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The Response of Western Forests to Air Pollution

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Forests of Arizona and New Mexico

Extensive conifer forests arc across central Arizona into western New Mexico, in and near the mountainous Mogollon Rim that separates the upland Colorado Plateau from the dry Basin and Range Province (Figure 10.1). The two dominant tree species are ponderosa pine (*Pinus ponderosa*) and Douglas-fir (*Pseudotsuga menziesii*), with other species including southwestern white pine (*Pinus strobiformis*), Engelmann spruce (*Picea engelmannii*), white fir (*Abies concolor*), blue spruce (*Picea pungens*), limber pine (*Pinus flexilis*) and subalpine fir (*Abies lasiocarpa*). In the Basin and Range Province of south central and southeastern Arizona, forests occur on several isolated mountains surrounded by shrublands, grasslands, and deserts. Large sectors of the mountainous and upland regions are also forested with varying proportions of pinyon pine (primarily *Pinus edulis*), junipers (*Juniperus* spp.) and oaks (*Quercus* spp.); pinyon-juniper woodlands are more extensive than all other forest types combined in both Arizona and New Mexico (USDA Forest Service 1981).

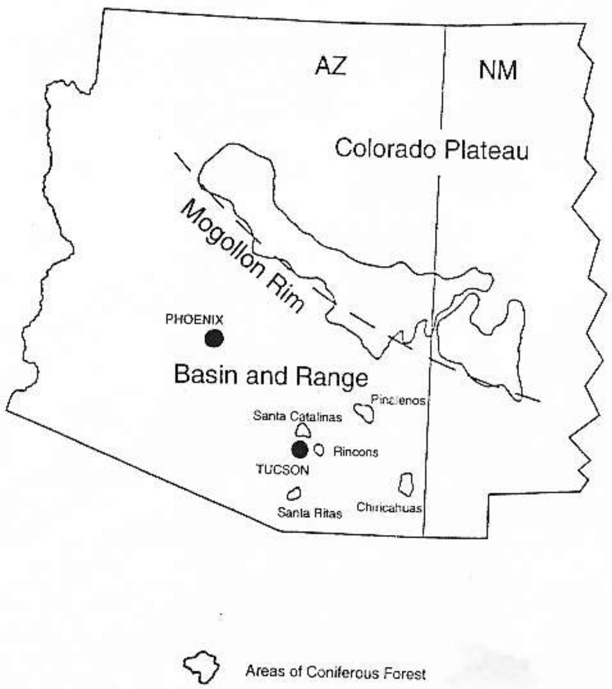

Figure 10.1 Physiographic features and coniferous forests of the research area.

Pinyon-Juniper Woodland

The pinyon-juniper woodlands occur at the lower elevational limits of forests in this region, typically occurring from 1370 to 2440 m. Estimates of the areal extent of these woodlands in Arizona and New Mexico range from about 9 million ha (USDA Forest Service 1981) to 12 million ha (Springfield 1976, Meeuwig and Basset 1983). This association is a source of fuel wood, fenceposts, Christmas trees, pinyon nuts, and important wildlife habitat. Its greatest economic importance may be as rangeland for cattle grazing. Lanner (1981) presents an intriguing introduction to the natural history and cultural use of pinyon pine, and a comprehensive summary of recent research and an extensive bibliography is available in Everett (1987).

Pinyon-juniper woodland exists in a variety of topographic and edaphic conditions. Low precipitation and high evaporative demand lead to moisture stress, modest leaf area indexes (1.0 to 3.6 m^2/m^2 on a projected basis; Schuler and Smith 1988) and low biomass productivity (maximum of about 1 m^3/ha annually; Buckman and Wolters 1987, Schuler and Smith 1988). Regeneration is intermittent and sparse (Samuels and Betancourt 1982, Ronco 1987). Within the woodland type, pinyon pine is the more common species at upper elevations and higher latitudes while juniper species are more common at the lower elevations and latitudes. The common juniper species include Utah juniper (*Juniperus osteosperma*), one-seed juniper (*Juniperus monosperma*), Rocky Mountain juniper (*Juniperus scopulorum*) and alligator juniper (*Juniperus deppeana*). Pinyon-juniper woodland is often bordered by grassland, oak woodland, or desert scrub at its lower limit, and by ponderosa pine or Gambel oak (*Quercus gambelii*) at upper limits.

Ponderosa Pine Forests

The ponderosa pine type forest is found throughout the region at elevations of 1525 to 2750 m, with its prime habitat between 2150 and 2450 m. It covers about 3.5 million ha in Arizona and New Mexico (Shupe 1965; USDA Forest Service 1981). There is an extensive literature regarding this major timber species in the Southwest (see also Chapter 9), such as the classic management monograph by Pearson (1950), and pioneering papers on ecology by Weaver (1951) and Cooper (1960, 1961). More recent silvicultural and fire ecology summaries are Schubert (1974), Ronco and Ready (1983), and Swetnam and Dieterich (1985).

At the lower elevations of its range, ponderosa pine is associated with juniper, pinyon, and Gambel oak. At upper limits, mixtures include Douglas-fir, aspen (*Populus tremuloides*) and various conifers, depending on latitude. Across most of its range, ponderosa pine occurs in extensive and pure stands, especially along the Mogollon Rim. In southeastern Arizona and southwestern New Mexico there is a ponderosa pine variety with five needled bundles (var. *arizonica* (Engelm.) Shaw) that may co-occur and interbreed with the three needled variety (*scopulorum* Engelm.).

