Analysis of Growth Trends and Variation in Conifers from Central Arizona

I. Network Chronology Development and Analysis

by

Donald A. Graybill and Martin R. Rose

Laboratory of Tree-Ring Research
University of Arizona
Tucson, Arizona 85721

List of Figures

List of Tables

1.0 INTRODUCTION

The research reported here is addressed to Scientific Question 1.1 of the Western Conifers Research Cooperative (WCRC) 1987 Research Plan:

"Are changes in forest condition greater than can be attributed to typical trends and levels of natural variability?"

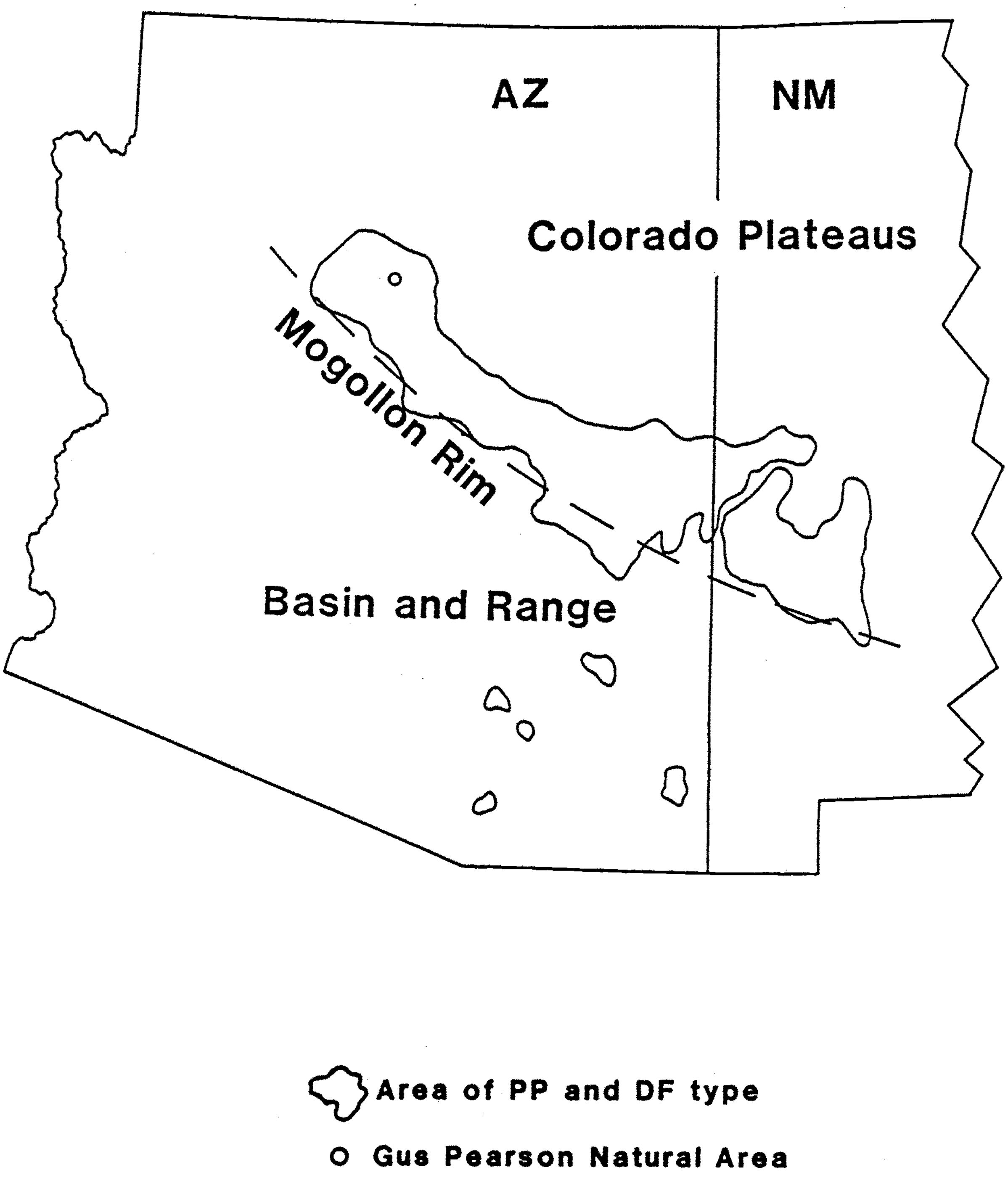
In consideration of that question we apply a series of analytical strategies to 41 tree-ring chronologies that were developed for this project and analyze archived forest plot measurement data. More than 60 years of dendrochronological and forestry research in central Arizona have resulted in appropriate controls and background data for these tasks.

This region was identified by the WCRC (1987:57) as one where such a study might have maximal value according to the following criteria:

(1) coniferous forest type,
(2) high levels of atmospheric deposition,
(3) good baseline data on tree physiology, stand development and ecosystem processes, and
(4) existing FIA and dendrochronological databases.

The extensive forests of commercial value here, primarily ponderosa pine (P. ponderosa), arc across central Arizona and into western New Mexico, generally in and near the mountainous Mogollon Rim that separates the upland Colorado Plateaus from the desertic Basin and Range Province (Figure 1). Other economically important species include Douglas-fir (Pseudotsuga menziesii and to a much lesser extent, southwestern white pine (P. strobiformis) and engelmann spruce (Picea engelmanii). In the Basin and Range areas of south central and southeastern Arizona the forests occur on several isolated mountain masses and generally include the same range of coniferous species just noted. Substantial portions of all mountainous regions are also forested with varying proportions of pinyon pine (primarily P. edulis), junipers (Juniperus sp.) and oaks (Quercus sp.). The pine-fir and pinyon-juniper forest types often form complex mosaics due to rapidly changing elevations, exposures and substrates.

Tree-ring chronologies developed in the research were therefore derived from the two species of primary economic importance - ponderosa pine and Douglas-fir - and from other conifers throughout this diverse area. A long record of archived 'gure 1. General physiographic divisions in Arizona and southwestern New Mexico.

