CLIMATE-TREE GROWTH MODELS IN RELATION TO LONG-TERM GROWTH TRENDS OF WHITE OAK IN PENNSYLVANIA

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ABSTRACT.—We examined long-term growth trends of white oak by comparing tree-ring chronologies developed from an old-growth stand, where the average tree age was 222 years, with a second-growth stand where average tree age was 78 years. Evaluation of basal area growth trends suggested that an anomalous decrease in basal area increment trend occurred in both stands during the 1950s. To determine whether climatic factors could explain this decrease we developed conventional and ridge regression models based on step-wise selection of mean monthly temperature and total monthly precipitation variables for the period 1895 to1940. The years from 1941 to 1950 were used for verification of developed models; only the ridge regression models produced verifiable models. All models failed to predict actual growth in the period from 1951 to 1980 for both stands. The inability to predict growth response in the more recent period may relate to a non-constant climatic response of white oak or to non-climatic factors such as air pollution or altered atmospheric CO_2 concentrations that have affected tree growth-climate relationships.

The oak-hickory forests of Pennsylvania encompass 3 million ha of commercial forest land (Powell and Considine 1982). These forests are the dominant vegetation of the ridge and valley section of central Pennsylvania where species such as northern red oak (*Quercus rubra* L.) and white oak (*Q. alba* L.) are two of the most commercially valuable components (Powell and Considine 1982).

Various studies have documented that air pollution may reduce growth rates of trees growing near point sources of pollution (Long and Davis 1999, McClenahen and Dochinger 1985), even over large scales (Nojd and Reams 1996). Speculation that atmospheric pollutants or acidic deposition may adversely affect the tree growth without the appearance of external symptoms has been proposed in relation to some studies (Woodman and Cowling 1987, Phipps and Whiton 1988, McClenahen 1995). McLaughlin and others (1983) suggested that northern red oak growth decreased in some areas of northeastern U.S.A. due to increased air pollution. They based this conclusion on comparison of mean radial increment in the 1931 to 1955 period with growth in the 1956 to 1980 period. However, their study did not assess whether the growth decline was related to other factors such as tree age or climate.

Other studies have implicated atmospheric pollutants as factors that may alter or decouple tree growth-climate relationships (McClenahen and others 1999), resulting in conditions more limiting to tree growth (Puckett 1982, McClenahen and Dochinger 1985). In addition, the response of old-growth forests compared with second-growth forests to concurrent pollutants and climate may be quite different. This study was initiated to determine if white oak growth response to climate has changed since the 1950s, and to compare the growth response of old- vs. second-growth white oaks during the same time period. This study is not intended to be a comprehensive assessment of tree growth-climate processes, but is instead intended as a case study to develop approaches and analytical methods that facilitate analysis of these processes.

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INCREMENT CORE COLLECTION

An old-growth white oak stand and a second-growth white oak stand, growing approximately 17 km apart, were located in central Pennsylvania on and near Leading Ridge, Huntingdon County (table 1). Two, and sometimes three, 5 mm diameter increment cores were taken at breast height (BH, 1.4 m) from dominant and codominant trees in each stand (old growth n = 33; second-growth n = 30). Cores were air-dried, glued to grooved wooden holders, sanded to enhance the appearance of ring boundaries, and visually cross-dated (Stokes and Smiley 1968).

To assure accuracy of assigned dates, crossdating was verified using the computer program COFECHA (Holmes 1983, 1985). Ring-widths were measured to the nearest 0.01 mm on a Bannister Incremental Measuring Machine (Fred C. Henson Co., Mission Viejo, CA) interfaced with the microcomputer program TRIMS (Tree Ring Incremental Measuring System) developed by Madera Software (Tucson, AZ). Crossdating and/or measurement errors were identified and corrected. If the observed errors could not be corrected, the core was omitted from the chronology.

TREE-RING ANALYSES

Several methods were used to examine the relationship between growth trends and possible declines using the raw ring-width time series. To examine the non-climatic growth trend of individual trees, the basal area increment (BAINC) was calculated for each tree (Phipps 1983, Phipps and Field 1988). A cubic spline function with a 50 percent frequency response equal to 100 years was fit to the BAINC values of each core (Cook and Peters 1981). The resulting trend values of this curve were assumed to represent the growth trend of the tree without the influence of high frequency year-to-year climatic variation (Phipps 1983). The BAINC trend values were averaged for individual trees in each stand, and for the stand as a whole, and plotted to determine any changes in growth trends. BAINC approximates a straight line for most trees in the forest canopy, and a change in the slope of the BAINC may be evidence of endogenous or exogenous disturbance (Phipps 1983).