Productivity of ponderosa pine forests is limited by low leaf area indexes (2.0 to 3.5 m^2/m^2 on a projected basis, Whittaker and Niering 1975, Peet 1988) that result from low supplies of water and nutrients. Rates of stem growth average about 2 to 4 m^3/ha in well-stocked stands (Ronco and Reddy 1983).

Cool and moist climatic conditions in 1919 allowed dense thickets to be established across much of the Southwest. Fire suppression and especially heavy grazing in preceding decades also helped insure survival of this large cohort of trees (White 1985).

Mixed Conifer Forests

Mixed conifer forests are complex assemblages of up to eight overstory conifers that cover over 500,000 ha of Arizona and New Mexico (Ronco et al. 1983) at elevations of 2450 to 3050 m. Mixed conifer forests occur as low as 1830 m in cool, moist canyon bottoms and on north-facing slopes (Pissot 1965, Jones 1974, Ronco et al. 1983). This forest type requires moister conditions than ponderosa pine, into which it grades at lower elevations. At upper limits, the mixed conifer type grades into the more cold-tolerant spruce/fir type. Douglas-fir is the dominant species across most of the mixed conifer type, mixed with ponderosa pine, white fir (*Abies concolor*), Engelmann spruce, blue spruce, limber pine, subalpine fir, southwestern white pine and corkbark fir (*Abies lasiocarpa* var. *arizonica* (Merriam) Lemm.).

Limitations on growth have not been experimentally determined in this forest type; leaf area indexes range from about 6 to 8 m^2/m^2 on a projected basis (Whittaker and Niering 1975), and stem growth of about 5 m^3/ha annually (Ronco et al. 1983).

Spruce-Fir Forests

Spruce-fir forests cover about 370,000 ha in Arizona and New Mexico (USDA Forest Service 1981), above the mixed conifer forests (about 2900 m) up to timberline at about 3350 m. Near timberline, subalpine and corkbark firs drop out of the stands, leaving pure stands of Engelmann spruce (Alexander and Engelby 1983). We did not sample this type because of its limited occurrence in the study region.

Pollutants of the Region

Parts of this region have recently experienced high levels of pollutant emissions, with spatial gradients in deposition amounts (Figure 10.2, USEPA 1978, Roth et al. 1985). Sulfur was primarily derived from nonferrous smelters in an area ranging from near the Arizona-Mexico border up to the base of the Mogollon Rim in central Arizona, and then eastward along the Mogollon Rim to the copper mining areas of eastern Arizona and southwestern New Mexico. While some of the mining activity has an extensive history that reaches back into the 19th century, the heaviest smelting activity occurred in the four decades following World War II (Dunning and Peplow 1959, Arizona Department of Economic Security 1983). Trijonis (1979) found a declining trend in visibility from the middle 1950s to the early 1970s, and hypothesized that this was most likely due to corresponding increases in sulfur dioxide, nitrogen oxides and hydrocarbon emissions. Nitrogen oxides and hydrocarbon emissions vary in source but changes in them can be inferred from increases in population and attendant increases in total vehicle and other sources of emissions since mid-century in Phoenix and Tucson. Because time series of ozone concentrations from those cities are less than two decades in length, and vary substantially in terms of monitoring frequency and number of stations, we did not use them in this project. Existing data on ozone patterns in this region are described in Chapter 3.

The Regional Sampling Approach

The forest types that we evaluated included pinyon-juniper woodland, ponderosa pine forests and mixed conifer types. These forests often form complex mosaics rather than extensive homogeneous communities, particularly in the southern mountain ranges. Major differences in moisture availability and evaporative demand occur on scales of hundreds of meters to a few kilometers, resulting from differences in elevation, aspect, and soils in this geologically complex region (see Chapters 1 and 4). Much of the annual precipitation (about half) occurs in winter, and water stored in the soil from winter drives tree growth early in the growing season. High temperatures and variable precipitation during the growing season are also important (Graybill 1989; Chapter 2).