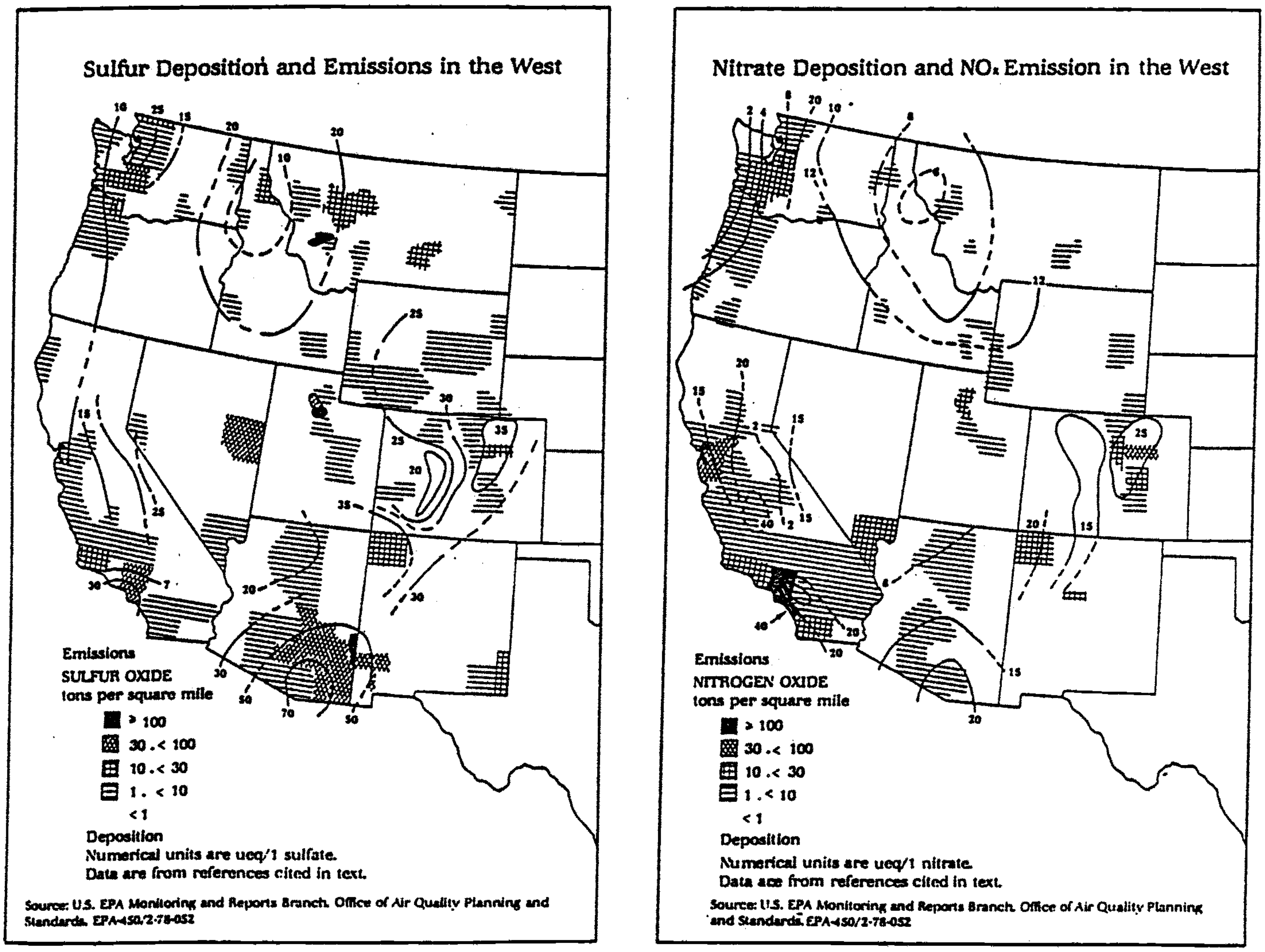


forest plot measurement data on ponderosa pine from the Fort Valley Experimental Forest near Flagstaff, Arizona provides an untapped and unique source of data for additional study in the region (Avery, Larson and Schubert 1976). The geographic distribution of our site collections was also designed to be reasonably congruent with the larger area of known pollutant production and in several cases we sampled stands in relatively close proximity to known pollution sources. It is apparent that the region of study has recently been experiencing relatively high levels of pollutant deposition, and that there appear to be some spatial gradients in the amounts of deposition. This can be seen in Figure 2, taken from a study by Roth and others (1985:27), but which is based on an EPA summary of deposition for the period of 1970-1977 (EPA 450/2-78-052). The sulfur appears to be primarily derived from nonferrous smelting activity in an area ranging from near the Arizona-Mexico border (Douglas-Cananea and Ajo to the west) up to the base of the Mogollon Rim in central Arizona (Miami-Globe-Superior area) and then eastward along the rim to the copper mining areas of eastern Arizona (Morenci) and southwestern New Mexico (Silver City area). One other major smelter is at San Manuel just to the northeast of the Santa Catalina and Rincon Mountains near Tucson. While some of the mining activity has an extensive history, i.e. back into the 19th century, the heaviest smelting activity appears to have taken place in the decades following World War II (Dunning and Peplow 1959, Arizona Department of Economic Security 1983). Nitrates vary in source but changes in them can be associated with population increases since mid-century in Phoenix and Tucson. Refined quantitative time series of length for those and other pollutants do not appear readily available at the present time although we are in contact with Dr. John Bunyak of the National Park Service (Air Quality Division - Denver Co.) who is exploring the possibility of their development.

Our approach to treatment of Scientific Question 1.1 follows the guidelines of the WCRC 1987 Project 13 (Analysis of trends and variability in growth of western forests; pp. 56-57) in that we: (1) develop a baseline characterization of natural variability in growth trends, and (2) look for deviations of recent growth trends from the norm. One major source of natural variation in the tree-ring series that can be identified is climatic variation, particularly that related to drought. This can be exploited to determine whether the tree-growth climate relationship has become deviant or anomalous over the past few decades and over the natural climatic gradients in this region. This kind of approach has been used recently in studies evaluating possible forest decline in the soutwestern U.S. (Rose 1988), eastern U.S. (Cook 1985b; Johnson, Cook and Siccama 1987; McLaughlin and others 1987) and in Germany (Eckstein and others 1983; Eckstein and others 1984).

The stages of the analysis that implement this approach here

Figure 2. Sulfur and nitrate deposition and emissions in the western U. S. (From Roth and others 1985).



are fourfold. The first is index chronology development which is directed at isolation of a common growth signal that is relatively free from noise (error variance) for each stand chronology. This is described below in sections 2.2-2.3 and 6.0-6.1.

Persistence is removed from these series in a second stage of analysis via the application of best fit ARMA models and development of white noise residual series. This is summarized in section 9.0.

The third analytic stage determines whether a satisfactory model of "normal" climate-tree growth relationships can be established with simple linear regression. The sum of precipitation for the annual period of August prior to the current year of growth through July of the current growth year is used as the independent variable, while the dependent variable is always a prewhitened tree-ring chronology. This is attempted over a "baseline" period that is thought to precede times of possible "abnormal" growth. Two periods are used here, 1896-1950 and 1896-1960. This stage of analysis includes calibration and independent verification tests as aids in evaluation of the reliability of the models that may be established. These procedures are described in section 10.0.

When satisfactory models are established, tree growth in the post baseline periods is estimated by precipitation series. The general null hypothesis being tested is that there are not significant differences between the predicted and actual growth.

Other perspectives on growth variation in conifers in some stands are under development as part of a cooperative project on National Park Service lands with Dr. K. Stolte of the N.P.S. Air Quality Division, Denver, Colorado. This involved visual vegetation survey and the collection of tree-ring cores that will be subjected to various elemental analyses. Further discussion of these topics is found below in section 14.0.

One final perspective on the research is pertinent at this point. The ring-width series that we have collected and the chronologies derived from them, provide a 'baseline' data set. It will be made available for potential use by other researchers in the near future, and it could be updated at intervals in future decades. Long-term observations of the changes in ring-width growth of the <u>same</u> data set over a relatively large region have not yet been realized (or put in motion) as far as we are aware, but may potentially provide a new and valuable form of environmental monitoring.

2.0 The Dendrochronological Background

This section provides background information and rationale for many of the research directions that were taken in this project. All of the topics are fundamental to this kind of research.

The use of tree-rings to study characteristic changes in forest environments due to natural or anthropogenic causes is referred to as dendroecology (Fritts and Swetnam 1986). A few examples of recent research include examination of the effects of increasing atmospheric CO_2 on forests (Graybill 1985, 1987), of the long-term history and dynamics of forests affected by spruce budworm (Swetnam 1986) and studies of forest decline (Cook and others 1986, Hornbeck and Smith 1985, Schweingruber and others 1983).

The hallmark of all of the research projects noted above was a reliance on tree-ring series that had been carefully crossdated and assigned calendar dates, and on chronologies whose time series properties were relatively free from extraneous, uncontrolled or biasing signals. The importance of these issues is treated in the subsequent two sections of this proposal.

2.1 Dating and Crossdating

At the most general level dendrochronology can be defined as a science whose fundamental data are time series of annual growth layers from woody plants. These growth layers are universally assigned accurate calendar dates in all legitimate studies that attempt to generalize about the precise historical covariation of annual increment growth with human activity or environmental factors or both. The most common attribute of these basic observational units, that is used both to match or crossdate series from different trees, and as a basis for analyzing the history of environmental variation they might record, is variation in their widths.

Establishment of the dates may first be based upon assignment of a known sampling year to the outermost growth increment of a series that was collected either during or shortly after the normal season of cambial activity. Before assigning dates backward in time along a series it is necessary to compare the relative variation in ring-width growth in each series with a number of other series from different trees. This crossdating procedure insures the integrity of date assignment by determining whether certain series may have either missing or multiple intra-annual growth bands for various years. The series collected for this project were all crossdated by experienced dendrochronologists. The mechanics of these procedures are treated in depth by Stokes and Smiley (1968).

If tree-ring series are not reliably crossdated, but are averaged to form a composite site or regional chronology, then the potential information it might hold regarding historical environmental variation can be completely lost. This has been one of a number of problems that have led to obscure or questionable results in some research projects that attempted to use tree-ring series to identify the timing and causes of observed forest growth decline (Cogbill 1977, McLaughlin 1984, McLaughlin and others 1983).

2.2 Variation in Tree-Ring Chronologies

The purpose of this section is to describe the types of variation or signals manifest in tree-ring chronologies. This is important because it provides a rational basis for examination of what is normal or abnormal growth variation.

A useful framework for discussing the types of variation that are of concern has come to be known as the Linear Aggregate Model (Cook, 1985a, b, 1987). An early version was used by Graybill (1982) in discussion of tree-ring chronology development, and its precursors are inherent in a consideration of natural disturbances in vegetation (White 1979). The following discussion applies only to tree-ring series that have been accurately dated.

2.3 The Linear Aggregate Model

There are several sources of variation that are commonly or potentially present in a series of ringwidths. A summary of those sources of variation can be seen as

$$R_t = f(B_t, C_t, D_t, A_t, E_t) \qquad (1)$$

where

R_t is a measured series of ringwidths

B_t is a biological growth trend that commonly decreases as a function of increasing tree age

C_t is growth variation common to trees at a site that is climatically induced

D_t is a series disturbance signal that may be either: $D1_t$ (endogenous), unique to a single series and caused by random events affecting growth such as inter tree competition, lightning strikes, etc., or $D2_t$ (exogenous), common to most or all series in a stand due for example to widespread fire or insect damage.

anthropogenic activity that may have affected an entire stand such as the introduction of chemical fertilizers or pollutants.

E_t is growth variation unique to each series due to factors such as genetic or micro-site differences.

Both the C_t and the A_t variables are special types of exogenous disturbances but given the focus on their properties in this study they are listed separately.

