NORTHERN RED OAK GROWTH REPONSE TO CLIMATE AND INDUSTRIAL AIR POLLUTION IN WESTERN PENNSYLVANIA

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Abstract—Northern red oak (*Quercus rubra* L.) radial growth response over time and space was examined along an inferred air pollution gradient on Laurel Ridge, a northeast - southwest anticlinal ridge, in relation to local and historically varying air pollutant emissions from coal-burning power generation and iron production within the greater Johnstown area (Conemaugh Gap) in west-central Pennsylvania. The specific objectives were to determine the effects, if any, of industrial air pollution (primarily sulfur dioxide) on: (1) the relationship of tree growth and climate, (2) tree growth as measured by basal area increment and, (3) the separate growth responses that may be related to long-term air pollution from Johnstown industry and more recent coal-burning power generation. On the east side of Conemaugh Gap, the city of Johnstown has been a major iron production center from the 1920's until 1977. Two power generating stations on the west side of Conemaugh Gap began operation in 1950 and 1970, respectively. We collected pairs of tree cores from at least 20 canopy northern red oaks in 11 mostly ridge top stands ranging from 11 km downwind to 34 km upwind of Conemaugh Gap. Indexed tree-ring chronologies for each stand were derived by standard dendrochronological techniques, and these chronologies were modeled with temperature and precipitation variables by stepwise multiple regression. The resulting growth-climate models indicated that growth of northern red oaks on Laurel Ridge most consistently and positively responded to July precipitation of the growth year, and warmer than normal summer temperatures in the preceding year. In general, upwind control stands showed the strongest relationship with climate, while growth in stands nearer to and downwind of Conemaugh Gap exhibited weaker or virtually no relationship with climate. The spatial patterns of basal area growth rates generally mimicked those of the growth-climate models; an increasing growth rate was evident with distance away from Conemaugh Gap. We conclude that growth of canopy northern red oaks on the upper slopes of Laurel Ridge near to, and downwind of, Conemaugh Gap exhibited anomalous long-term low growth rates and climatic decoupling. The most likely cause of this growth anomaly is historical industrial emissions from Johnstown, with little or no indication of an additional growth impact when the power generating stations went on-line. Whether red oak growth and climatic sensitivity recover in the Conemaugh Gap area as a result of improving air quality is under investigation.

INTRODUCTION

The health of forests and natural ecosystems is a major focus of public agencies and private forest owners. This focus has emerged from an awareness that native and introduced pests, air quality, changing land use patterns, forest management practices, climatic extremes, and many other potential stressors may be increasingly affecting forest health (Smith 1990). Measuring forest health is a major challenge in part because the concept lacks specific definition (Kolb and others 1994). There is no concensus about which critical indicators to measure and there is a deficiency of data about the normal range of many proposed health indicators. A further complication is the difficulty in identifying causal factors after forest or tree declines occur (Manion and Lechance 1992).

Tree growth variation, as manifested in annual ring widths, is one approach for identifying stress or declining vigor (McClenahen 1995). Some studies have shown marked changes in tree-ring response to climate and (or) growth reductions in a variety of species in the presence of high pollutant dose (Sutherland 1990, Thompson 1981, Fox and others 1986). A few instances of growth-climate decoupling or growth decreases have been reported in the absence of unusual mortality or decline symptoms (McClenahen and Dochinger 1985, Phipps and Whiton 1988, Puckett 1982, Tryon and others 1979). Further, dead or symptomatic trees may reveal anomalous tree-ring responses compared to healthy trees (McClenahen 1995), but means for detecting predisposing stress that may portend declining health have not been specifically developed.

This study focuses on the potentially interacting effects of climate variation and regional air pollution on tree growth. The research was conducted on Laurel Ridge in the vicinity of Johnstown, a major industrial city, in westcentral Pennsylvania, USA (Fig. 1).