Table 1.—*Site characteristics and chronology statistics of white oak tree-ring chronologies developed from a second-growth and an old-growth stand in central Pennsylvania*

	Old-growth	Second-growth
<u>Site characteristics</u>		
Latitude (N)	40°40′	40°41′
Longitude (W)	77°45′	77°57′
Elevation (m)	363	442
% slope	10	5
<u>Chronology statistics</u>		
Chronology (yrs)	1562-1983	1876-1984
Number of trees	33	30
Number of radii	70	63
Mean sensitivity	0.175	0.170
Serial correlation	0.381	0.221
Standard deviation	0.221	0.175
Average age (yr)	222	78

Alternatively, to examine potential climatic factors affecting tree growth, non-climatic variance due to age trend and differential growth rates was removed by standardization. Raw ring-width values were divided by the value on a fitted line or curve (similar to the trend line that was used above) to provide a dimensionless tree-ring index (Fritts 1976). Ring-width data from the old-growth stand were double detrended with a negative exponential curve or linear regression line followed by a stiff cubic spline fit successively to the ring-width data (Cook and Holmes 1985). To limit the removal of climatic information from second-growth trees, ring-width data were detrended using a stiff cubic spline with a 50 percent frequency response of 100 years. Detrended, standardized ring-width indices were then averaged together by year into a robust mean value standard chronology for each stand (Cook and Kairiukstis 1989).

The standard chronologies from both stands were further characterized by calculating the mean sensitivity, first-order autocorrelation (or serial correlation), and standard deviation (Fritts 1976). Mean sensitivity, a measure of the ring-width index variation from one year to the next over the length of the chronology, was estimated by calculating the average of twice the absolute difference between adjacent indices divided by the mean of the two indices. First-order autocorrelation, an estimate of non-randomness in the ring-width series, was calculated as the correlation between year t and t-1 for all years in a chronology (Fritts 1976).

GROWTH-CLIMATE MODELS

The South Central Mountains Pennsylvania Climatic Division data, consisting of mean monthly temperature and total monthly precipitation averaged from all available single station records in the division for the period 1894 to

1980 was assembled and used to predict ring index growth (U.S. Environmental Data Service 1894-1984). Divisional data were used because only limited single station data were available from stations closest to the sampled areas. Because of the lag response of tree growth to climate (Fritts 1976), the climatic predictor variables were arranged in a 17-month dendroclimatic year beginning in May of the previous year and ending in September of the current year. This resulted in a pool of 34 candidate predictor variables for subsequent regression analyses.

Preliminary analyses indicated that the old-growth and second-growth chronologies were highly correlated ($P < 0.01$) with each other and with climate variables. Because of this correlation and to increase climate signal, the chronology ring-width indices from the old-growth and the second-growth stands were averaged to obtain a master chronology. This chronology was used for development of climatic models using stepwise regression for the calibration period from 1894 to 1940. The probability level for a climatic variable to enter and remain in the model was 0.15. The climatic data from 1941 to 1980 were used for model verification, and to determine whether growth response to climate was altered during this period.

Autocorrelation in tree-ring chronologies may obscure identification of climatic signal (Meko 1981). To limit the influence of the autocorrelation structure on derived climatic models, the master chronology was prewhitened with an order-2 autoregressive (AR) model for the period from 1730 to 1950. Prewhitening produces a white noise residual series by removing autocorrelation. The coefficients of the model were then used to prewhiten the data from 1951 to 1980. This procedure prevents the removal of any anomalous decline signal in the 1951 to 1980 time period, and assumes that the AR model describing the persistence structure from 1730 to 1950 is a time-stable representation of the autocorrelation structure of the chronology (Cook 1985). The AR coefficients were 1 = 0.246 and 2 = 0.197 with the model selected on the basis of the minimum AIC selection criterion (Akaike 1974).

For the climatic models developed in this study, both chronologies, one with the existent autocorrelation (unwhitened) and one produced by prewhitening (prewhitened) were used for all analyses. We did this because Monserud (1986) reported that hypothesis tests associated with unwhitened chronologies (those with existent autocorrelation left in the chronology) might be biased.

Multicollinearity, or linear dependencies among climatic variables, may also prevent identification of a reliable model, or lead to estimated regression coefficients which are too large in absolute value due to large variances and covariances of the least squares estimates of regression coefficients (Cropper 1985). To remedy this, ridge regression was used to produce biased coefficient values with smaller, though biased, standard errors. Ridge regression produces coefficient estimates after adding a small biasing parameter (k) to the diagonal elements of the $X'X$ matrix. This produces an inverse matrix ($X'X^{-1}$) in which the diagonal elements are less inflated (Cropper 1985).