Now, it is important to recognize at this point of project description, that the analyses we use to treat SQ1.1 will focus on determining whether there are temporal changes in the covariation of tree growth and some of the variables on the right side of equation (1) above. Sections following will provide rationale for treatment of those various signals but for the moment it is useful to briefly describe what is needed at the onset of final analysis. At that time we will be working with tree-ring chronologies composed of the average of several series from individual trees at the sites we collect. They will simply be referred to here as AC_t (Analytical Chronologies) that can be seen as

$$AC_t = C_t + A_t + E_t \qquad (2)$$

These will be stationary, stochastic processes with a mean near 0.0. Note that in comparison to equation (1) above, the B_t and D_t terms are missing. These are removed or controlled by procedures described below and the error term (E_t) is also reduced. Our analytical approaches then become those of identifying and understanding the nature of the remaining signals, and possible changes in them over time.

A number of points regarding equation (2) need consideration. First, how much variability might be understood in the chronologies during a period prior to the probable onset of pollution or A_t effects, e.g. pre-1950? If A_t drops from the equation and E_t is relatively small, then what might 'normally, or 'typically' be expected? In some tree-ring chronologies from the southwestern U.S. that were carefully developed for these purposes we may find as much as 60% - 70% of the variation in common (using simple linear regression) with a single integrative climatic variable such as the June or July Palmer Drought Severity Index or winter streamflow (Rose and others 1982, Graybill 1986, Palmer 1965). This is possible in part because our sampling strategies are often directed at maximizing the C_t signal. This provides a means of characterizing 'natural' tree growth variation. Our analytical strategies then primarily pursue the question of whether there are unexpected changes in the nature of that signal during more recent times (e.g. post 1950) when the A_t signal may have intervened and altered the natural tree growth-climate relationship.

3.0 The Regional Climatic Background

The operation of major climatic regimes that affect Arizona and the adjacent part of southwestern New Mexico have been discussed at length in the climatological literature and various classifications have been proferred (Bryson 1957; Sellers 1960; Green and Sellers 1964; Mitchell 1969; Douglas and Fritts 1973; Hales 1974; Hirschbock 1985). A brief review is appropriate at this point.

In general, winter precipitation in the months of November through March derives primarily from the Pacific Ocean. At this time the continental mass of western North America cools faster than the Pacific Ocean. High pressure developes over northern North America because of persistent radiational cooling, and semipermanent lows are present over the oceans. The Aleutian and Icelandic lows are well developed, and the Pacific and Bermuda highs are generally weaker and displaced farther south than in summer. Stormy weather and precipitation in the western United States is associated with the movement of the Aleutian low pressure system, or parts that break off and move south-southeastward.

Large scale cyclonic storms embedded in the prevailing westerlies normally follow a northern path around the semipermanent subtropical high pressure ridge off the west coast, entering around the Oregon/Washington area. They usually move eastward, passing south of a low pressure trough in the Hudson Bay area. Typically they follow the east side of the Rockies, where they often strengthen and intensify, through the Great Plains, and northeast through the St. Lawrence River Valley to the Atlantic. Under these conditions the Southwest normally has moderate winters.

To get much winter precipitation in the Southwest there needs to be a westward displacement of the high pressure ridge in the Pacific and formation of a semipermanent low pressure trough over the western U.S. Instead of passing along the more northernly route, storms then follow the prevailing southernly flow of fast moving air currents along the west coast before entering the continent, often as far south as San Francisco. Once this flow pattern is established it tends to persist and recur. Much of the moisture is precipitated over the coastal and inland mountain ranges of California, Nevada, Arizona, and Utah. The Mogollon Rim, oriented in a west northwest - east southeast direction, does not significantly affect the paths of these storms. The "Kona storms" originating in the Hawaii area are capable of producing winter storms of summer intensity. Sellers and Hill (1974:14) describe this event in considerably more detail. Winter storms may continue for most of a 24-hour period, and above 4000 ft. (1200 m.) precipitation generally falls as snow.

Summer (July to September) normally begins with a major reorganization of the atmospheric circulation that is seldom slow.

Summer (July to September) normally begins with a major reorganization of the atmospheric circulation that is seldom slow. Continental land masses heat up faster than adjacent oceanic areas, resulting in continental lows and oceanic highs. Maritime tropical air masses are pulled into the Southwest from the Gulf of Mexico, and secondarily, the Gulf of California and Pacific Ocean. This effectively ends the spring regime of dry air that exists from about April through June. The mass of moist air that moves inland in late June moves west as far as Arizona in August, returning east in September. In comparison to winter, the Mogollon Rim complex of high plateaus and mountains lies below the flow of moist air in the summer. Thus, northwestern New Mexico and northeastern Arizona lie in the "rainshadow" of this complex. Therefore, in spite of their relatively higher elevations compared to the southern parts of Arizona and New Mexico, the northern parts of Arizona and New Mexico are notably drier.

Summer storms result from the invasion of moist air coupled with convection, orographic uplift, and air mass convergence. Convective storms result from hot moist air rising to altitudes of less pressure, where expansion and cooling result in condensation and precipitation. However, continual moisture replacement is required for this type of storm to continue. Frequently, convective storms are superimposed on general air mass convergence and orographic lifting, yielding the showery summer type of precipitation. Though most of the moist air is derived from the Gulf of Mexico, some of the heaviest precipitation recorded historically is a result of maritime tropical Pacific incursions. Sellers (1974:14) notes that these deep surges of tropical air occur most frequently in late August and September, usually resulting from tropical hurricanes off the west coast of Mexico.

Divisional climatic data from Arizona and New Mexico are used in the tree-ring - climate calibrations developed later in this study. The four climatic divisions from Arizona (Figure 3) that are used are the northeast (2), north central (3), east central (4), and southeast (7). Only one New Mexico division (4), the southwestern mountains region, is incorporated in the analyses (Figure 4). Total annual precipitation for previous August through current July from 1896 to 1986 for each of the climatic divisions mentioned above is shown in Figures 5 to 9. A detailed set of exploratory correlation analyses between tree-ring index chronologies and different seasonal and annual monthly combinations of precipitation and temperature variables demonstrated the August to July period to be consistently the most highly correlated with chronology variability.

Figure 3. Arizona climatic divisions. Divisions used in the present study are 2 (northeast), 3 (north central), 4 (east central), and 7 (southeast). From NOAA, Arizona 1987, V. 91, No. 13.

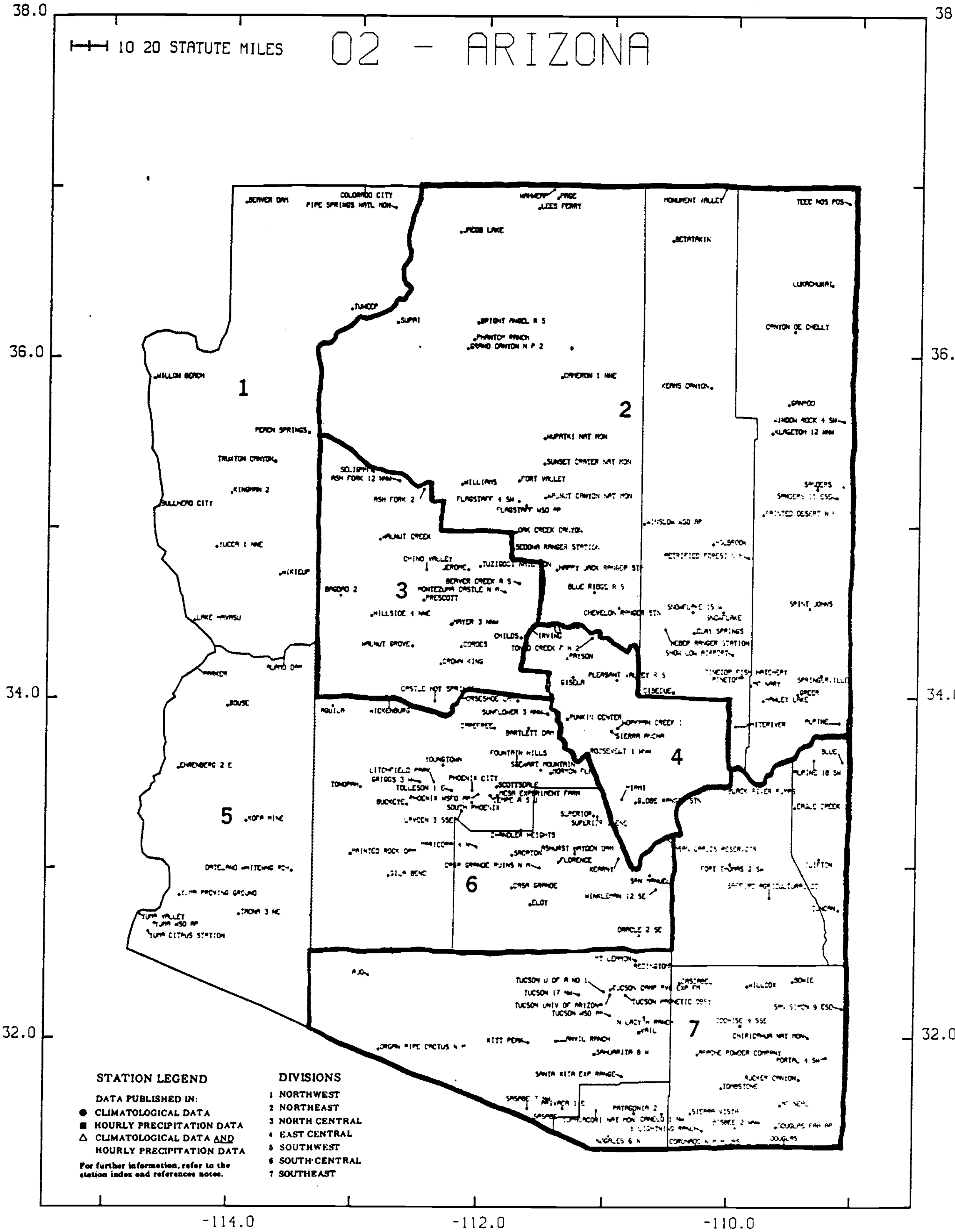


Figure 4. New Mexico climatic divisions. Only division 4 (southwestern mountains) was used in the present study. From NOAA, New Mexico 1987, V. 91, No. 13.