Laurel Ridge affords partial isolation of pollutant emissions from industrial Johnstown to the east and two local power generating stations to the west. Periods of non-overlapping emissions from these two sources also provided a temporal isolation of emissions. Thus, a unique opportunity was available to study the separate and combined effects of air pollution from these two pollutant sources on tree growth.

We compared the regional patterns of tree growth-climate responses and growth rates of northern red oaks (*Quercus rubra* L.) across an inferred gradient of industrial emissions from Johnstown and the two power generating stations

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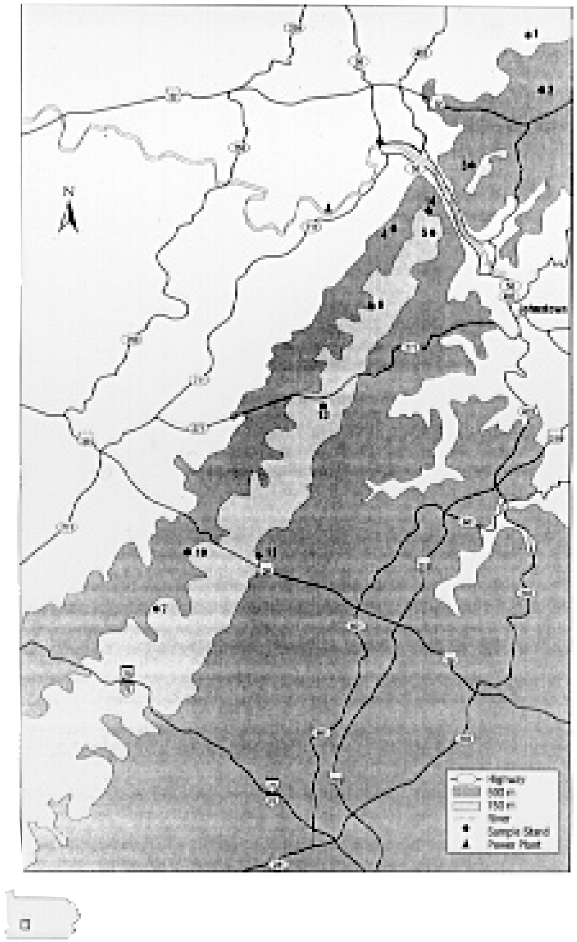

Figure 1—Study area and numbered sample stands. Scale is approximately 1 cm = 5 km.

(Fig. 1). The specific objectives of this study are to determine the effects, if any, of air pollution within the Conemaugh Gap (Greater Johnstown) industrial area on: (1) the relationship of tree growth to climate, (2) tree growth as measured by basal area increment and, (3) the separate growth impacts that may be related to long-term air pollution from Johnstown industry and more recent power generation from local coal-burning power stations.

METHODS

Study Area

Tree coring sites were located on Laurel Ridge, a NE to SW-oriented anticlinal ridge 700-800 m in elevation. The area lies within the Allegheny Plateaus Physiographic Province in portions of Cambria, Indiana, Westmoreland and Somerset Counties (Fig. 1). The climate is continental with a mean growing season temperature of 9.8°C and annual precipitation averaging 104 cm. Forests on Laurel Ridge are second and third growth mixed hardwoods. Oaks (*Quercus* spp.) dominate the ridgetops and drier slopes. Coves and moist slopes have mixtures of *Prunus serotina* Ehrh., *Acer rubrum* L., *Liriodendron tulipifera* L., *Quercus* spp., and others.

Historically, sulfur dioxide (SO_2) has been the primary air pollutant in the Conemaugh Gap area since the late 19th century (Fig. 2). On the southeast side of Laurel Ridge at the eastern side of Conemaugh Gap, Johnstown iron and steel production, and attendant coke plants, began operation in 1872, increasing exponentially from about the 1920's through the 1960's (Brown 1989). Beginning about 1977, a drastic decline in iron production and cleaner technology resulted in reduced SO_2 emissions (Brown 1989).

