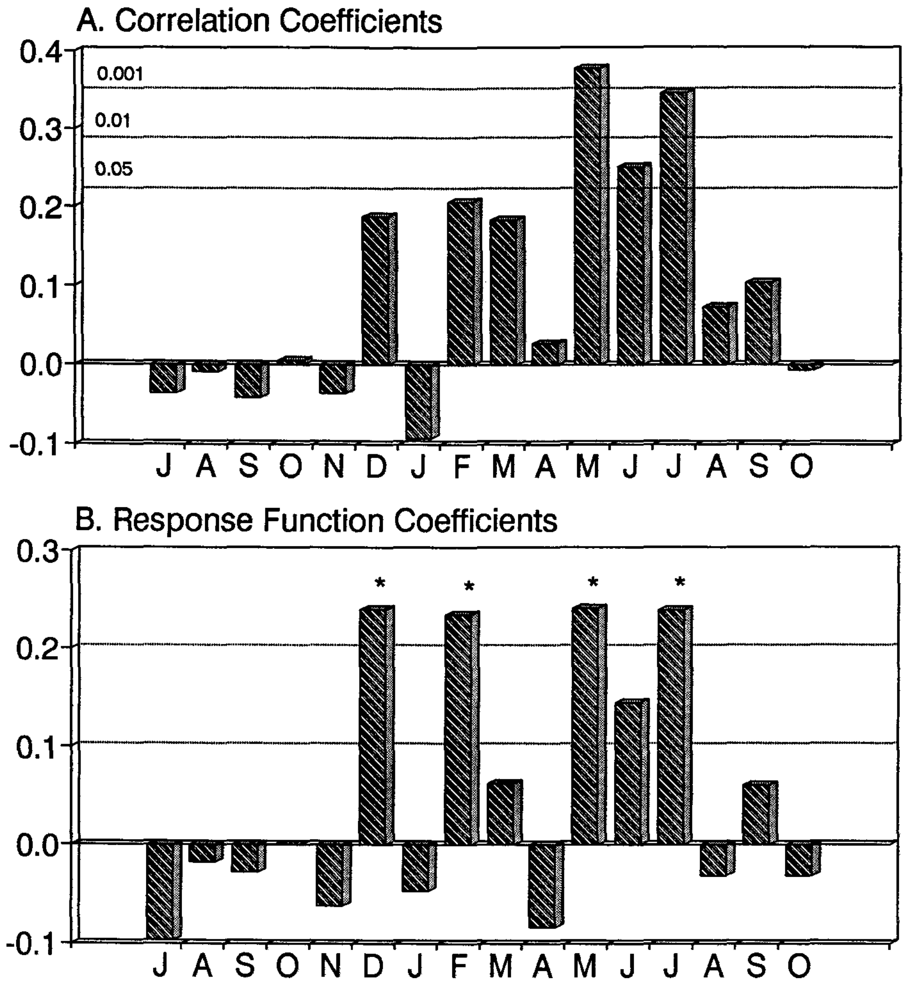

Fig. 2. Results from correlation (A) and response function (B) analyses between shortleaf pine growth and local monthly precipitation, previous July to current October. (*) indicates significant ($p < 0.05$) values for the response function analysis.

0.05) and continuing through September (PDSI $r = 0.47$, $p < 0.0001$; PHDI $r = 0.53$, $p < 0.0001$), reflecting the integration of precipitation, temperature, and soil conditions into one variable. However, the high correlations for these two indices can partly be attributed to the high degree of autocorrelation that exists in the Palmer indices, as previously noted.