Figure 5. August - July total annual precipitation for the northeast climatic division (2), Arizona.

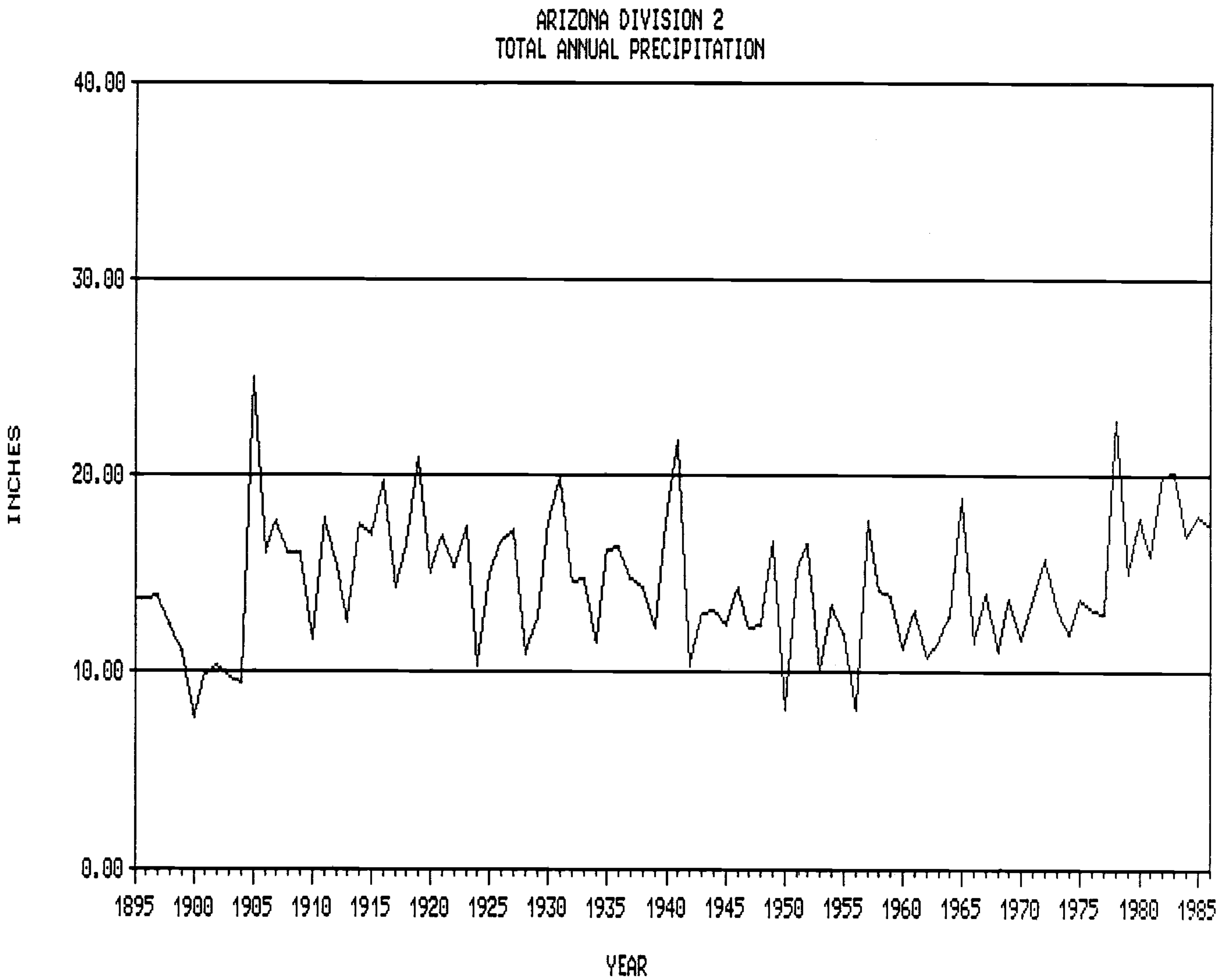


Figure 6. August - July total annual precipitation for the north central climatic division (3), Arizona.

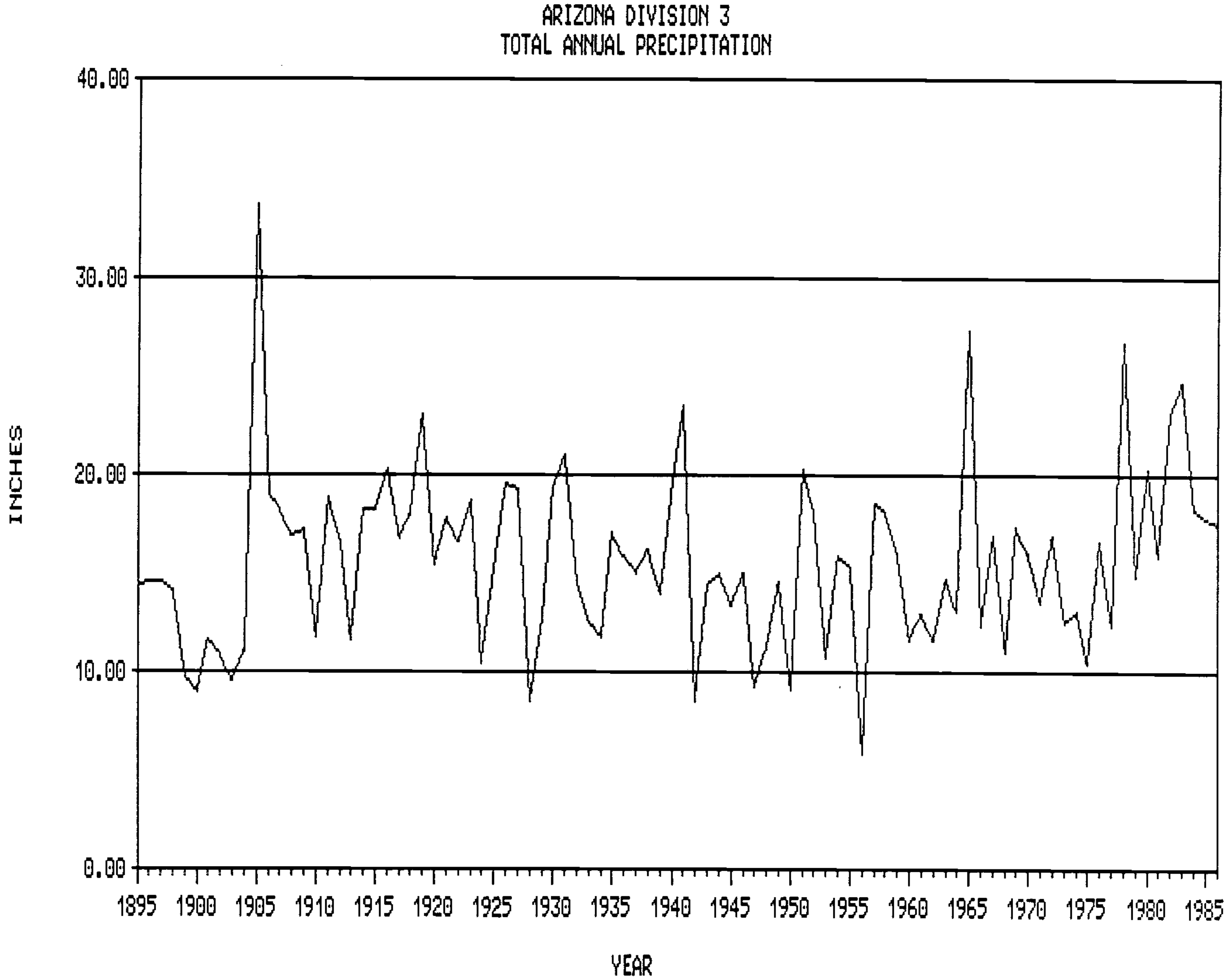


Figure 7. August - July total annual precipitation for the east central climatic division (4), Arizona.