Table 10.1 *Tree-ring collections.*

Site	Code	Species[1]	Elevation (m)	No. Trees	Dated Range	Signal:Noise Ratio 1850–1986
AGUA FRIA, NM	AFN	PN	2225	17	1361–1987	53.448
513 BEAVER CREEK, AZ	BCR	PP	2393	21	1559–1987	30.335
BLACK MTN, NM	BKF	DF	2697	39	1462–1987	34.499
BLACK MTN, NM	BKP	PP	2697	26	1555–1987	29.130
514 BLACK RIVER, AZ	BRF	DF	2438	24	1565–1987	25.682
DRY CREEK, AZ	DCP	PN	1378	23	1608–1987	40.070
EAGLE CREEK, AZ	EPN	PN	1695	20	1639–1987	28.501
G.C.DWELLINGS, NM	GCP	PP	1768	15	1528–1987	—[2]
GUS PEARSON, AZ	GPN	PP	2255	35	1571–1987	39.448
GIRL'S RANCH, AZ	GRP	PP	1969	23	1594–1987	46.315
GRASSHOPPER, AZ	GRS	PP	1798	32	1661–1986	46.951
MULETANK, AZ	MTP	PP	2309	40	1595–1987	6.169
MIMBRES JUNCT, NM	MJN	PN	1951	23	1604–1987	30.678
S.F. PEAKS, AZ	PDF	DF	2682	20	1762–1987	9.767
ROCKY GULCH, AZ	RGP	PP	1966	20	1659–1987	32.474
ROBINSON MTN, AZ	RMP	PP	2225	39	1620–1987	26.965
ROSE PEAK, AZ	RPP	PP	2316	16	1641–1987	52.667
SHOWLOW, AZ	SGP	PP	2073	22	1603–1987	60.870
SLATE MTN, AZ	SMP	PP	2194	19	1589–1987	61.684
WALNUT CYN, AZ	WCP	PP	2057	12	1413–1987	26.239
WALNUT CYN, AZ	WDF	DF	2027	20	1668–1987	20.530
515 BEAR WALLOW, AZ	BWF	DF	2484	22	1600–1987	11.282
DEVIL'S BATHTUB, AZ	DBN	PN	2286	19	1769–1987	7.968
GREEN MTN, AZ	GMF	DF	2194	25	1547–1986	17.358
GREEN MTN, AZ	GMT	PP	2194	43	1412–1986	19.681
HELEN'S DOME, AZ	HDE	PP	2536	14	1625–1987	18.564
HELEN'S DOME, AZ	HDW	WP	2536	13	1718–1987	16.861
MT. HOPKINS, AZ	MHP	PP	2133	12	1714–1987	17.650
NOON CREEK, AZ	NOO	PP	2347	20	1764–1987	15.456
NORTH SLOPE, AZ	NSA	WF	2438	10	1778–1987	18.390
NORTH SLOPE, AZ	NSE	PP	2438	10	1678–1987	9.456
NORTH SLOPE, AZ	NSF	DF	2438	17	1637–1987	19.067
NORTH SLOPE, AZ	NSW	WP	2438	12	1692–1987	13.853
ORD MTN, AZ	ORD	PP	2133	16	1560–1987	17.145
PINERY CYN, AZ	PCD	DF	2286	22	1641–1987	18.903
POST CREEK, AZ	PST	DF	2731	21	1516–1987	17.278
RHYOLITE CYN, AZ	RCF	DF	1829	27	1620–1987	27.190
RHYOLITE CYN, AZ	RPE	PP	1829	18	1629–1987	14.122
SANTA RITA, AZ	SRH	DF	2400	21	1486–1987	29.888
TUCSON SIDE, AZ	TSE	PP	2365	23	1654–1987	24.041
TUCSON SIDE, AZ	TSW	WP	2365	9	1663–1987	8.630

[1] PN = *Pinus edulis* (pinyon pine)
PP = *Pinus ponderosa* (ponderosa pine) PIPO
WP = *Pinus strobiformis* (southwestern white pine)
DF = *Pseudotsuga menziesii* (Douglas-fir) PSME
WF = *Abies concolor* (white fir)

[2] Inadequate constant specimen depth during 1850–1986 period. Signal information not calculated.

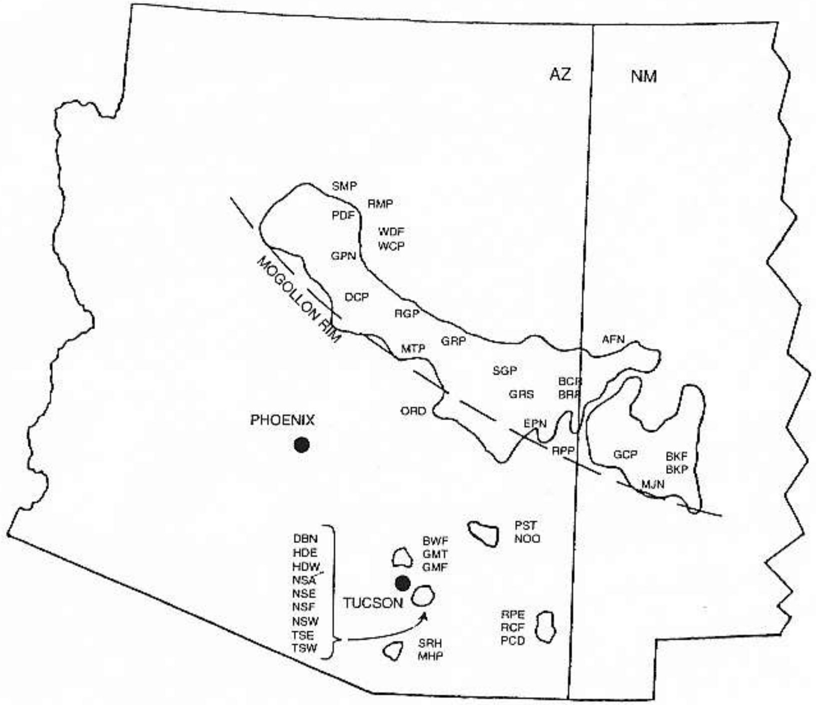

Figure 10.3 Location of stands selected for sampling. See Table 10.1 for site names and characteristics.