Two coal-fired power plants are located on the northwest side of Laurel Ridge near the western side of Conemaugh Gap (Fig. 1). The Seward plant began operation in 1950 with one 64 mw unit and a stack height of 70 m. A second unit added in 1957 increased generating capacity to 137 mw. Stack height was increased to 183 m in 1977. The Conemaugh station, with a stack height of 305 m, started one 850 mw unit in 1970 and a second unit of equal capacity in 1971. SO_2 emissions from two other large power stations to the northwest apparently do not appreciably impinge the area of this study (Hutnik and others 1989).

Sample Stands

Beginning in 1987, data were collected within 11 mostly ridge top or upper slope, mature, closed canopy, even-aged, northern red oak stands (1-10 ha). Ideally, stands lacking partial cutting were chosen, but many had received light thinnings as part of forest management practices. Stands 7, 10 and 11, to the southwest and upwind of pollutant sources, served as controls in regard to pollutant emissions from the power generating stations and Johnstown industries to the northeast (Fig. 1), although transport of sulfur and nitrogen from sources outside the region and subsequent deposition onto Laurel Ridge is well-recognized (e.g., Pierson and others 1989).

Soils on the study sites are well to moderately well drained, very stony loams and silt loams, predominantly Typic Dystrochrepts, occasionally including some Typic Hapludults and Aquic Fragiudults.

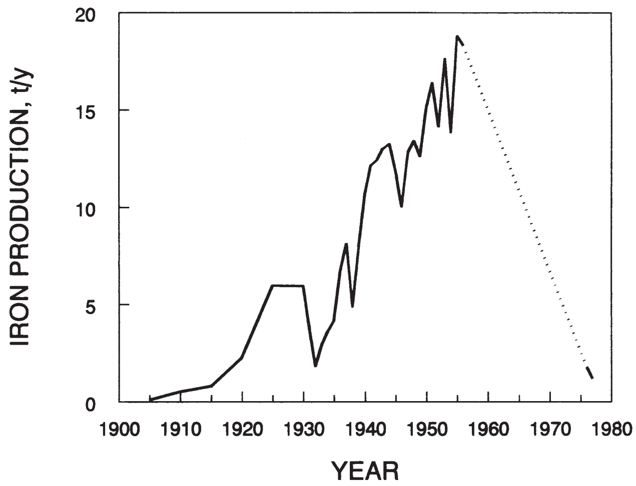

Figure 2—Historical iron production at Johnstown (Data from Brown, 1989).

Tree-Ring Sampling

Pairs of 5 mm diameter cores were extracted at 1.3 m height from boles of at least 20 dominant and codominant red oaks in each of the 11 stands. Trees without dieback or mechanical crown or bole injury were selected. Cores were air-dried, glued into wooden holders, and surfaced with successively finer sanding papers. Visual crossdating was performed, ring widths were measured to 0.01 mm precision, and crossdating was verified using computer program COFECHA (Holmes 1985).

Statistical Analyses

The ring-width series of each core within a stand was standardized to create stationary time series and to remove autocorrelated trend largely associated with age and competition. This was achieved by a double-detrending procedure followed by autoregressive modelling, using Cook's (1987) method and computer program ARSTAN. First, a linear or negative exponential trend line was fit to each series and indices were computed from the ratio of curve value to ring width. The second detrending was achieved by fitting a spline curve to the initial indices and recalculating. Lastly, an appropriate autoregressive (AR) model was fit to each detrended series, and to the mean stand chronology. This step yielded two types of mean stand chronologies: the mean indices after AR modeling of individual series (residual chronology), and the arstan chronology consisting of the residual chronology plus that portion of the original trend (persistence) common to most individual series. Thus, the residual chronology represents the mean "white noise" stand chronology. The arstan chronology additionally contains the common (pooled) persistence that may be associated with some exogenous factors affecting growth.