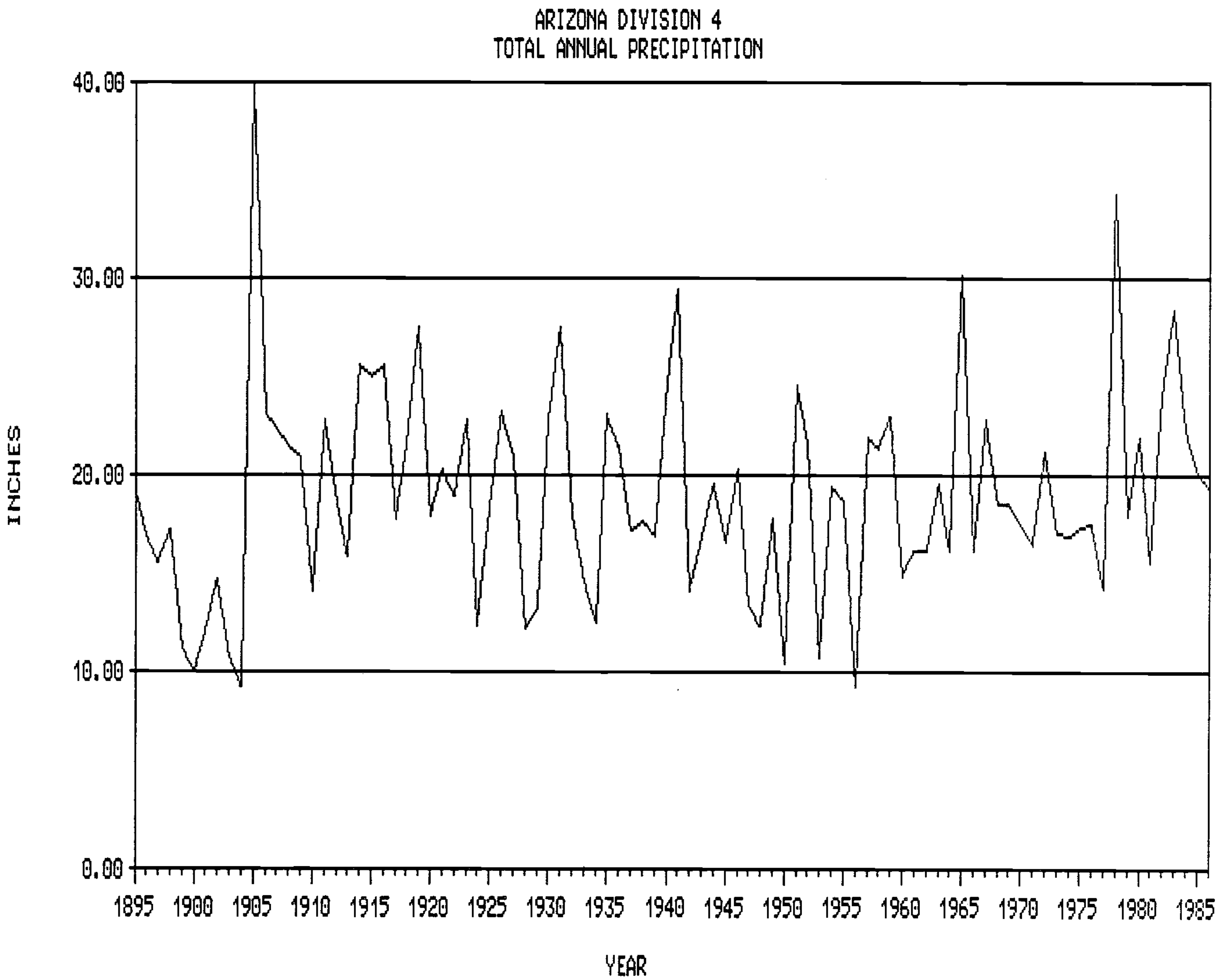


Figure 8. August - July total annual precipitation for the southeast climatic division (7), Arizona.

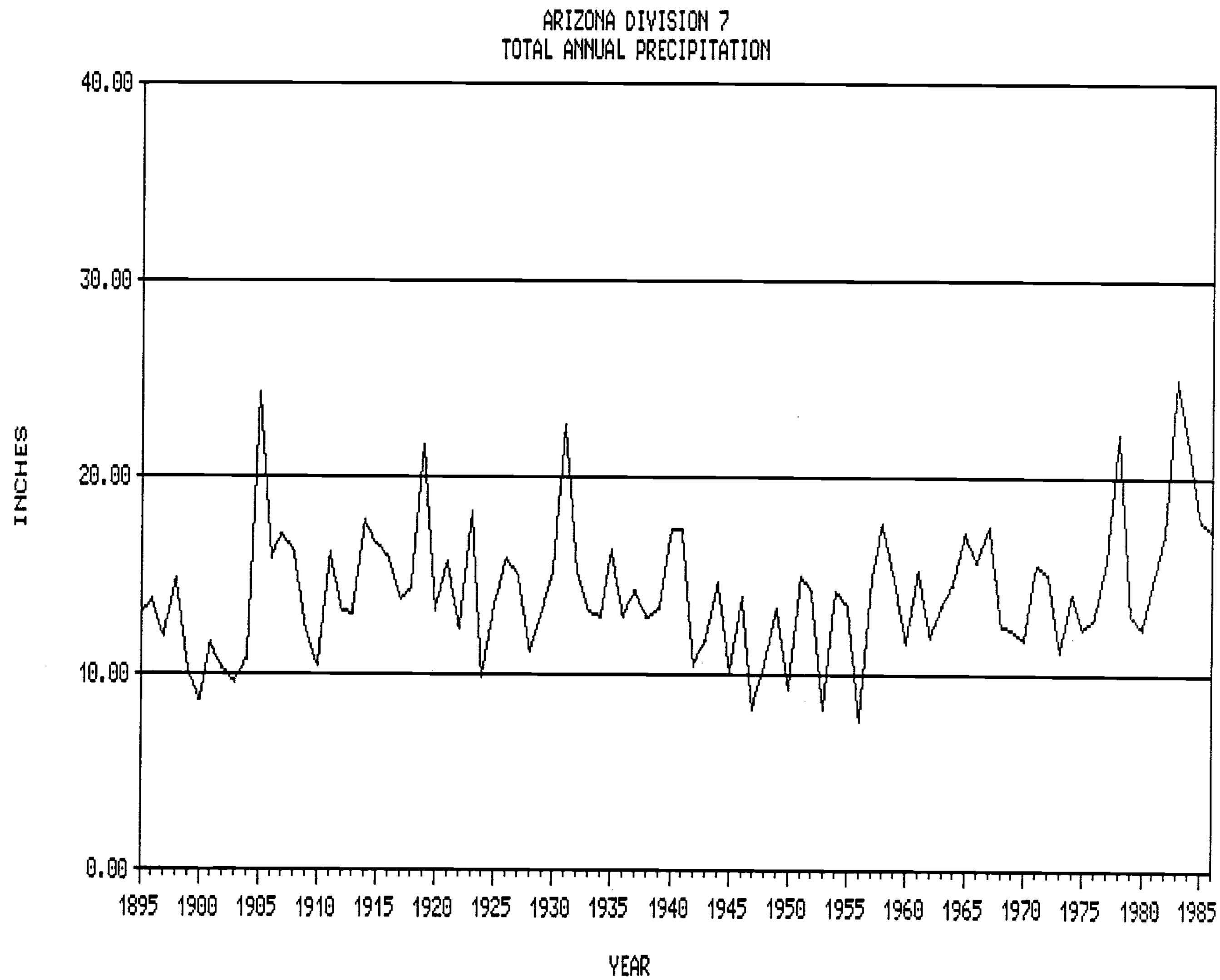
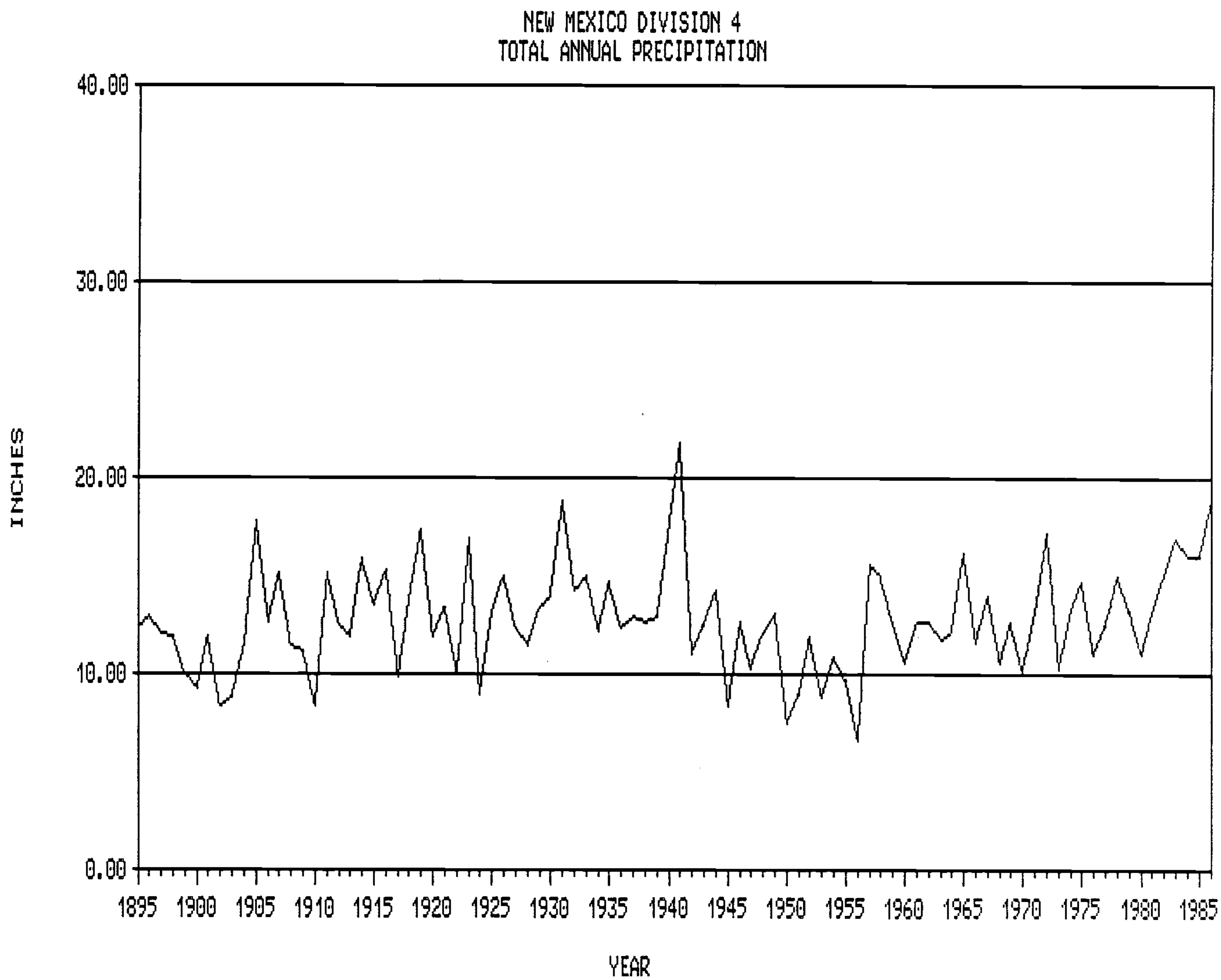