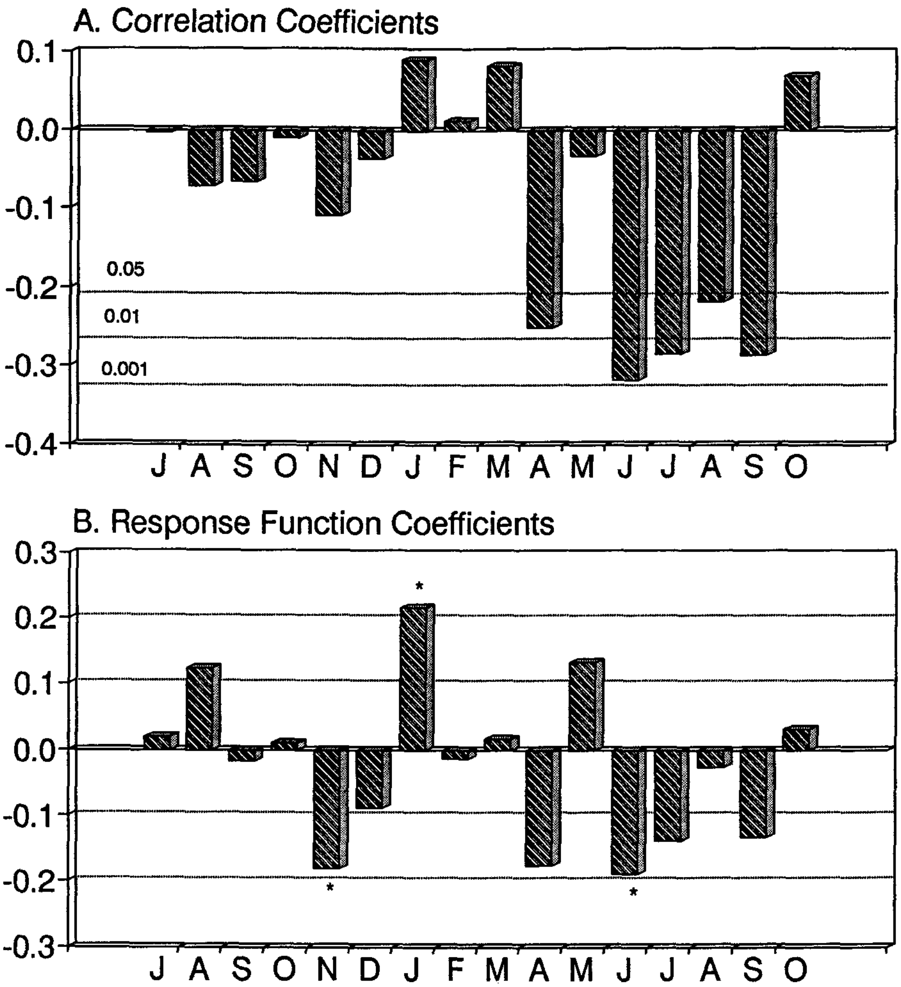

Fig. 3. Results from correlation (A) and response function (B) analyses between shortleaf pine growth and regional monthly temperature, previous July to current October. (*) indicates significant ($p < 0.05$) values for the response function analysis.

Significant correlations are also evident between pine growth and seasonalized total precipitation and average temperature (Table 2). The strongest correlation for total seasonal precipitation is seen for the period May–September, when approximately 78% of total pine growth occurs for this region (Zahner and Grier, 1990). The strongest correlation for average seasonal temperature is found during the period June–

TABLE 2
CORRELATION COEFFICIENTS BETWEEN THE SHORTLEAF PINE INDEX CHRONOLOGY AND VARIOUS INTERVALS OF THE GROWING SEASON

Interval	Precipitation[1]	Temperature[2]
April–June	0.37	−0.31**
April–July	0.47	−0.35***
April–August	0.47	−0.36***
April–September	0.50	−0.40***
May–June	0.44	−0.21*
May–July	0.51	−0.27**
May–August	0.52	−0.29**
May–September	0.56	−0.35***
June–July	0.38	−0.35***
June–August	0.38	−0.37***
June–September	0.44	−0.40***

[1] All coefficients significant ($p < 0.0001$), $n = 77$.
[2] Coefficients significant at 0.05 (*), 0.01 (**), and 0.001 (***), $n = 92$.

September. These seasonal correlations are more highly significant than those derived using monthly precipitation and temperature data, indicating that pine growth can perhaps be modeled more accurately using combinations of monthly climate variables rather than precipitation or temperature during any one month.

Using a minimum eigenvalue of one for entry of any variable into the response function model, 27 of the original 35 principal components regressors were retained and explained 38% of the total variance (adjusted for loss of degrees of freedom) in the shortleaf pine index chronology. The response function for precipitation (Fig. 2B) shows significant positive effects using December preceding the growth season, and during February, May, and July of the current year. The response function for temperature (Fig. 3B) shows significant negative effects during November of the previous year and June of the current year, and a significant positive effect during January of the current year. The growth index variable lagged by two years also entered significantly into the response function model, and had a positive value.