Stepwise multiple regression models were developed to relate red oak residual and arstan growth indices for each of the eleven stands to regional climate (objective one). Total monthly precipitation and mean monthly temperature data were each averaged from Historical Climatic Network database stations at Johnstown, New Castle and Uniontown (Boden 1987, Bradley and others 1985). A 17-month climate year (prior May through September of the growth year) comprised the 34 total variables in the stepwise regression analyses with residual and arstan indices for each stand. A common calibration period of 1920-1969 (51 years; pre-Conemaugh power station emissions) was used. Stepwise regression climate calibrations were performed using PRECON (Fritts and others 1991). A value of $F = 4.00$ was used for adding variables. The resulting models were evaluated in terms of lack of fit, Durbin-Watson statistic, variance inflation factors, and the residuals plots. A series of tests described by Cook and others (1987) were employed to verify the calibration models using independent climate data from 1970-1986, and to address objective three. Actual and predicted indices were examined for similarity of pattern by simple linear correlation, for significant predictive bias by t-tests of the residuals for difference from zero, and for indication of predictive skill by reduction of error (RE).

Annual basal area increment (BAI) was computed for each ring width series from core radii and the ring widths using computer program AREA (Phipps and Fields 1988). Radial growth trend differences among stands were examined by comparing the slopes of linear regressions fitted to the individual stand cumulative mean BAI data (objective two).

RESULTS

Chronology Characteristics

Chronology statistics were initially examined for indication of comparative stand growth disturbance histories (Table 1). Autoregression parameter differences, in terms of the model coefficients (Φ) and percent explained variation (R^2), between the mean of individual series models and the pooled model for all series imply a spatially varied disturbance history within the stand, while similar parameter values suggest spatially homogeneous disturbances (Cook 1988). In this regard, stands 1, 2, 10, and 11 show relatively heterogeneous disturbances by virtue of large differences in both R^2 and Φ. In fact, charred snags indicated the occurrence of fire in stand 1; stand 2 had a light partial cutting approximately 20 years earlier. However, growth disturbance histories appeared fairly uniform within most stands. In fact, the remaining seven stands were similar in common persistence (pooled R^2) and pooled AR coefficients (Φ) (Table 1). These stands had 30-45 pct common growth persistence, indicative of even-aged forests lacking significant heterogenous disturbances.

These chronologies portray the historic natural disturbances, stand development trends, and direct human interventions such as cutting and fire that partly molded present forests on Laurel Ridge, but they show no specific relationship to the Conemaugh Gap area.

Growth-Climate Models

Red oak growth relationships with climate varied considerably among stands, with the percentage of growth explained by climate variables ranging from 9.3 to 49.1. Mean monthly temperature variables entered the regressions more frequently than precipitation variables (Fig. 3). Growing season temperature, especially in the prior year, had a generally positive growth relationship, although the specific temperature variables were not very consistent among stands or between residual and arstan chronology models within stands. Some of these inconsistencies could be related to variation in site and tree ages, although sample tree ages were mostly similar among stands (Smith and Rennie 1995). The single most consistent and important climate variable appearing in models was July precipitation in the growth year, which was always positive in its relationship.

The strength of the climate relationships among stands, indicated by the percentage of explained variation (R^2(pct), adjusted for number of variables), revealed some striking spatial patterns (Fig. 4). Growth in the southernmost, upwind stands (control stands 7, 10, 11) was consistently and relatively strongly coupled with climate. This was reflected in both the residual and arstan chronology models. These three stands were originally selected as controls by virtue of their distance and upwind direction from the Conemaugh

Table 1—Red oak chronology statistics; Φ_1 and Φ_2 are the series mean or pooled autoregression (AR) coefficients for models up to AR(2); R^2 is the variation explained by autoregression averaged over individual series or from pooled autoregression