Stands with evidence of thinning or other anthropogenic disturbance such as road construction were avoided in order to limit disturbance signals unrelated to pollution. We also avoided trees with obvious defects such as heavy lightning damage, extreme lean, or dwarf mistletoe (*Arceuthobium* spp.) infection that was rated 3.0 (moderate infection) or greater with the Hawksworth (1977) system. We extracted two increment cores at breast height, transverse to the slope, from 15–25 dominant to codominant trees in each collection. Trees older than 150 years were sought. The final chronologies are from stands in a variety of environmental settings that range from the middle-elevation ranges of forests to lower elevation limits of forests.

criteria (Draper and Smith 1981). The dependent variable was always a residual tree-ring chronology while the independent variable was an annual precipitation sum of divisional data (NOAA 1988) for the period of August prior to growth through July of the year of growth. This annual sum was determined to be the strongest and most common predictor of annual growth after extensive screening of various monthly and seasonal values of temperature, precipitation and the Palmer Drought Severity Index (Palmer 1965).

We established statistical models in each baseline period over two subintervals for each of the 41 chronologies; the intervals from 1897 to 1950 and to 1960 were divided into halves. The first interval was initially used for calibration (model development) while the second interval was used for verification (model testing). Then the process was reversed and the second interval was employed in calibrating the model while the first segment was used for verification. This split period calibration/verification approach during the baseline period was adopted to test for time stability of the relationships between climate and tree growth. Only after the split period results were evaluated was a final calibration established with the full baseline period data set. This was important because the climatic data available during the baseline periods spanned only 55 to 65 years. All of the data were used to insure that the final calibration models were developed on the fullest possible range of data covariation.

The equations derived in the model development phase were used to estimate tree growth series in the 1951–1986 and 1961–1986 periods. The null hypothesis was that the estimated growth should be reasonably similar to actual growth in the recent intervals. Failure to reject the hypothesis would support the contention that there has been no change in the relationship between climate and tree growth. If so, the covariance between the predicted and actual growth should not be significantly different, and should be similar to the covariance between actual growth and annual precipitation in the baseline periods. In addition, the means of the predicted and actual growth after mid century should not be significantly different, and they should not exhibit divergent trends.

Alternatively, the covariance between the actual and predicted series may be poor or drop precipitously from that seen in the calibration period. In addition, significant differences may be seen between the means and variances of the actual and the predicted series or the actual and predicted series may have different trends. Inability to reject any of the alternative hypotheses implies that the actual and predicted growth differed in some manner. It does not necessarily mean that an anthropogenic impact on tree growth is the cause of the difference, merely that a difference exists and that some factor(s), including pollution, could be the causal agent(s). That pollution is actually the cause of any tree growth change would remain to be demonstrated.

Covariance was evaluated with Pearson's correlation coefficient and its square, the coefficient of determination. Differences of means and central tendency were tested with the t-test and the Wilcoxon matched-pairs signed-ranks test, while differences in variances were evaluated with an F ratio test. An alpha level of .05 was set for all tests and these were two-tailed. Descriptions of these statistical procedures are found in many basic texts (cf. Snedecor and Cochran 1979, Bradley 1968).

Results

Indications of Recent Growth Abnormalities

During the early stages of research we discovered a strong trend in recent growth that was not typical or natural, owing to divergence from the trend in annual precipitation. In the dating process we found that a moderate to substantial portion (up to about 50 percent) of the tree-ring series from ponderosa pine in seven stands could not be dated after times ranging from about 1920–1950 on to the final year of collection in 1986. In some cases more than 40 rings were absent from samples during the period of 1920–1986. The most extreme suppressions of growth were found in the post-1950 years. This was unexpected. Precipitation trends throughout the region show particularly high values near the beginning of the century with decline from the 1920s into drought conditions at mid-century (Chapter 2). This drought was followed by large increases in moisture in the 1970s and 1980s. Most tree-ring series we have dealt with in Arizona and New Mexico tracked this overall U-shaped pattern (Rose et al. 1981, Graybill 1989). However, the cores in the present study are the first series from the Basin and Range area, and six of the seven chronologies exhibiting this period of growth suppression are from that southern sector of Arizona. Discussion of possible reasons for these growth anomalies is presented below in the Summary and Discussion section. We next consider some of the quantitative aspects of climate and tree growth covariation.

Relationships Between Climate and Tree Growth

Predictive relationships between divisional climate data (August to July total precipitation) and each of the 41 residual tree-ring chronologies were established during the two baseline periods (Table 10.2). The final

Table 10.2 Model calibrations and predictions. See Table 10.1, Figure 10.3 for site information.