Figure 9. August - July total annual precipitation for the southwestern mountains climatic division (4), New Mexico.



The line plots show that Arizona regions 3 and 4 have the greatest August - July precipitation. They essentially represent the mountainous area of the Mogollon Rim region. Arizona division 2, which lies in the northeastern part of the state, along with division 7 in the southeast, and New Mexico division 4 are at lower elevations and possess more semiarid precipitation characteristics. Notable in all of the precipitation figures, however, is the drought at the beginning of the century immediately followed by a large amount of high precipitation. There is a decrease in precipitation through the 1940's, which in turn is followed by an increase through the 1960's to the present. These characteristics combine to yield a "bowl" or "U" shape to the line graph portrayal of annual precipitation that is present in all of the figures. The general similarity among all of the plots also suggests similar atmospheric controls of precipitation across all of the climatic divisions, though modified by elevation, land mass, and distance from the dominant moisture source regions.

4.0 Regional Sampling Approach

This section provides an overview of the locations where tree-ring series were collected, of the species sampled and of variation in sampling strategies. Table 1 summarizes the basic locational variables for each collection as well as number and code that are both used for identification in various discussions that follow. A more detailed summary of site attributes is found in Appendix 1. The distribution of sites throughout the study region keyed by collection number is shown in Figure 10 and the distribution by species is shown in Figure 11.

Our collection efforts were directed at stands considered unlikely to be removed by human agents in order that they might continue in the future as monitors for this type of research. This was feasible in most situations because we were collecting on lands controlled by various federal agencies such as the N.P.S. and U.S.F.S.

The overall collection strategy that we adopted was wide-ranging in coverage and exploratory in nature. Several different kinds of sites and several species were sampled. Obtaining a broad initial overview of this nature appeared the most useful strategy in the absence of any <u>apriori</u> knowledge that conifers in any single sector of the region were experiencing abnormal growth. However, given the relatively long-standing and known sources of pollution from copper smelting, several collections were made in the southern isolated mountains and from the lower forested edges of the Mogollon Rim.

TABLE 1. Tree-ring collection codes, species and location.

NO.	SITE	CODE[1]	SPECIES[2]	LATITUDE	LONGITUDE	ELEVATION (ft.)
1.	ROBINSON MTN, AZ	RMP	PP	35°23'45"N	111°23'W	7200-7400'
2.	WALNUT CYN, AZ	WDF	DF	35°10'N	111°31'W	6600-6700'
3.	S.F. PEAKS, AZ	PDF	DF	35°19'N	111°43'30"W	8800'
4.	SLATE MTN, AZ	SMP	PP	35°50'N	111°50'W	7200'
5.	MULETANK, AZ	MTP,O, Y,T	PP	34°19'N	110°46'W	7750-7600'
6.	SIT.GRAVEL PIT, AZ	SGP	PP	34°15'N	109°56'30"W	6800'
7.	GIRL'S RANCH, AZ	GRP	PP	34°23'30"N	110°25'W	6400-6520'
8.	DRY CREEK, AZ	DCP	PN	34°53'50"N	111°49'W	4480-4560'
9.	ROCKY GULCH, AZ	RGP	PP	34°43'45"N	110°30'W	6400-6500'
10.	GRASSHOPPER, AZ	GRS	PP	34°04'N	110°37'W	5900'
11.	GREEN MTN, AZ	GMT	PP	32°23'30"N	110°41'30"W	7200'
12.	SANTA RITA, AZ	SRH	DF	31°43'30"N	110°50'45"W	7450-8300'
13.	PINERY CYN, AZ	PCD	DF	31°56'N	109°16'W	7500'
14.	POST CREEK, AZ	PST	DF	32°41'30"N	109°53'45"W	8800-9120'
15.	NOON CREEK, AZ	NOO	PP	32°39'N	109°49'50"W	7700'
16.	BEAVER CREEK, AZ	BCR	PP	33°42'30"N	109°14'30"W	7850'
17.	GREEN MTN, AZ	GMF	DF	32°23'30"N	110°41'30"W	7200'
18.	BEAR WALLOW, AZ	BWF	DF	32°25'N	110°44'W	8000-8300'
19.	RHYOLITE CYN, AZ	RCF	DF	32°0'N	109°20'W	6000'
20.	RHYOLITE CYN, AZ	RPE,T	PP	32°0'N	109°20'W	6000'
21.	ORD MTN, AZ	ORD,E,T	PP	33°54'N	111°24'30"W	7000'
22.	BLACK RIVER, AZ	BRF	DF	33°48'N	109°19'W	8000'
23.	BLACK MTN, NM	BKF	DF	33°23'N	108°14'W	8400-9300'

TABLE 1. (CONTINUED) Tree-ring collection codes, species and location.

NO.	SITE	CODE[1]	SPECIES[2]	LATITUDE	LONGITUDE	ELEVATION (ft.)
24.	BLACK MTN, NM	BKP	PP	33°23'N	108°14'W	8400-9300'
25.	MIMBRES JUNCT, NM	MJN	PN	32°57'30"N	108°01'W	6400'
26.	AGUA FRIA, NM	AFN	PN	34°14'40"N	108°37'29"W	7300'
27.	G.C.DWELLINGS, NM	GCP	PP	33°13'35"N	108°16'W	5800'
28.	ROSE PEAK, AZ	RPP	PP	33°25'N	109°22'W	7600'
29.	EAGLE CREEK, AZ	EPN	PN	33°28'N	109°29'W	5560'
30.	WALNUT CYN, AZ	WCP	PP	35°10'N	111°31'W	6750'
31.	GUS PEARSON, AZ	GPN,O,Y	PP	35°16'N	111°45'W	7400'
32.	HELEN'S DOME, AZ	HDE,T	PP	32°13'N	110°33'30"W	8280-8360'
33.	HELEN'S DOME, AZ	HDW	WP	32°13'N	110°33'30"W	8280-8360'
34.	NORTH SLOPE, AZ	NSE,T	PP	32°13'30"N	110°33'W	7960-8040'
35.	NORTH SLOPE, AZ	NSW	WP	32°13'30"N	110°33'W	7960-8040'
36.	NORTH SLOPE, AZ	NSF	DF	32°13'30"N	110°33'W	7960-8040'
37.	NORTH SLOPE, AZ	NSA	WF	32°13'30"N	110°33'W	7960-8040'
38.	TUCSON SIDE, AZ	TSE,T	PP	32°12'20"N	110°33'45"W	7640-7880'
39.	TUCSON SIDE, AZ	TSW	WP	32°12'20"N	110°33'45"W	7640-7880'
40.	DEVIL'S BATHTUB, AZ	DBN	PN	32°12'N	110°33'W	7500'
41.	MT. HOPKINS, AZ	MHP	PP	31°42'N	110°52'W	7000'

[1] O,Y,T, and E as the last character in the code designation are used to indicate the following:
O-old trees
Y-young trees
T-tough to crossdate, in some cases impossible during certain time intervals
E-easy to crossdate, compared to T(ough) specimens

[2] PN = *Pinus edulis*
PP = *Pinus ponderosa*
WP = *Pinus strobiformis*
DF = *Pseudotsuga menziesii*
WF = *Abies concolor*

Figure 10. Locations of sites collected in Arizona and southwestern New Mexico. Numbers correspond to sites listed in Table 1.