				Autoregressive model					
				Series means			Pooled		
Stand	Chron. length	No. series	AR order	Φ_1	Φ_2	R^2	Φ_1	Φ_2	R^2
	No. yrs.					*Pct.*			*Pct.*
1	103	40	1	.529	-	29.6	.409	-	16.7
2	114	40	1	.489	-	25.8	.431	-	18.6
3	73	40	1	.584	-	35.9	.604	-	36.5
4	107	40	1	.617	-	39.1	.675	-	45.6
5	91	40	2	.533	.064	36.7	.502	.184	40.0
6	141	46	1	.540	-	30.1	.549	-	30.2
7	141	42	3	.478	.047	31.5	.384	.122	33.8
10	132	31	1	.518	-	29.4	.434	-	18.8
11	129	42	1	.469	-	23.2	.394	-	15.5
13	140	40	2	.575	.034	37.5	.518	.158	39.3
14	75	40	1	.541	-	30.8	.537	-	28.9

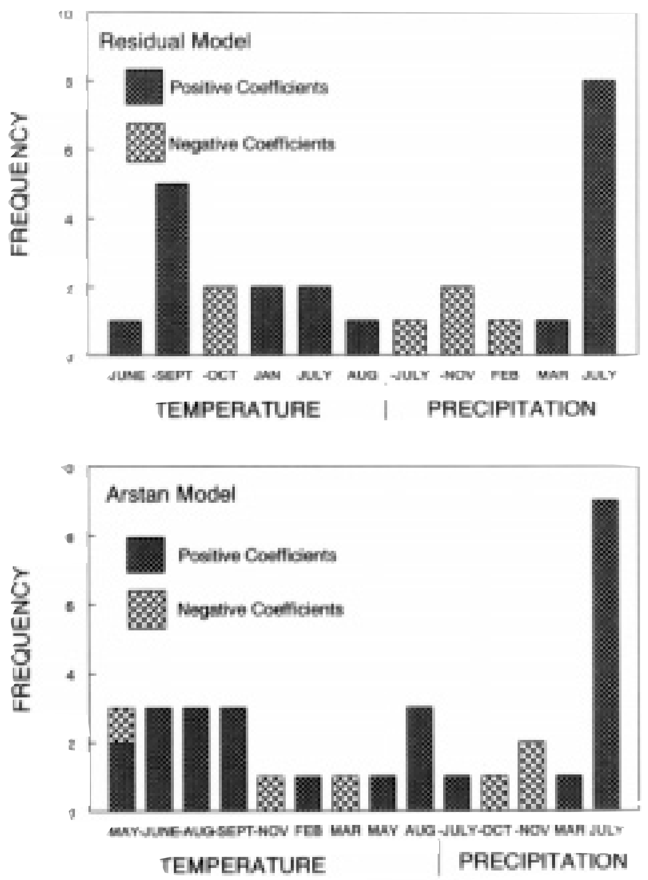

Figure 3—Frequencies of monthly mean temperature and monthly total precipitation variables appearing in calibration models of the eleven stands using residual and arstan chronologies. Numbers indicate stands. Negative signs preceding months indicate prior year.

Gap area. Compared to the control stands, residual chronology models of stands near Conemaugh Gap were notably weaker; while common (pooled) growth persistence in the arstan chronologies dramatically strengthened the growth-climate relationships in certain of these stands (viz., stands 1, 2, 4, 13). However, stands 5 and 6 exhibited virtually no growth response to climate variation.

Evaluation of the growth-climate calibration models for each stand indicated that all were significant in terms of correlated patterns of actual and predicted indices, and all exhibited some predictive skill (Table 2). However, these criteria revealed weaker models for stands 5 and 6 and, to a lesser extent, stands 1, 3 and 14.