Empirical evaluation of simulated climatic and tree-ring data suggested that a bias value of $k = 0.4$ would provide verifiable climatic response models (Cropper 1985). The ridge-biasing parameter for our study was selected after examination of the ridge trace plots of all 34 potential predictor variables (Montgomery and Peck 1982). Successive iterations of regression coefficients were calculated with the biasing factor beginning at 0 and continuing in 0.05 intervals to 1.0, in order to determine the minimum bias that resulted in reduced variance inflation factors (VIFs) (Montgomery and Peck 1982).

VIFs in excess of 5 to 10 indicate that associated regression coefficients are poorly estimated (Montgomery and Peck 1982). Because the VIFs in the data for the present study were slightly higher than those in the simulation studies, the ridge trace of all variables was examined to determine the bias where regression coefficients stabilized (Cropper 1985). The bias selected for our study was $k = 0.4$, based on both the ridge trace plots and the associated decrease in the VIFs. Stepwise regression of the biased climatic variables was performed as described previously with the unwhitened and prewhitened chronologies.

To determine whether tree growth response to climate has been altered since 1950, four climatic models (1 = unwhitened ordinary least squares (OLS) regression, 2 = unwhitened ridge regression, 3 = prewhitened OLS regression, 4 = prewhitened ridge regression) were first tested using successive 10-year verification periods from 1941 to 1980. The verification period predates the period of the suspected intervention of other growth-limiting factors so that model stability can be evaluated prior to the intervention (Cook 1985). Pearson product-moment correlations between predicted indices and actual indices were calculated for each 10-year period, along with the associated probability level of the correlation.

A one-sided t-test was used to test whether the mean difference between actual and predicted indices (x) was significantly different from zero for each verification period. The reduction of error statistic (RE) was also evaluated (Lorenz 1956). This statistic has no associated probability level but is a rigorous verification statistic strongly affected by few deviations from observed values (Fritts and others 1979). RE values greater than zero that are accompanied by statistically significant product-moment correlations indicate that there is some predictive skill with the associated model (Cook 1985).

RESULTS

Plots of the stand-averaged BAINC trend with year-to-year climate fluctuations removed (fig. 1) indicate a slight decrease in the positive slope of BAINC within both the old-growth and second-growth stands. A linear regression line was calculated for the period 1870 to 1950 for the old-growth stand and used to estimate the predicted straight-line BAINC growth to 1980. The predicted straight-line growth was similarly estimated for the second-growth stand based on a linear regression for the 1920 to 1950 period.

For both stands, there is an apparent decrease in the BAINC trend starting in the 1950s. Because of the limited sample size in this study and the increase in standard deviation of the observed BAINC values, this predicted straight-line growth is within the 95 percent confidence interval of the actual BAINC curves. However, the consistent and simultaneous response of both the old growth (mean age = 222 years) and the second-growth (mean age = 78 years) stands suggests some non-climatic or low frequency climatic factor may be influencing tree growth.

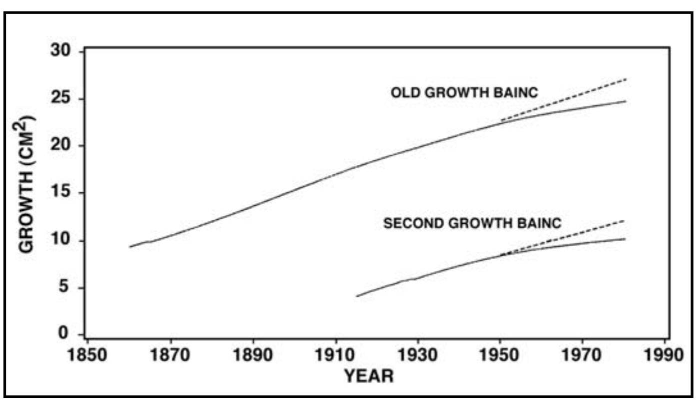

Figure 1.—*Actual (solid line) and predicted (dashed line) growth in terms of basal area increment (BAINC, cm^2/yr) trends within old- and second-growth stands.*

Growth-Climate Models

Climatic models were developed to explore whether this decrease in growth was related to climatic variation, and to determine if growth response to climatic factors was altered during the 1950 to 1980 period. Because the chronologies were highly correlated, a master chronology was created by using the weighted average of the chronologies from the old- and second-growth stands (table 1). The master chronology mean sensitivity was 0.177, first-order autocorrelation was 0.417, and standard deviation was 0.206 for the chronology period 1562 to 1984.

The unwhitened and prewhitened chronologies (fig. 2, see appendix) showed no evidence of a sustained decrease in tree growth in the 1940 to 1980 period, though evidence of the severe mid-1960s drought was indicated by below-average growth during this time period.