CODE	[1]Period	[2]Calibration r^2	[3]Prediction r^2	[4]t-test	[5]F-test
Northern group					
AFN	1	.42	.45	Rd	A
	2	.43	.44	Rd	A
BCR	1	.13	.41	A	Ri
	2	.18	.35	A	Ri
BKF	1	.43	.54	Rd	A
	2	.44	.60	Rd	A
BKP	1	.37	.58	A	Ri
	2	.40	.58	A	Ri
BRF	1	.43	.54	A	Ri
	2	.46	.51	A	Ri
DCP	1	.51	.50	A	Ri
	2	.47	.59	A	A
EPN	1	.37	.17	A	A
	2	.33	.20	A	A
GCP	1	.35	.42	Rd	Ri
	2	.40	.35	A	Ri
GPN	1	.31	.33	Rd	Ri
	2	.36	.34	Rd	A
GRP	1	.43	.19	A	A
	2	.47	.09R	A	A
GRS	1	.50	.30	A	Ri
	2	.47	.28	A	Ri
MTP	1	.16	.02R	A	Ri
	2	.18	.00R	A	Ri
MJN	1	.25	.64	A	Ri
	2	.33	.57	A	A
PDF	1	.35	.47	A	Ri
	2	.37	.41	A	Ri
RGP	1	.45	.34	Rd	A
	2	.46	.34	A	A
RMP	1	.40	.37	Ri	Ri
	2	.39	.31	A	Ri
RPP	1	.41	.33	Rd	A
	2	.40	.32	A	A
SGP	1	.48	.48	Rd	A
	2	.50	.46	Rd	A
SMP	1	.37	.50	Rd	A
	2	.43	.46	Rd	A
WCP	1	.55	.49	A	Ri
	2	.59	.42	A	Ri
WDF	1	.38	.52	A	Ri
	2	.39	.53	A	Ri
Southern Group					
BWF	1	.23	.09R	A	Ri
	2	.16	.18	A	Ri
DBN	1	.09	.09R	A	Ri
	2	.11	.06R	A	Ri
GMF	1	.35	.22	Rd	A
	2	.31	.31	Rd	A
GMT	1	.27	.12	Rd	A
	2	.23	.16	Rd	A
HDE	1	.10	.03R	Rd	Ri
	2	.11	.01R	Rd	Ri
HDW	1	.24	.34	A	A
	2	.24	.30	A	A
MHP	1	.29	.30	A	Ri
	2	.29	.27	A	Ri
NOO	1	.33	.27	A	Rd
	2	.31	.22	Ri	Ri
NSA	1	.37	.48	A	A
	2	.36	.51	A	A
NSE	1	.17	.09R	Rd	Ri
	2	.16	.06R	Rd	Ri
NSF	1	.25	.24	Rd	A
	2	.24	.25	Rd	Rd
NSW	1	.16	.36	Rd	A
	2	.15	.45	Rd	A
ORD	1	.30	.20	Rd	Ri
	2	.28	.20	Rd	Ri
PCD	1	.37	.45	Rd	A
	2	.40	.43	Rd	A
PST	1	.29	.33	A	Ri
	2	.25	.43	A	Ri
RCF	1	.41	.50	Rd	A
	2	.43	.46	Rd	A
RPE	1	.23	.31	Rd	Ri
	2	.27	.27	Rd	A
SRH	1	.42	.41	Rd	Rd
	2	.40	.50	Rd	A
TSE	1	.25	.14	Rd	A
	2	.22	.09R	A	A
TSW	1	.16	.26	A	Ri
	2	.17	.19	A	Ri

Table 10.2 footnotes

[1] 1 indicates period of calibration is 1897 -1950, period of prediction is 1951 - 1986. 2 indicates period of calibration is 1897 - 1960 and period of prediction is 1961 - 1986.

[2] Covariation of prewhitened tree-ring indices and the sum of August through July precipitation for the period of 1897 - 1950 and 1897 - 1960. R indicates nonsignificant values (alpha = .05).

[3] Covariation of actual and predicted tree growth measured by prewhitened index chronologies. R indicates nonsignificant values (alpha = 0.05).

[4] T-test results of mean differences in actual and expected growth. Throughout the remainder of the table, A indicates no significant differences (alpha = .05) in test statistics, R indicates there are significant differences, d indicates actual values were less than predicted, i indicates actual values were greater than predicted.

adjusted r^2 values for the full calibrations across the baseline periods were significant in all cases, but two of the relationships in the south were weak and not clearly interpretable (DBN, HDE). Those covariances were however relatively constant per chronology for each of the two baseline periods. The range of r^2 values for the 20 chronologies in the south was slightly lower than for the 21 in the north (0.09–0.42 vs 0.13–0.55, 1896–1950 period) and the means were different (0.26 in the south, 0.38 in the north, $t = 3.69$, $p<.001$). The lower mean value in the south is primarily due to low calibration values for chronologies in the mountains near Tucson.

Results of the comparison of actual and estimated tree growth are summarized in Table 10.2. During the recent test periods, the covariation between actual and climatically predicted tree growth was not significant in 11 cases. Eight of the non-significant covariances were associated with chronologies in the southern area although some were not surprising because their climatic sensitivity in the calibration period was low. With the exception of the GRP chronology, all tests yielding non-significant covariances were associated with chronologies from dense stands on relatively mesic sites.

Normally, we would not expect to find major changes in the covariance of actual and predicted tree growth after mid-century, compared to the covariance of actual growth and climate before mid-century. Exceptions would probably be due to changes in the relationship between climate and tree growth, or to stand level disturbances that we did not detect in either the baseline or test periods. In most cases (28 chronologies) no major changes occurred in covariance when moving from the calibration to the recent test periods. Two kinds of exceptions were noteworthy, showing either a decrease or an increase in r^2 of 50% or more in either recent test period when that value was compared to the calibration r^2 of the respective baseline period. Eight chronologies showed a decrease, with three in the north (EPN, GRP, MTP) and five in the south (BWF, GMT, HDE, NSW, TSE). All of the southern chronologies were from the two mountain ranges nearest Tucson (Rincons and Santa Catalinas) and four were ponderosa pine sites with extreme growth suppression in many trees after 1950 (although those particular cores had too many missing rings to use in the chronologies). The site and stand characteristics of all but EPN and GRP tend toward mesic and dense rather than xeric and open.