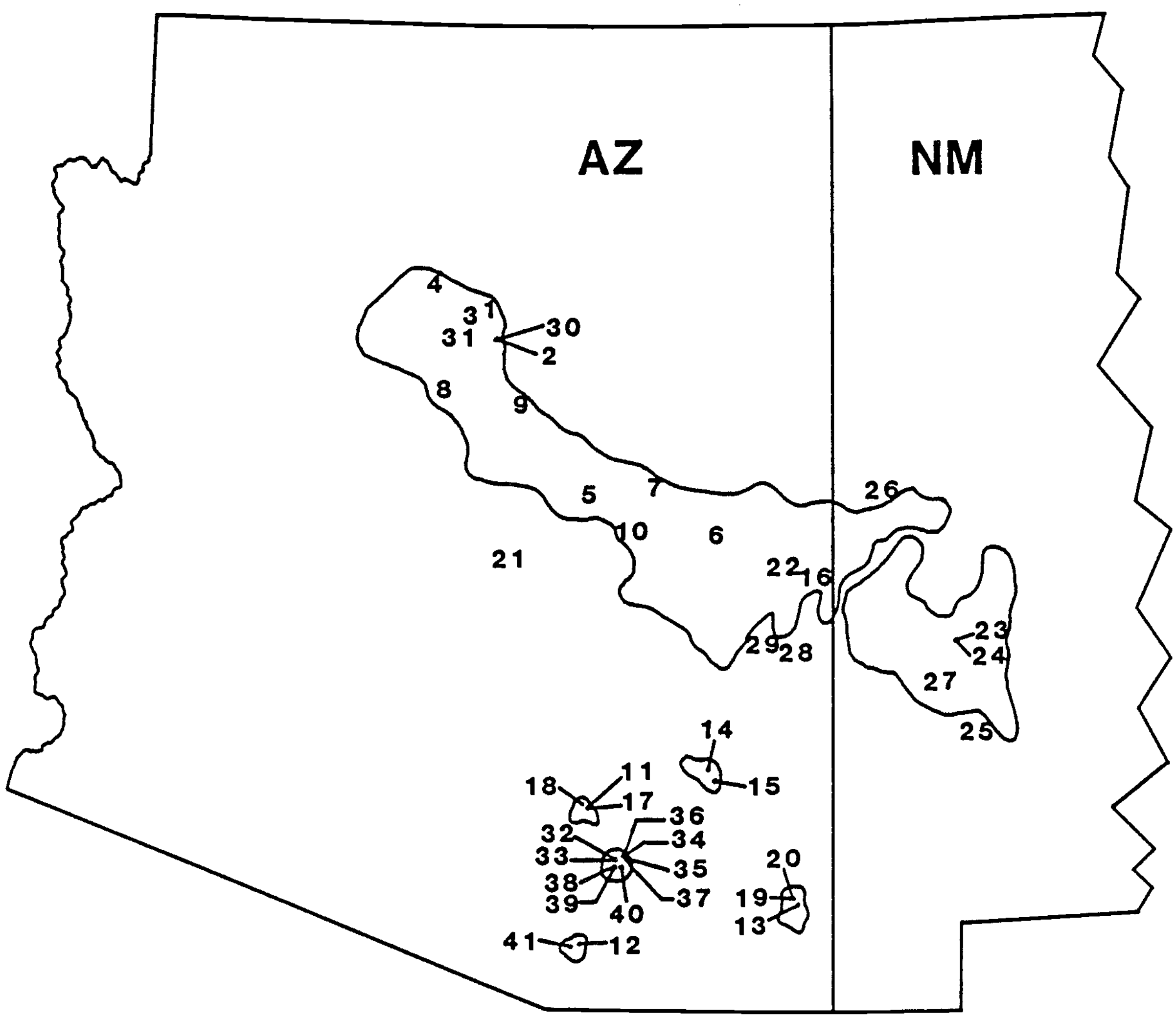
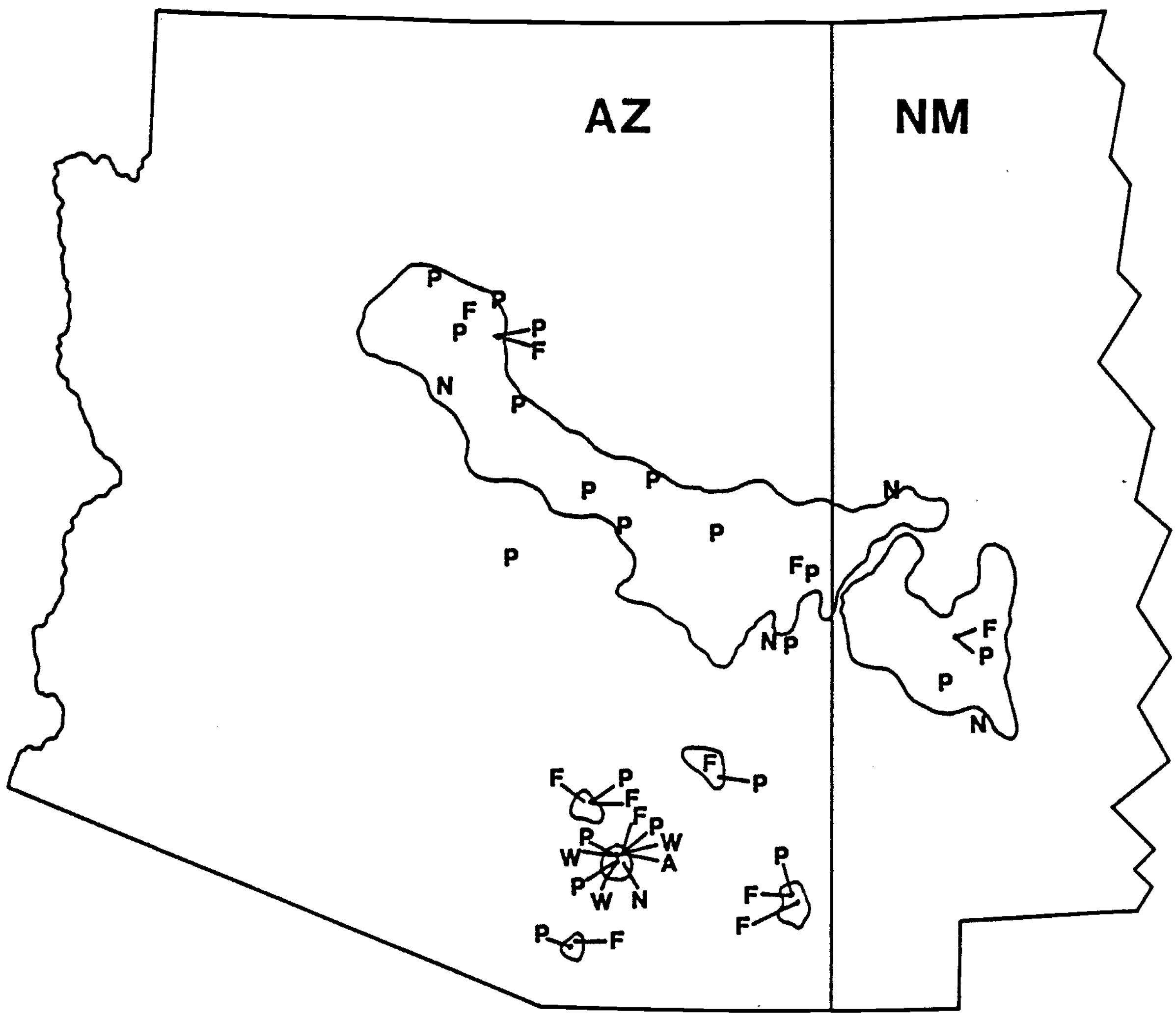


Figure 11. Species distribution in tree-ring sites collected.



P - Ponderosa pine

F - Douglas fir

N - Pinyon pine

W - Southwestern white pine

A - White fir

In the southern ranges that were sampled (Chiricahuas, Santa Ritas, Rincons, Catalinas, Pinalenos) it was possible to collect multiple species from each. This included Douglas-fir and ponderosa pine in all cases while additional species were sampled in the Rincons (see Table 2 below).

Table 2. Sample identification numbers by species collected in southern Arizona mountain ranges.

Mountain Range	Species				
	PP*	DF	WF	WP	PN
Chiricahuas	20	13,19			
Catalinas	11	17,18			
Pinalenos	15	14			
Rincons					
North Slope	34	36	37	35	
Helen's Dome	32			33	
Tucson Side	38			39	40
Santa Ritas	41	12			

*PP = <u>Pinus ponderosa</u> DF = <u>Douglas-fir</u>
WP = <u>Pinus strobiformis</u> PN = <u>Pinus cembroides</u>
Wf = <u>Abies concolor</u>

Some of the southern Arizona sites were also collected due to their proximity to the rapidly growing cities of Tucson and Phoenix. Although smaller than Phoenix in population (650,000 vs 1,000,000), Tucson's pollution may potentially have the greatest immediate impact on forests at present or in the near future. The city has expanded to the base of two of the ranges (Catalinas and Rincons), is not far from a third (Santa Ritas) and lies less than 4000' - 5000' below and 10 miles distant from ponderosa pine-Douglas-fir and mixed conifer forest types.