The coefficients of the climatic variables selected by stepwise regression to predict the unwhitened chronology indices are presented in table 2. For this model, nine variables were selected. The large standardized regression coefficients for the previous year's August precipitation (0.468) and the current year's June precipitation indicate the influence of these variables on tree growth. The fractional variance accounted for by the regression model (R^2) in the 1895 to 1940 calibration period was 0.714. The climatic model developed for the prewhitened chronology differed in variable selection from the model developed for the unwhitened chronology.

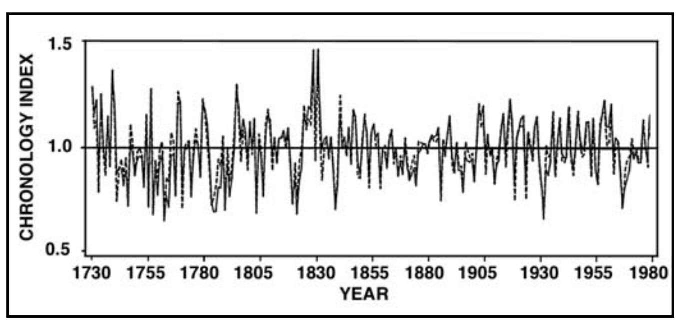

Figure 2.—*Unwhitened (solid line) and prewhitened (dashed line) standard master chronology derived by averaging the old- and the second-growth chronologies into a single master chronology.*

Table 2.—*Stepwise regression results for the unwhitened and pre-whitened chronologies. The standardized regression coefficients (b) and their standard errors (se) are given for the variables that entered the model. The probability level to enter and remain in the model was 0.15. The fractional variance explained by the model (R^2) and the R^2 adjusted for lost degrees of freedom (R^2 adjusted) were also calculated*.

	CHRONOLOGY TYPE			
	Unwhitened		Prewhitened	
Variable	b	se	b	se
Previous June temperature	-0.269	0.093	—	—
Previous June precipitation	—	—	0.196	0.101
Previous July precipitation	0.195	0.109	—	—
Previous Aug. precipitation	0.468	0.096	0.491	0.097
Previous Sept. precipitation	0.154	0.099	0.213	0.102
Previous Nov. temperature	0.341	0.101	0.418	0.099
Current Jan. temperature	—	—	0.208	0.102
Current Feb. temperature	0.172	0.100	0.179	0.105
Current April temperature	0.360	0.103	0.288	0.105
Current June precipitation	0.420	0.100	0.402	0.102
Current Sept. precipitation	-0.337	0.114	-0.342	0.104
R^2	0.714		0.704	
R^2 adjusted	0.643		0.630	

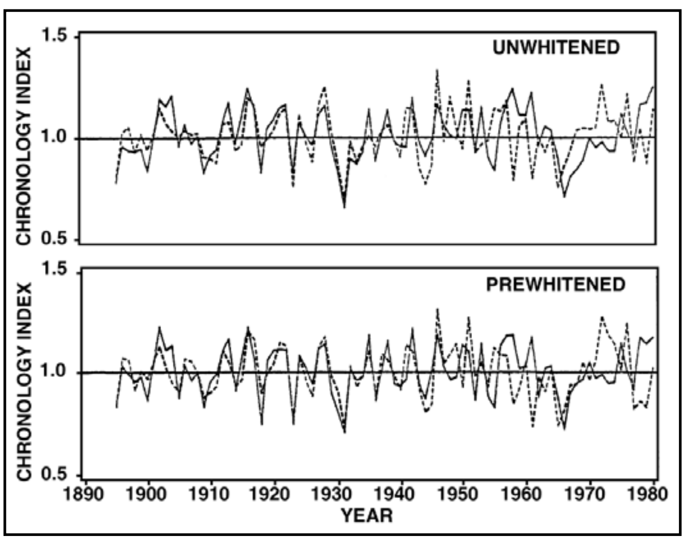

Figure 3.—*Actual (solid line) and predicted (dashed line) indices for the unwhitened and prewhitened chronologies calculated with ordinary least squares (OLS) regression models.*

The actual and predicted indices are plotted in figure 3. The previous year's June precipitation and current year's January temperature entered into the model, whereas the previous year's June temperature and previous year's July precipitation did not enter. The largest standardized regression coefficients were for the previous year's August precipitation (0.491) and for the previous year's November temperature. The R^2 for the model in the calibration period was 0.704, slightly lower than the R^2 for the model associated with the unwhitened chronology (table 2).