During the final analysis, we encountered difficulty validating the generated models based on the half-sample calibration periods as both models failed in the verification process. Several explanations for the failure of these half-sample models can be hypothesized. First, growth of shortleaf pine during either of the calibration periods may be affected by some factor not being modeled. This would generate weak models that would predict values for pine growth insufficient for verification purposes. Second, because tree biomass continues to change over time, relationships between climate and tree growth will change over time as well (Gholz, 1982, p. 477). This concept can be demonstrated by following the relationship between climate and pine growth over successively lagged 30-year periods. Moving correlation coefficients between shortleaf pine growth and June temperature, which is significant to growth during the period 1910–1948, show a decrease in significance over time until the relationship is no longer significant during the 1949–1986 period. Conversely, the same analysis using September temperature, which is significant to growth during the period 1949–1986, shows increasing significance over time beginning in the 1910–1948 period when the relationship was insignificant. This suggests a time-dependency between environmental factors and changes in biomass accompanying changes in the life stages of shortleaf pine.

We therefore used the original full dataset for the final analysis. The F-statistic for the preliminary model was 9.7 ($p < .0001$, $n = 77$), with an adjusted R^2 of 0.41. However, two observations, years 1976 and 1978, were detected as statistical outliers exhibiting large values for both the studentized residual and Cook's *d*. These were subsequently deleted and a new model was developed. The F-statistic for the final model was 13.4 ($p < .0001$, $n = 75$) with an adjusted R^2 of 0.46, indicating 46% of shortleaf pine growth is being accounted for by the predictor variables. First-order autocorrelation for this model is insignificant ($r_1 = -0.07$, Durbin-Watson $d = 2.12$), indicating no violation of the assumption of random error in the residuals after regression.

Four climate variables and the previous year's growth variable entered significantly into the regression model (Table 3). This model is dominated by precipitation during the current growing season, especially during May and July, explaining over half of the total variance in the final model. The inclusion of one variable from the previous growing season, November temperature, may indicate some preconditioning of current year's growth by climate during the previous growing season, as noted previously. Actual and predicted yearly values are plotted in Figure 4, along with their respective residuals.

DISCUSSION. The chronology statistics indicate that shortleaf pines exhibit sufficient variability for crossdating due in part to a significant

TABLE 3
VARIABLE PARAMETER ESTIMATES AND STATISTICS FOR THE CLIMATE/GROWTH MODEL FOR SHORTLEAF PINE

Variable	Parameter Estimate	*t* value	Prob > |*t*|
Lagged growth index	0.338	3.66	0.0005
Previous November temperature	−0.013	−2.61	0.0111
Current April temperature	−0.015	−2.37	0.0207
Current May precipitation	0.0003	4.84	0.0001
Current July precipitation	0.0002	2.97	0.0041

F = 13.4 ($p < 0.0001$), adjusted $R^2 = 0.46$.

relationship with climate. Precipitation is by far the dominant climatic variable affecting shortleaf pine growth. The correlation and response function analyses both indicate significant positive effects during the current summer growing season (May through July). The strength of this relationship increases when precipitation is totaled over the May–September interval. Significant negative effects due to high temperatures are also found during the current growing season. Averaging temperature over various intervals of the growing season significantly improved the strength of this relationship. These results indicate shortleaf pines will experience increased growth when precipitation is above normal and temperature is at or below normal during the growing season.