The calibration model verifications using the period 1970-1986 showed uniformly poor predictive potential (Table 2). Although none had significant bias, there was no evidence that predicted indices correlated with observed indices, and no models exhibited predictive skill. Thus, although potentially useful calibration models were obtained for many of the stand chronologies, none were adequate for predicting growth in the post-1969 period. Further, calibrations based on the entire 1920-1986 period for each stand chronology yielded consistently lower percentages of explained variation than the 1920-1969 calibrations. Calibration of the control chronology (mean of stands 7, 10 and 11) with climate for the entire 1920-1986 period identified only two significant variables, July precipitation and prior April temperature, and it explained less than half of the growth variation (21.9 pct) explained by the 1920-1969 calibration model. These results portray a regionally

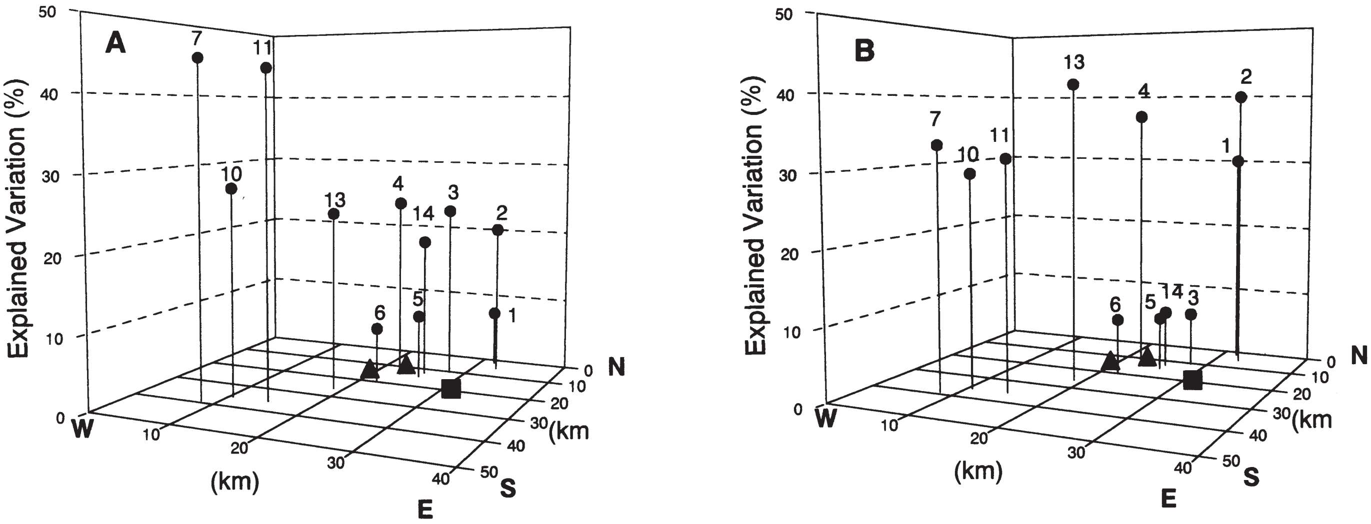

Figure 4—Geographical patterns of percentages of explained variation ($R^2_{adj.}$) for climatic calibration models based on (A) residual and (B) arstan tree-ring chronologies. Triangles indicate power station locations, the square indicates the location of Johnstown.

Table 2—Comparison of arstan and residual indices-based climate model performance for 1920-1969 (calibration period) and 1970-1986 (verification period); the simple correlation coefficient (r) measures the correspondence in pattern between actual and predicted indices; bias is the mean residual, with significant values an indication of over- or under-prediction; reduction of error (RE) >0 suggests predictive skill over using the mean index value (no significance test available)