The verification statistics for these models are presented in table 3. For the model predicting the unwhitened chronology indices in the 1941 to 1950 period, the correlation (r) was 0.547, significant at P = 0.07. However, the reduction of error statistic (RE) was -1.335, indicating that the model did not have predictive capabilities. The mean difference between actual and predicted indices (x) was not significantly different from zero for this time period. The three subsequent verification periods did not indicate any positive correlation between predicted and actual unwhitened indices, or any predictive ability for this model as evidenced by the negative RE statistics. This model was only weakly verifiable in the 1941 to 1950 period, and had no ability to predict tree growth in the other three periods.

Verification of the prewhitened climatic model in the 1941 to 1950 period was even weaker, with the correlation (r) between actual and predicted indices (0.507) being significant at p = 0.133. The RE statistic was -0.511, indicating a lack of predictive ability for this model, and the mean difference between actual and predicted indices (x = -0.002) was not significantly different from zero. In the other three verification periods the correlations were either negative or close to zero, whereas the RE statistic remained negative. As with the model predicting the unwhitened indices, the verification is poor in the 1941 to 1950 period, while the model is unverifiable in all subsequent periods.

Ridge Regression

The diagonal elements of the X′X matrix, also known as the variance inflation factors (VIFs), were examined to determine if there was substantial multicollinearity or linear dependence among the candidate predictor variables. For the 34 climatic variables in the 1895 to 1940 calibration period, the VIFs varied from a minimum of 1.88 for the current year's April

Table 3.—*Pearson product-moment correlation (r), mean difference between actual and predicted indices (x), and the reduction of error (RE) statistic for verification of unwhitened and pre-whitened climatic models. Probability levels for r and the probability that x is significantly different from zero are indicated by asterisks (* < 0.15, ** < 0.10, *** < 0.05). No probability level is associated with RE; however values > 0 indicate substantial predictive capabilities for the model.*

Verification period	N	Model type: Unwhitened r	x	RE	Prewhitened r	x	RE
1941-1950	10	0.547**	0.011	-1.335	0.507*	-0.002	-0.511
1951-1960	10	-0.079	0.009	-1.336	0.064	0.002	-0.603
1961-1970	10	-0.111	-0.001	-0.706	0.038	0.048	-0.900
1971-1980	10	-0.116	-0.017	-1.424	-0.401	-0.004	-3.904

precipitation to a maximum of 8.91 for the current year's June precipitation. For the ridged climatic data, the VIFs varied from a minimum of 1.25 to a maximum of 1.87, indicating little or no multicollinearity among the candidate predictor variables.

The results of the stepwise selection of the ridge-biased climatic variables to predict the unwhitened chronology indices are presented in table 4. For the unwhitened chronology an 11-variable model was selected. Seven of these variables were also selected using the ordinary least squares (unbiased) regression. All estimated regression coefficients were lower than those estimated using ordinary least squares regression, a result of the shrinkage created by adding the bias. The largest coefficients were the previous year's August precipitation (0.240) and the current year's September temperature (-0.211). The fractional variance explained by the model was 0.544.

The stepwise model selected using ridged climatic variables to predict the prewhitened chronology indices was very similar to the model for predicting the unwhitened indices (table 4). The actual and predicted indices are plotted in figure 4. Eleven variables entered the model and those with the largest absolute coefficients were the previous year's August precipitation (0.263) and the previous year's November precipitation (0.213). As with the ordinary least squares regression model, the prewhitened prediction model included the previous year's June precipitation and the current year's January temperature variables. This model omitted the previous year's June temperature and previous year's July precipitation variables, which were included in the unwhitened prediction model. The fractional variance explained by this model was 0.529.

Table 4.—*Stepwise ridge regression results using climatic variables with a 0.4 bias to predict the growth of the unwhitened and prewhitened chronologies. The standardized regression coefficients (b) and their standard errors (se) are given for the variables which entered the model, along with the fractional variance explained by the model (R^2) and the R^2 adjusted for lost degrees of freedom (R^2 adjusted).*

Variable	CHRONOLOGY TYPE: Unwhitened b	se[a]	Prewhitened b	se[a]
Previous June temperature	-0.017	0.0068	—	—
Previous June precipitation	—	—	0.109	0.0002
Previous July precipitation	0.129	0.0003	—	—
Previous August precipitation	0.240	0.0002	0.263	0.0002
Previous Sept. precipitation	0.149	0.0002	0.189	0.0002
Previous Oct. temperature	0.137	0.0058	0.135	0.0056
Previous Nov. precipitation	0.177	0.0003	0.213	0.0002
Current Jan. temperature	—	—	0.164	0.0032
Current April temperature	0.185	0.0059	0.162	0.0058
Current June temperature	-0.189	0.0068	-0.191	0.0067
Current June precipitation	0.168	0.0002	0.156	0.0002
Current July precipitation	0.113	0.0002	0.129	0.0003
Current Sept. temperature	-0.211	0.0060	-0.199	0.0060
R^2	0.544		0.529	
R^2 adjusted	0.472		0.411	

[a]The standard error estimates are biased and ordinary inference procedures are not applicable because the distributional properties are not known.