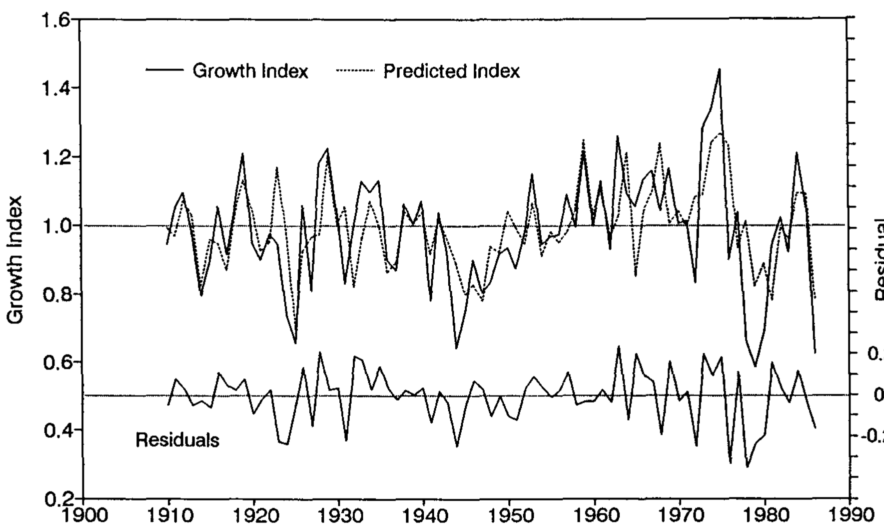

Fig. 4. Actual (solid line) and predicted (dotted line) values and their residuals (bottom graph) of shortleaf pine growth indices generated by the final model.

The strongest relationships are found between shortleaf pine growth and the Palmer indices, though this strength will undoubtedly decrease after fitting autoregressive models to the Palmer indices to remove autocorrelation.

Similar results are found in other studies, including Cleaveland (1975) who studied the relationship between shortleaf pine growth and climate near Clemson, South Carolina. Significant positive effects were found for the current June–August period, similar to the positive effects during the May–July period that we found. However, Cleaveland found significant positive effects due to temperature while we found little evidence for this relationship. Cleaveland showed that 39–43% of pine growth could be modeled using eight climate predictor variables, percentages that are remarkably similar to our findings. Friend and Hafley (1989) found that 31–34% of shortleaf pine growth could be accounted for by four variables that included soil water conditions, rain days, and temperature. Jordan and Lockaby (1990) also found significant positive effects due to precipitation upon loblolly pine during the current May, June, and August period, as well as a significant negative effect due to current June temperature, similar to our study. Climate variables used in their study were able to model 34–47% of the index series variability, similar to the percentages in our study. Jordan and Lockaby additionally were able to develop a superior model between pine growth and August PDSI that explained 57% of the pine growth variability.

The pine growth indices and the residuals from the generated climate/growth model dramatically show increasing variability (Fig. 4) with the residual variance for the period 1963–1986 (0.032) over five times as high as the variance during the preceding 24-year period from 1939–1962 (0.006), and over three times as great as the residual variance during the period 1910–1961 (0.01). Nearly 25% of the residual variability during the 1963–1986 period arises due to the observations for 1976 and 1978. Even without these years, the residual variance for the remaining subset of years (0.024) is four times as high as the previous 24-year period, and over twice as high as the residual variance for the entire 1910–1962 period. A review of the climatic data for 1976 and 1978 shows no particularly anomalous climatic events that would result in growth below that expected given the climate for those years.

If a shift in climate was responsible for this change in residual variance, we should see shifts in the variance over time for total precipitation during the May–September period and average temperature during the June–September period, two climatic variables with high correlations with the growth index chronology (Table 2). Figure 5 shows running variance plots for successive 21-year periods for these two variables and the index chronology. Beginning in the early 1960s, there is a noticeable shift in variance in the index chronology that is not seen in the two climatic variables. This points to other nonclimatic factors that would result in changes in pine growth.

This increased variability may be a physiological response to changing local environmental conditions. We did not endeavor to isolate those factors responsible for changes in pine growth since 1963, but we must conclude that this changing variance in the model residuals must be due to other factors, possibly related to acidic deposition. However, increasing variability may also be due in part to increasing tree age as maturing shortleaf pine may become more sensitive to the surrounding environment. Increasing variability may also be due to changes in stand-level processes, such as an increase in competition from neighboring trees and understory vegetation or changes in the stand nutrient levels, as well as from changes due to local anthropogenic disturbances, such as thinning and logging. It is therefore desirable to know of previous land-use practices for the study area before assessing possible impacts due to atmospheric pollutants.