		Residual			Arstan		
Stand	Period	r	Bias	RE	r	Bias	RE
1	Calib.	0.38*		0.09	0.60*		0.36
	Verif.	0.24	0.018	0.05	0.01	0.040	-0.84
2	Calib.	0.50*		0.25	0.69*		0.47
	Verif.	0.01	-0.001	-0.32	0.02	0.039	-0.41
3	Calib.	0.52*		0.27	0.32*		0.10
	Verif.	0.34	-0.058	-0.01	0.10	-0.056	-0.32
4	Calib.	0.53*		0.28	0.66*		0.43
	Verif.	0.16	-0.014	-0.05	0.10	-0.045	-0.63
5	Calib.	0.32*		0.11	0.31*		0.09
	Verif.	-0.20	0.032	-0.48	-0.12	-0.019	-0.19
6	Calib.	0.31*		0.09	0.31*		0.10
	Verif.	0.23	0.039	0.02	0.17	0.030	0.01
7	Calib.	0.70*		0.49	0.61*		0.37
	Verif.	0.12	0.020	-0.17	0.28	-0.057	-0.12
10	Calib.	0.63*		0.39	0.66*		0.44
	Verif.	0.08	-0.036	-0.11	0.06	-0.030	-0.63
11	Calib.	0.69*		0.48	0.60*		0.36
	Verif.	0.17	0.054	-0.07	0.21	0.038	-0.01
13	Calib.	0.54*		0.29	0.69*		0.47
	Verif.	0.13	0.022	-0.20	0.00	0.013	-1.43
14	Calib.	0.47*		0.22	0.31*	0.10	
	Verif.	0.26	-0.019	-0.01	0.07	0.008	-0.12

*Significant at $P \le 0.05$.

unstable growth response to climate in addition to the spatial differences noted above.

Basal Area Growth

Linear regressions closely and accurately described the cumulative mean basal area increments between 1920 and 1986 for 10 of the 11 stands ($R^2 \geq 0.98$). Stand 14 had a curvilinear growth pattern (linear $R^2 = 0.90$) due to a growth release around 1955 and is excluded from the following discussion.

The spatial pattern of basal area growth rates (Fig. 5) generally mimics that of the growth-climate model strengths depicted in Figure 4. As a group, stands 2, 3, 5, 6 and 13 exhibited lower growth rates than stands 1, 4, 7, 10 and 11. These growth rates depict a generally increasing growth gradient away from the Conemaugh Gap area. An exception is stand 4 on the northwest base of Laurel Ridge near the power plants, which exhibited a growth rate comparable to stands remote from Conemaugh Gap despite its proximity to the power stations. The physiographic location of stand 4 would probably shield it from pollutants originating at Johnstown (Fig. 1). Stands 5 and 6 were notable for lacking a growth relationship with climate, and the mean sustained growth rates of these stands (and stand 2) implies a history of non-climatic growth stress. There was no physical evidence within these stands to indicate a possible explanation.

DISCUSSION AND CONCLUSIONS

The 1920-1969 climate response calibration models show that above normal July rainfall in the growth year, and warmer than normal summer temperatures in the preceding year, promote red oak growth in these stands. The arstan chronologies were generally better correlated with climate than the residual chronologies, indicating a general persistence in the effect of climate on growth that may be a physiological characteristic of the species. However, this

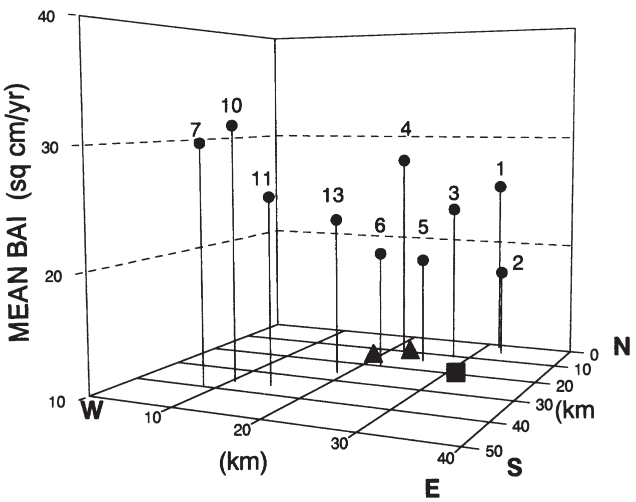

Figure 5—Geographical patterns of stand cumulative mean basal area increment (BAI) growth rates. Numbers indicate stands. Triangles show power station locations and the square indicates the location of Johnstown.

persistence was especially evident in chronologies from the vicinity of Conemaugh Gap, suggesting the presence of additional exogenous environmental stress in that area.