The verification statistics for the stepwise ridge regression model indicate that the predicted unwhitened chronology indices were positively correlated with the actual indices in the 1941 to 1950 verification period (r = 0.654, p = 0.04, table 5). Coupled with the positive RE statisitic (0.145), this indicates that the model has predictive capabilities. The mean difference between actual and predicted indices (x = 0.022) was not significantly different from zero.

The remaining three verification periods indicated that the model could not predict tree growth during these periods (table 5). For 1951 to 1960, and 1961 to 1970, r was negative or close to zero. In the 1971 to 1980 period, r increased to 0.184, but the RE statistic was -0.206. The mean difference between actual and predicted indices (x) was not different from zero for any of the verification periods.

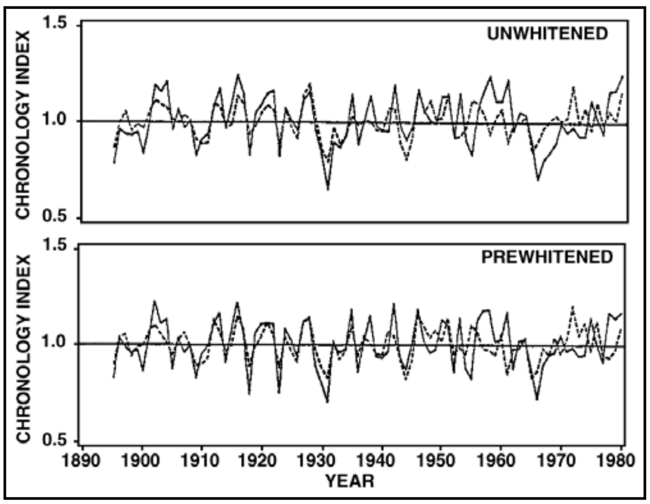

Figure 4.—*Actual (solid line) and predicted (dashed line) indices for the unwhitened and prewhitened chronologies, with predicted indices calculated with the ridge regression models.*

For the stepwise ridge model developed to predict the prewhitened chronology indices, the verification statistics were similar to those for the unwhitened chronology (table 5). The product-moment correlation (r) was 0.591 and the RE statistic was 0.254, indicating predictive skill for the model during the 1941 to 1950 verification period. The model was not verifiable in any of the subsequent three verification periods since correlations were not significant and RE statistics were negative. The mean difference between the actual and predicted indices (x) was not significantly different from zero during any period.

DISCUSSION

The apparent decrease in the non-climatic BAINC growth trend of both the old- and second-growth white oak stands suggests that an anomalous growth decline may have occurred. However, before the cause of this decline can be identified, other factors must be considered and a much larger sample size should be used. Some chestnut oak and white oak stands in northern Huntingdon County suffered high levels of mortality in the 1950s and 1960s from attacks of the pit-making scale, *Asterolecanium minus* (Ratz.), and some weakened trees were subsequently attacked by the two-lined chestnut borer (*Agrilus bilineatus* (Web.)) (Nichols 1968).

No specific stand history was available for the second-growth stand sampled in this study; however, it is possible that such insect attacks could account for the decrease in BAINC in this stand. Drought (McIntyre and Schnur 1936, Jenkins and Pallardy 1995), climate (Tainter and others 1990), diseases (Fergus and Ibberson 1956), and other factors (McClenahen and others 1997) also may cause oaks to decline and resultant growth symptoms to persist for many years (Staley 1965, Biocca and others 1993).

Table 5.—*Pearson product-moment correlation (r), mean difference (x) between actual and predicted indices, and the reduction of error (RE) statistic for verification of unwhitened and pre-whitened ridge regression climatic models. Probability levels for r and the probability that x is significantly different from zero are indicated by asterisks (* < 0.15, ** < 0.10, *** < 0.05). No probability level is associated with RE; however values > 0 indicate substantial predictive capabilities for the model.*

		MODEL TYPE					
		Unwhitened			Prewhitened		
Verification period	N	r	x	RE	r	x	RE
1941-1950	10	0.654***	0.022	0.145	0.591**	0.009	0.254
1951-1960	10	-0.073	0.036	-0.564	0.044	0.018	-0.247
1961-1970	10	0.048	-0.029	-0.209	0.144	0.008	-0.200
1971-1980	10	0.184	-0.013	-0.206	-0.305	-0.005	-1.256

Similarly, the advanced age of trees in the old-growth stand could account for the observed decrease in BAINC. However, examination of the individual tree BAINC curves from the old-growth stand did not reveal a consistent association of the older tress (tree > 230 years old) with decreasing BAINC. Other stand-wide disturbances including, but not limited to, such factors as insect defoliations or disease epidemics, must by considered before assessing the role of atmospheric pollutants.