Five chronologies showed substantially increased r^2 values in the recent periods; three in the north were from relatively dry and open settings (BCR, BKP, MJN), and two in the south were from relatively wet sites and dense stands (NSW, TSW).

The results of F-ratio tests showed that for about half of the series (22 of 41, 1951–1986; 19 of 41, 1961–1986) the variance of the expected series both in the north and south was significantly less than that of the actual growth series (Table 10.2, F-test, Ri). This usually indicates that not all of the variance in the actual series was estimated by the original calibration models, which is not uncommon. More surprisingly, three cases showed variances of the estimated series that exceeded the variances of the actual growth series (Table 10.2, F-test, Rd), indicating that the variance of the actual series decreased after mid-century. All instances were in the south (NOO, NSF and SRH, 1951–1986, NSF, 1961–1986). Figure 10.4 provides a good visual example of this kind of pattern that is also associated with a difference in trend and a difference of means in the actual and predicted growth for chronology SRH near Tucson.

Differences between the estimated and actual mean growth are of some interest. Both the t-test (Table 10.2) and the Wilcoxon test (results not presented) show many instances where the two means, or central tendencies, are significantly different, with the mean of the actual tree growth usually being less than that predicted from climate (denoted by a "d" in Table 10.2). For a few chronologies the means of actual growth were greater than predicted (denoted by an "i" in Table 10.2). The results of the t and Wilcoxon tests were similar, with just three of 82 possible disagreements; therefore only the t-tests are considered in further discussion.

The spatial distribution of chronologies with significant differences of actual and predicted mean growth in the 1951 to 1986 period are shown in Figure 10.5. Dark dots following each code indicate that actual growth is less than predicted from August to July divisional precipitation. Taking the data set as a unit, and generously permitting chance to operate 10% of the time, we might only expect that four of the chronologies per time period would exhibit significant differences in actual and expected mean growth. Instead, 20 of 41 series (51%) in the 1951–1986 period and 16 of 41 series (39%) in the 1961–1986 period show significantly less than expected growth.

Actual and predicted growth levels differed on a spatial basis, and to some degree by species. This involved sites in and near the Mogollon Rim (northern sector) vs those in the southern Basin and Range area, and regional differences in ponderosa pine and Douglas-fir growth predictions. These differences will next be considered from the standpoint of the entire data set and from one of a reduced data set. Some chronologies had low calibration r^2 values in one or both baseline periods, indicating a low climatic response. They were excluded from some comparisons when that value was less than 0.25 (or, the simple correlation was 0.5), thus creating the reduced data set.

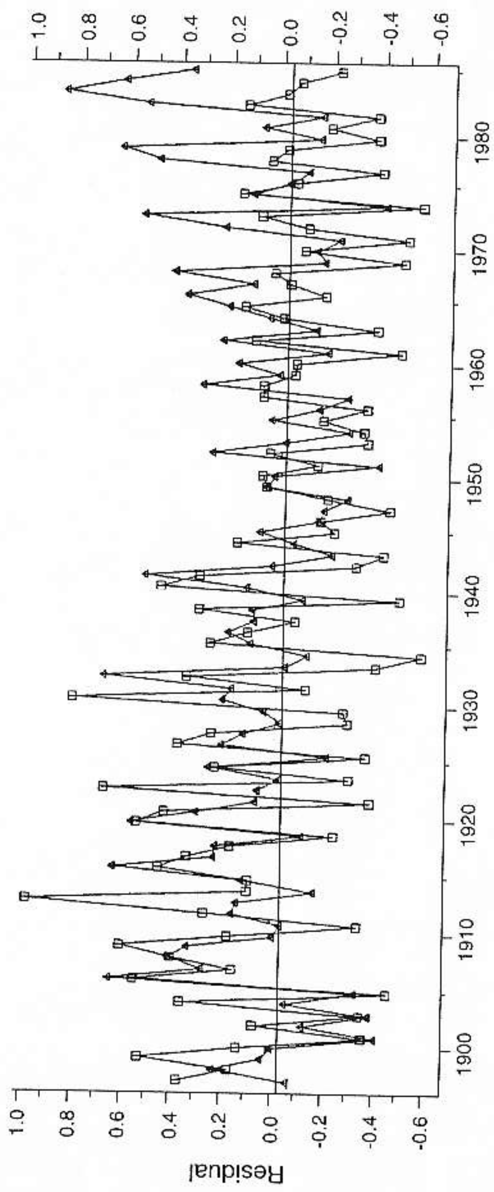

Figure 10.4 Time series plots of actual (squares) and predicted (triangles) tree growth for chronology SRH (ponderosa pine).