Future research may wish to investigate conducting wood cross-sectional area determined from extracting increment cores at several

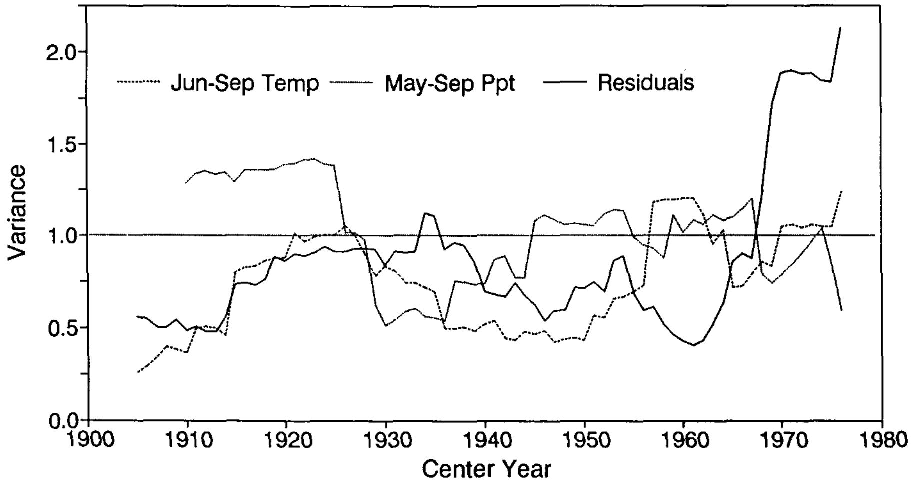

Fig. 5. Running variance plots of successive 21-year periods for May–September total precipitation, June–September average temperature, and the growth index chronology. A dramatic change in variance beginning in the early 1960s is evident in the tree-ring index chronology.

heights on the bole of several trees located on permanent plots (Waring, 1983, pp. 344–347). Because of the relationship that exists between sapwood area and canopy leaf area, this technique could generate a more physiologically based model between growth processes and environmental factors that is not limited to only using tree-ring widths as a measure of growth rates. Once we understand better the relationships among sapwood area, tree-ring width, and leaf canopy area, we then may make better estimates of the growth efficiency for shortleaf pine under certain environmental conditions. The use of leaf canopy area to assess changes in basal area over time is also more desirable because stemwood production has lower priority than other biological plant processes under extreme environmental conditions (Waring, 1983, pp. 331).

CONCLUSIONS. We have shown that tree rings of shortleaf pines growing in northern Georgia are sensitive to annual changes in local and regional climatic variables. The growth indices show a highly significant positive response to precipitation and a significant negative response to temperature during the current growing season. Stronger relationships were found between tree growth and seasonalized climate, and even stronger relationships were found using the Palmer indices. Based on the response function and multiple regression analyses, between 38–46% of pine growth variance can be accounted for by the climate/growth models. A strong time-dependent response by shortleaf pine to climate was found such that difficulty was encountered during the calibration and verification procedures. Climate variables do not adequately model growth beginning in 1963, as the residuals from the climate/growth model show increased variability over the previous periods. This change in pine growth rates since 1963 must therefore be due to nonclimatic factors.

NOTE

[1] The authors wish to thank Paul R. Sheppard, Lisa J. Graumlich, and four anonymous reviewers for comments on preliminary drafts of this paper.

LITERATURE CITED

Adams, H. S., Stevenson, S. L., Blasing, T. J., and Duvick, D. N. 1985. "Growth-trend Declines of Spruce and Fir in mid-Appalachian Subalpine Forests," *Environmental and Experimental Botany*, Vol. 25, pp. 315–326.

Cleaveland, M. K. 1975. "Dendroclimatic Relationships of Shortleaf Pine (*Pinus echinata* Mill.) in the South Carolina Piedmont," M.S. thesis (Clemson, SC: Clemson University).

Cook, E. R. 1988. "A Tree Ring Analysis of Red Spruce in the Southern Appalachian Mountains," In *Analyses of Great Smokey Mountain Red Spruce Tree Ring Data*, USDA Forest Service *General Technical Report* SO-69, pp. 6–19.

Cook, E. R., 1990. "A conceptual linear aggregate model for tree rings," In E. R. Cook and L. A. Kairiukstis, eds., *Methods for Dendrochronology: Applications in the Environmental Science* (Boston, MA: International Institute for Applied Systems Analysis, Kluwer Academic Publishers), pp. 98–104.

Cook, E. R., and Peters, K. 1981. "The smoothing spline: a new approach to standardizing forest interior tree-ring width series for dendroclimatic studies," *Tree-Ring Bulletin*, Vol. 41, pp. 45–53.

Daultrey, S., 1976. "Principal components analysis," In *Concepts and Techniques in Modern Geography*, Vol. 8 (London: Institute of British Geographers).