Growth-Climate Models

The unwhitened and prewhitened standardized chronology indices (fig. 2) provide no evidence of any sustained decline in ring-width growth since the 1950s. Analysis of climatic models indicated that models developed using ordinary least squares (OLS) regression were weakly verifiable in the 1941 to 1950 period, and unverifiable in any subsequent periods.

Several factors either alone or in combination may prohibit identification of a verifiable climatic model (Cook 1985). First, the 34 candidate predictor variables may not contain the variables necessary to accurately describe and predict tree growth. Secondly, the screening of the predictor variables may have been confounded by multicollinearity, or the selected model(s) may have been spurious since the number of candidate predictor variables was a large fraction of the number of observations. Thirdly, the tree-ring time series may not contain a stationary, time-stable climatic signal. Also, the intervention period when growth was altered may actually precede the hypothesized 1950 to 1980 period. Finally, a stand-wide disturbance may have affected tree growth during the verification period. To prevent this latter problem the two individual chronologies were averaged into a master chronology, thus limiting the influence of stand disturbance(s).

Because of the large number (34) of candidate predictor variables, multicollinearity may have affected variable selection and prevented verification of the OLS stepwise regression models. Stepwise ridge regression was used to ameliorate this multicollinearity problem. Using simulation studies with known inputs and outputs, Cropper (1985) observed that ridge regression more frequently and accurately estimated known coefficients of climatic response function variables than either OLS multiple linear regression or principal components regression. While Cropper's analyses used simulated data, the results indicated that ridge regression could adequately account for multicollinearity and limit its influence on derived climatic models.

In the present study both ridge regression models (using unwhitened and prewhitened dependent variables) were verifiable in the 1941 to 1950 period. Both models predicted tree growth that was significantly correlated with actual growth, and both models had positive RE statistics, indicating that they had predictive skill during this verification period. This suggests that the ridge regression models derived from the 1895 to 1940 calibration period were a time-stable representation of growth response to climate. The failure of both ridge regression models to predict tree growth in the 1950s indicates a possible change in tree growth response to climate.

Various hypotheses have been suggested to explain such a change (Puckett 1982, Cook 1985, McClenahen and Dochinger 1985). If the tree-ring time series used for climatic modeling in this study did not contain a stationary climatic signal, then no model would be successful in describing tree growth. The verification of the ridge regression models in the 1941 to 1950 period refutes this explanation; however, climatic change, or threshold climatic response could account for such a change in tree growth response to climate. A climatic variable such as drought may not significantly affect tree growth until it exceeds a critical threshold of severity (Cook 1985), and this threshold may differ depending on soil conditions at the microsite or individual tree level.

Anomalous climatic patterns have been documented throughout the northern hemisphere during the 1960s and 1970s. A series of extreme winter temperatures in the United States since 1975 has been shown to have a return time of 1,000 years (Karl and others 1984). Cook (1985) suggested that such a phenomenon might have caused increased susceptibility of red spruce in the northern Appalachians to winter freeze injury. The higher frequency of winter freeze damage since 1967 may have led to increased tree injury, decreased growth, and altered growth response to climatic variables (Cook 1985). In addition, several anomalous climatic events occurred in Pennsylvania during the 1950s, at which time an unexplained dieback and decline of oaks occurred in various areas within the northeastern United States.

Staley (1965) suggested that the decline could have been related to growing season moisture deficits in some years, but that drought was not the primary cause of the decline. Moisture deficits averaging 10 cm per year were recorded in Pennsylvania for the period from 1952 to 1955, and total annual precipitation was substantially below normal in 1957 (Nichols 1968). During the 1960s a prolonged drought affected the northeastern United States. The effects of this drought are notable in the chronology plots (fig. 2), with the most severe growth reduction occurring in 1965 or 1966.

Three successive severe winters occurred in Pennsylvania in 1976-77, 1977-78, and 1978-79, with the winter of 1976-77 the coldest ever recorded in Pennsylvania (Yarnal 1987). These climatic events may have exceeded a threshold so as to alter tree growth response to climate, and may be inadequately described by climatic models. Persistent climatic anomalies may limit tree growth and possibly trigger physiogenic forest declines (Hepting 1963).