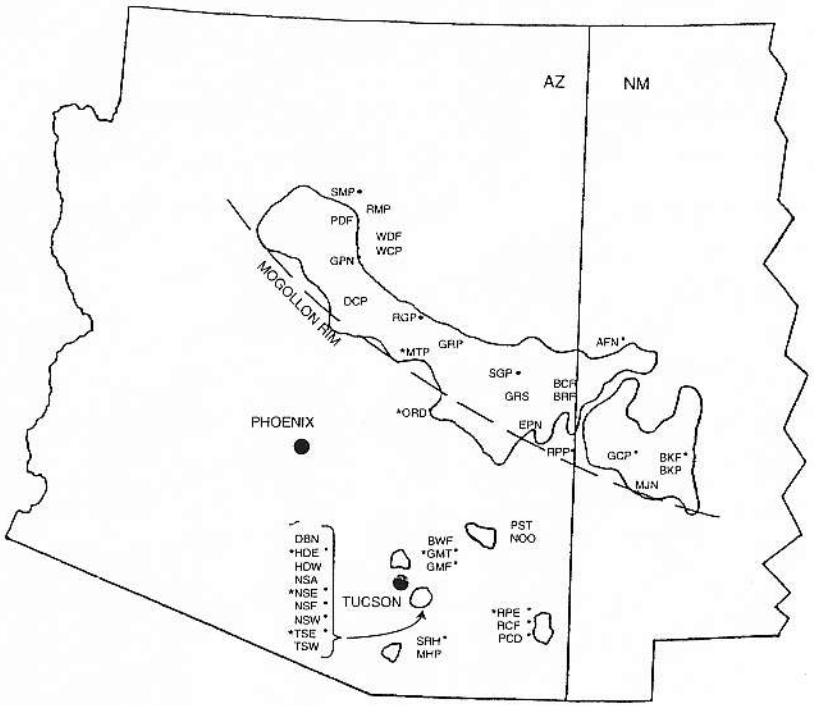

Figure 10.5 Geographic distribution of t-test results. A black dot following a chronology code indicates significantly lower mean growth in the actual series than in the predicted series for the 1951–1986 test period. An asterisk before a code indicates that approximately 50% of the trees sampled had extreme growth suppression after the mid-20th century.

Fisher exact tests and one-tailed probability levels for some of the most basic breakdowns of variation in mean growth response for both the full and reduced data set are provided in Table 10.3. The categories for each table are region (north, south) and evidence of significantly less than expected mean growth (fail) or of significantly greater than expected mean growth (pass). Cell values are simple counts of chronologies by category. However, these tests can only be considered gross descriptive statistics and cannot be used as estimates of population parameters for two reasons. First, the samples were not randomly selected. Second, not all chronologies are members of the same kind of population because the

Table 10.3 *Fisher exact tests on mean growth variation.*

Full Data Set — Reduced Data Set

Ponderosa pine, 1951–1986

A

	Pass[1]	Fail
North	7	6
South	2	6

$p = 0.200$

B

	Pass	Fail
North	5	6
South	2	3

$p = 0.635$

Ponderosa pine, 1961–1986

C

	Pass	Fail
North	10	3
South	3	5

$p = 0.090$

D

	Pass	Fail
North	8	3
South	2	2

$p = 0.682$

Douglas-fir, 1951–1986

E

	Pass	Fail
North	3	1
South	2	5

$p = 0.197$

F

	Pass	Fail
North	3	1
South	1	5

$p = 0.119$

Douglas-fir, 1961–1986

G

	Pass	Fail
North	3	1
South	2	5

$p = 0.197$

H

	Pass	Fail
North	3	1
South	1	4

$p = 0.167$

All species 1951–1986

I

	Pass	Fail
North	13	8
South	8	12

$p = 0.138$

J

	Pass	Fail
North	11	8
South	4	6

$p = 0.168$

All species 1961–1986

K

	Pass	Fail
North	16	5
South	9	11

$p = 0.042$

L

	Pass	Fail
North	14	5
South	4	6

$p = 0.085$

[1] Pass counts include chronologies with actual growth that is equal to or greater than expected. Fail counts include chronologies with growth that is significantly less than expected based on t-test results.

collections were made over gradients of growth conditions that range from open canopied and xeric to relatively dense and mesic for the region. In essence, each chronology represents a case study.

A review of the results for ponderosa pine (Table 10.3A–D) suggests that in the full data set there are some hints at north-south differences. This is not apparent in the reduced data set. However, the chronologies removed in this case were all from sites where many series could not be dated after mid-century. Four are from the mountains near Tucson (GMT, HDE, NSE, TSE), one is from the Chiricahuas (RPE) and only one is from the north (MTP—a dense forest interior site). Thus, removal of sites with relatively low calibration r^2 values, and for the most part, dramatically lower r^2 values between actual and estimated growth post-1950, may be obscuring the overall relationships best seen in the full data set.

The cell values for Douglas-fir (Table 10.3E–H) are low but there are limited indications of differences in mean expected growth by region. When all species are lumped (Table 10.3I–L) the strongest regional difference is in the 1961–1986 period in both the full and reduced data sets.

Reviewing the test results for other species, the only white fir chronology in the collection (NSA) showed no difference of means. It also has a large amount of explained variance during the verification period. Additionally, only one of the five pinyon chronologies (AFN) and only one of the southwestern white pine series (NSW) showed a difference between the predicted and actual mean growth.