Della-Bianca, L. and Olson, Jr., D. F. 1961. "Soil-site studies in Piedmont hardwood and pine-hardwood upland forests," *Forest Science*, Vol. 7, pp. 320–329.

DeWitt, E., and Ames, M. 1978. "Tree-ring Chronologies of Eastern North America," *Chronology Series* IV, Vol. 1 (Tucson, AZ: Laboratory of Tree-Ring Research, University of Arizona).

Freund, R. J., and Littell, R. C. 1986. *SAS System for Regression* (Cary, NC: SAS Institute).

Friend, A. L. and Hafley, W. L. 1989. "Climatic Limitations to Growth in Loblolly and Short-leaf Pine (*Pinus taeda* and *P. echinata*): A Dendroclimatological Approach," *Forest Ecology and Management*, Vol. 26, pp. 113–122.

Fritts, H. C. 1976. *Tree Rings and Climate* (New York: Academic Press).

Gholz, H. L. 1982. "Environmental Limits on Aboveground Net Primary Productivity, Leaf Area, and Biomass in Vegetation Zones of the Pacific Northwest," *Ecology*, Vol. 63, pp. 469–481.

Graybill, D. A., and Rose, M. R. 1989. "Analysis of Growth Trends and Variation in Conifers from Arizona and New Mexico," in R. K. Olson and A. S. Lefohn, eds., *Effects of Air Pollution on Western Forests* (Pittsburgh, PA: Air and Waste Management Association), pp. 395–407.

Grissino-Mayer, H. D., Rosenberger, M. S., and Butler, D. R. 1989. "Climatic Response in Tree Rings of Loblolly Pine in North Georgia," *Physical Geography*, Vol. 10, pp. 32–43.

Guiot, J. 1990. "Methods of Calibration," in E. R. Cook and L. A. Kairiukstis, eds., *Methods of Dendrochronology: Applications in the Environmental Science* (Boston, MA: International Institute for Applied Systems Analysis, Kluwer Academic Publishers), pp. 165–178.

Hodler, T. W., and Shretter, H. A. 1986. *The Atlas of Georgia* (Athens, GA: Institute of Community and Area Development, University of Georgia).

Holmes, R. L. 1983. "Computer-assisted Quality Control in Tree-ring Dating and Measurement." *Tree-Ring Bulletin*, Vol. 43, pp. 69–75.

Karl, T. R., and Knight, R. W. 1985. *Atlas of Monthly Palmer Drought Severity Indices (1931–1985) for the Contiguous United States* (Asheville, NC: National Climatic Data Center).

Jordan, D. N. and Lockaby, B. G. 1990. "Time Series Modelling of Relationships Between Climate and Long-term Radial Growth of Loblolly Pine," *Canadian Journal of Forest Research*, Vol. 20, pp. 738–742.

Phipps, R. L. 1985. "Collecting, Preparing, Crossdating, and Measuring Tree Increment Cores," U.S. Geological Survey *Water-Resources Investigations Report* 85-4148.

Pitelka, L. F., and Raynal, D. J. 1989. "Forest Decline and Acidic Deposition," *Ecology*, Vol. 70, pp. 2–10.
Schulman, E. 1942. "Dendrochronology in Pines of Arkansas," *Ecology*, Vol. 23, pp. 309–318.
Sheffield, R. M., Cost, N. D., Bechtold, W. A. and McClure, J. P. 1985. "Pine Growth Reductions in the Southeast," USDA Forest Service *Resource Bulletin* SE-83.
Waring, R. H. 1983. "Estimating Forest Growth and Efficiency in Relation to Canopy Leaf Area," *Advances in Ecological Research*, Vol. 13, pp. 327–354.
Zahner, R., and Grier, C. E. 1990. "Concept for a Model to Assess the Impact of Climate on the Growth of the Southern Pines," in R. K. Dixon, R. S. Meldahl, G. A. Ruark, and W. G. Warren, eds., *Process Modeling of Forest Growth Responses to Environmental Stress* (Portland, OR: Timber Press), pp. 383–392.
Zahner, R., Saucier, J. R., and Myers, R. K. 1989. "Tree-ring Model Interprets Growth Decline in Natural Stands of Loblolly Pine in the Southeastern United States," *Canadian Journal of Forest Research*, Vol. 19, pp. 1365–1375.