The ridge regression climatic models indicate some effect of changed environmental conditions affecting tree growth during 1950 to 1980. McClenahen and Dochinger (1985) observed a similar change in tree growth response to climate near an urban-industrial complex in Ohio after the 1930s. Similarly, Puckett (1982) speculated that atmospheric pollutants might act alone or in synergy with other growth-limiting factors to alter the relationship of tree growth to climate. Such a phenomenon may have altered growth response of pitch pine, eastern white pine (*Pinus strobus* L.), and chestnut oak (*Q. prinus* L.) to climate in southeastern New York (Puckett 1982).

Trees sampled in the present study were remote from any significant point sources of air pollution and from large urban-industrial complexes. However, other air pollutants such as ozone may be transported long distances and may adversely affect remotely located forest trees (Hayes and Skelly 1977). Similarly, the trees sampled for the present study receive precipitation with an average pH of approximately 4.0 along with substantial inputs of sulfates and nitrates (Lynch and others 1985). It is unknown whether these factors could alter growth response to climate. The absence of long-term atmospheric monitoring data at remote locations limits the ablility to draw conclusions about changes in these parameters.

Based on the ridge regression climate models developed for this study, a sustained decline in white oak growth is inconsistent both with model predictions and with actual growth during the 1950 to 1980 period. However, substantially altered growth response to climatic variables is indicated by the absence of model verification in this period. Other growth-limiting factors are apparently modifying tree growth response to climate. Anthropogenic pollutants, climate change, or other biotic and abiotic factors mentioned above may play a role in altering growth response to climate. More spatially extensive sampling will be necessary to rigorously test these relationships before causal factors can be identified.

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APPENDIX

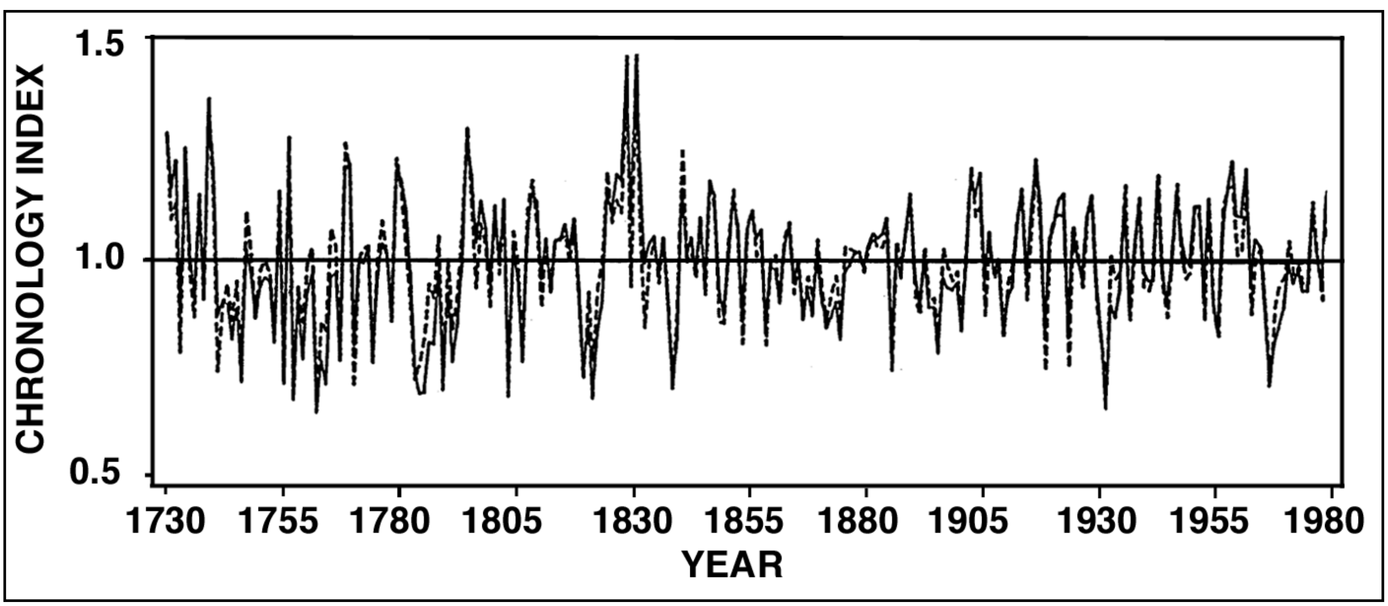

Figure 2.—*Unwhitened (solid line) and prewhitened (dashed line) standard master chronology derived by averaging the old- and the second-growth chronologies into a single master chronology.*