Caution must be exercised in evaluating these empirical tests. Some tests, such as t-tests, are sensitive to the presence of one or a few large differences or outliers. A review of the time series plots of actual and predicted growth suggested that for three of the northern chronologies, rejection of the null hypothesis was due to this problem, and not to any aberrant level of growth (AFN, BKF, GCP). For example, Figure 10.6 illustrates the actual and predicted growth values for a Douglas-fir chronology from stand BKF in a remote area of southwestern New Mexico (see Figure 10.3 for site location). The covariance of actual and predicted growth was among the highest in the data set. However, the year 1973 was one of the wettest in the century and apparently the trees did not respond to that high value. This is not unexpected in the Southwest, especially when one or more of the preceding years had been relatively dry and stressful for growth, such as 1972. Removal of the 1973 values from the t-test computation dropped the significance of the t-value from .03 to .05 and removal of the 1984 values further dropped the significance to .09. In contrast, Figure 10.7 illustrates another chronology from the north (GPN-PP) where there was a striking change in both level

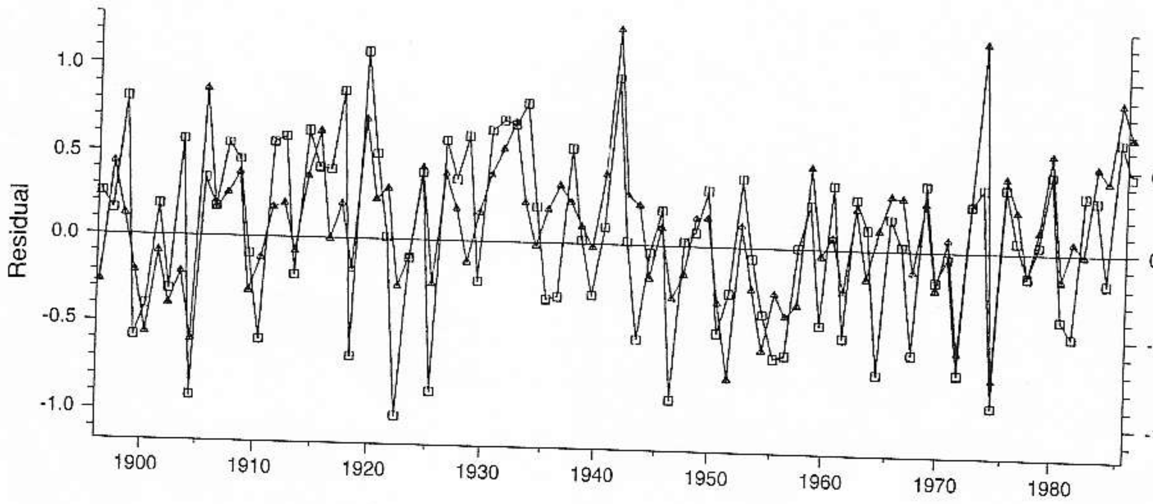

Figure 10.6 Time series plots of actual (squares) and predicted (triangles) tree growth for chronology BKF (Douglas-fir).

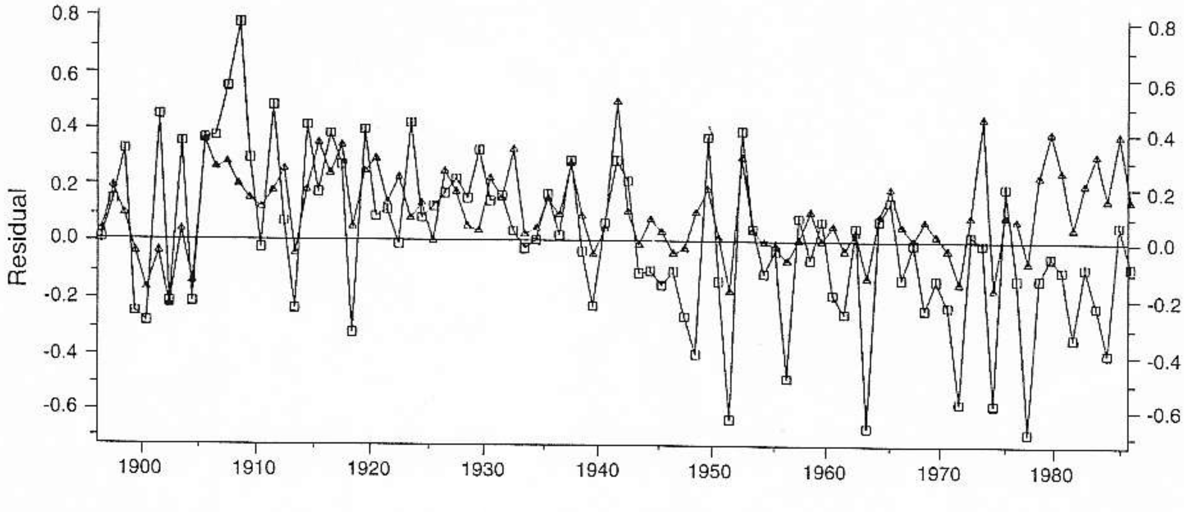

Figure 10.7 Time series plots of actual (squares) and predicted (triangles) tree growth chronology for GPN (ponderosa pine).