The climatic response is generally consistent with the ecophysiological nature of oak growth. Oaks tend to occupy relatively warm, dry habitats. Their ring-porous characteristic results in a dependency on stored energy from the previous year for earlywood formation, while latewood production relies more upon current season growing conditions. July precipitation is clearly the most critical climatic factor in growth of red oaks on Laurel Ridge.

Red oaks within the northeastern portion of the study area generally exhibited an anomalous uncoupling of the climate-growth relationship that generally predates the Conemaugh, Seward or other local power stations. Red oaks have also had notably low growth rates within this same locality during pre- and post-operational times. These findings raise the possibility that anthropogenic disturbances, perhaps including fire, destructive logging practices, and industrial emissions from Jownstown, may have strongly impacted red oak growth in the locality at least two decades prior to 1986.

Stands 5 and 6 show the most consistent lack of climatic growth response (and the lowest basal area growth rates), followed by stands 1, 2, 3 and 14. Notably, these appear to lie within the Johnstown airshed. In particular, stands 5 and 6 are situated on the ridge top directly above the city. Although geographically within the same general area, stands 1, 4, 13 and 14 were somewhat better correlated with climate. However, stands 1 and 13 are more remote from Johnstown, while stands 14 and 4 lie respectively on the mid-slope and at the base of the opposing side of Laurel Ridge from the city, and may have been relatively sheltered from Johnstown emissions. Although a similar sheltering effect might be true for stands 1, 2 and 3, Johnstown emissions could be carried to these stands through Conemaugh Gap by prevailing winds.

Evaluation of 1920-1969 growth-climate calibrations, and comparisons with models derived for 1920-1986, indicated that the relationship of red oak growth on Laurel Ridge has not remained stable. Precisely when this transition took place cannot be established from our analyses, but it is evident in the post-1969 period at all sites. Comparatively high frequencies of insect defoliations and droughts during 1970-1992 resulted in extensive red oak mortality on Laurel Ridge between 1990-1992 (McClenahen and others 1997). Comparisons of red oak and tuliptree chronologies indicate that relatively few oak defoliations occurred in the study area between 1930 and 1957, while the more recent, recorded defoliations were confirmed (unpublished data of the authors). These droughts and increasing defoliation events, a number of which fell within the chronology period 1969-1986, may have contributed greatly to the general red oak growth-climate uncoupling.

Summarizing these results: (1) the importance of common persistence in the arstan calibrations may reflect an interactive effect of climate and other environmental stress within ridgetop and upper slope stands near the Conemaugh Gap during power plant pre-operational times, (2) there was a long-term depressed growth-climate relationship for most stands within the Conemaugh Gap area, especially on the ridgetop above Johnstown, (3) the comparative structures of the AR models mitigate against differences in endogenous disturbance histories as a sufficient explanation for these anomalous spatial patterns of growth-climate response and, (4) stands most likely exposed to Johnstown industrial emissions exhibited comparatively lower basal area growth trends.

We conclude that growth of canopy northern red oaks on the upper slopes of Laurel Ridge near to, and downwind of, Conemaugh Gap exhibited an anomalous long-term low growth rate and more pronounced climatic decoupling. The most likely cause of this growth anomaly is historical industrial emissions from Johnstown. There is little indication that sulfur emissions from local power stations established mostly in the late 1960's and early 1970's had an additional growth impact. Whether comparative red oak growth and climatic sensitivity recover in the Conemaugh Gap area as a result of improved air quality in Johnstown (and reduced power plant emissions) is presently under investigation.

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