Phoenix is somewhat more distant from forested areas. The closest accessible ponderosa stand that we could locate was sampled and it is about 50 miles northeast of the city center (collection number 21).

The stands from these areas vary substantially in slope, exposure, drainage, openness and ultimately in quality of their climatic signal. However, it was considered important to make an initial attempt to sample sites in obvious positions of probable pollutant exposure and these do not always coincide with ideal world hopes for specific site characteristics.

Specific locations that were sampled with respect to close, known and sometimes visually obvious pollution first include the Bear Wallow locality on the north side of the Santa Catalina Mountains and the North Slope site in the Rincon Mountains. These are, respectively, located 14 and 27 miles up the San Pedro River drainage from the smelter at San Manuel, Arizona. The Green Mountain locality in the Catalinas faces Tucson to the south and west while the Tucson side locality in the Rincons is also directly exposed to city pollution. The Devil's Bathtub pinyon site is in a similar setting. The Helen's Dome site was selected because it is located at the north end of the Rincons just above Reddington Pass, a low point between that range and the Catalinas, where pollution from the San Manuel smelter and from Tucson may mix or both may travel.

Northward from the Basin and Range, the next "tier" of site collections follows the lower reaches of the Mogollon Rim. With the exception of junipers which were not treated in this study, pinyon pine and ponderosa pine are the only common coniferous species in these areas. They are variously represented by collection numbers 8,21,29,28,25. Most are from relatively open-canopied zeric sites, conditions that are common here due to prevailing aridity at this lower forested edge of the Rim country. Sites 28 and 29 are located less than 30 miles from a copper smelter at Morenci, Arizona and site 25 is about 15 miles north of smelting activity near Silver City, New Mexico.

Collections further to the north follow the arc of forested region stretching from just south of the Grand Canyon over into southwestern New Mexico. In this area we developed eight ponderosa pine chronologies (the most common species), four of Douglas-fir and one of pinyon.

Two of the ponderosa collections were purposefully made in relatively dense forest settings for the region. One in the Gus Pearson Natural Area (GPNA) is treated more extensively in a separate report now in preparation. Another for comparative purposes is from the Mule Tank, Az. locality (collection number 5). In each case we collected samples and developed chronologies for younger as well as older trees in order to determine what different kinds of information might potentially be present in each class.

One Douglas-fir collection was also purposefully made in a mesic forest interior site in the San Francisco Peaks area near

Flagstaff, Arizona (collection number 3). It is examined for similarities or differences in signal content with respect to that of another collection of the same species from the same general vicinity, but from a more xeric site (Walnut Canyon - collection number 2).

5.0 Stand and Tree Sampling Approaches

Attempts to identify, control and maximize or minimize the signals described under equation 1 (The Linear Aggregate Model) are inherent in legitimate research projects utilizing tree-ring chronologies. Consideration of the control of these signals necessarily begins with the actual field sample selection strategy, both with respect to stand and site characteristics as well as to the selection of trees within a stand. The following paragraphs summarize the common strategies that are used in collection of tree-ring series when the goal is to to maximize a common climatic signal in a stand. The focus here is on a drought signal. However, it is noted that these are "idealized" strategies that can be implemented only if specific types of trees or stands occur in an area of interest and no other types are of interest. In order to obtain adequate geographic coverage for this project, and in order that we might evaluate stand growth over a variety of environmental settings, it was not always possible to use sites that met all of the various criteria discussed here.

Climatically sensitive tree-ring chronologies are based on series that are selected to minimize the disturbance signals. These can and would obscure or confound the C_t and A_t signals that are of primary interest. In terms of stand characteristics, those which are relatively open and free from inter-tree competition are selected. This minimizes the potential for endogenous growth disturbance pulses or variation ($D1_t$) due to changes in overstorying and competition for sunlight or soil nutrients. Further control over this disturbance factor is maintained by not sampling trees with obvious evidence of injury or disease. Control over the $D2_t$ disturbance signal is maintained by avoiding sites where the trees have been widely affected by factors such as overstory harvest or nearby road construction.

Stands with desirable characteristics for minimizing $D1_t$ disturbance signals are generally of that nature because they are on sites with limited moisture retention characteristics. This enhances the C_t signal as a response to effective moisture. However, the widely held perception by many non-dendrochronologists that tree-ring chronologies from the arid southwest are only developed from the most stressed trees in the driest sites is essentially incorrect. Tree-ring series from individuals in these settings are often not datable due to a very high percentage of missing rings, and in some cases, extensive numbers of intra-annual or false growth bands. Even if they can sometimes be dated, the common signal becomes lessened (E_t increases) and we have not found them useful (See esp. Fritts and others 1965).

The tree-ring series that we collected are not from sites of this nature. Given the real-world distribution of the trees and a range of interests that are specific to this project, the final chronologies that were developed are from stands in a variety of environmental settings that range from near the forest interior to near the lower forest border. This kind of idealized transect should not, however, be interpreted as one ranging from 'extremely wet' to 'very dry'. There is prevailing aridity over the entire region. In the central area of the state along the Mogollon Rim, the range of annual precipitation over the distribution of most ponderosa pine type forests is only 20-25 inches (Beschta 1976:5).

Two other sampling strategies are notable as they relate to the potential value of our tree-ring chronologies for this research. The first concerns control over the error term (E_t) arising from variation unique to each series. When possible, two or more samples were taken from 10-20 or more trees in a stand. Averaging a large number of these series to form a site chronology minimizes this variability.

Another goal in sampling was to obtain series from the older trees in a site. This is particularly important because it provides relatively long time series of natural growth variation prior to times when anthropogenic pollutants (A_t) might have affected tree growth. It is also important in the development of a stable estimate of the time series properties of the final chronologies. However, as noted above, in some cases we purposefully selected a sample of younger trees in addition to the older ones for various comparative and analytical purposes.

A summary of the data that were collected, dated, measured and finally used for chronology building is provided in Table 3. In general, we 'oversample' at collection time. It has been our experience that distortions due to branch scars or other problems not apparent in the field will ultimately render some series unusable for final analysis. It is also important to have a relatively large sample in order that confidence in the dating is attained and that adequate numbers of series are available for final analysis.

6.0 Chronology Development

The chronology development process provides the second level of control over the variability that is available for analysis in a final average of several tree-ring series. These procedures, particularly as they apply to series from arid site open-canopied

Table 3. Chronology data processing summary.

No.	Code	Species	Dates	Yrs	# trees sampled	# trees dated	# trees measured	Rings in Chrons.
1	RMP	PP	1620-1987	368	39	79	26	7806
2	WDF	DF	1668-1987	319	20	42	22	5153
3	PDF	DF	1762-1987	226	20	41	25	3915
4	SMP	PP	1589-1987	399	19	37	37	10207
5	MTP,O,Y,T	PP	1595-1987	393	40	76	50	8968
6	SGP	PP	1603-1987	385	22	45	24	7354
7	GRP	PP	1594-1987	394	23	49	28	8133
8	DCP	PN	1608-1987	380	23	49	25	7267
9	RGP	PP	1659-1987	329	20	40	25	6326
10	GRS	PP	1661-1986	326	32	55	26	6019
11	GMT	PP	1412-1986	575	43	70	30	8729
12	SRH	DF	1486-1987	502	21	49	26	8087
13	PCD	DF	1641-1987	346	22	49	23	6466
14	PST	DF	1641-1987	472	21	44	26	8305
15	NOO	PP	1764-1987	224	20	36	22	2733
16	BCR	PP	1559-1987	429	21	40	32	10243
17	GMF	DF	1547-1986	440	25	58	28	2462
18	BWF	DF	1600-1987	388	22	44	22	6251
19	RCF	DF	1620-1987	368	27	50	30	8677
20	RPE,T	PP	1629-1987	359	19	36	29	8066
21	ORD,E,T	PP	1560-1987	428	16	34	34	12093
22	BRF	DF	1565-1987	423	24	46	24	8005
23	BKF	DF	1462-1987	526	39	75	51	9419
24	BKP	PP	1555-1987	433	26	41	21	7659
25	MJN	PN	1604-1987	384	23	39	24	6127
26	AFN	PN	1361-1987	627	17	33	33	8204
27	SCP	PP	1528-1987	460	15	22	18	4426
28	RPP	PP	1641-1987	347	16	39	22	5944
29	EPN	PN	1639-1987	349	20	41	30	5551
30	WCP	PP	1413-1987	575	12	24	21	7948
31	SPN,O,Y	PP	1571-1987	417	35	72	73	14160
32	HDE,T	PP	1625-1987	363	14	31	28	6628
33	HDW	WP	1692-1987	296	13	30	27	4461
34	NSE,T	PP	1678-1987	310	10	36	28	5351
35	NSW	WP	1718-1987	270	12	30	22	3976
36	NSF	DF	1637-1987	351	17	30	22	5804
37	NSA	WF	1778-1987	210	10	20	20	3239
38	TSE,T	PP	1639-1987	349	23	47	42	9613
39	TSW	WP	1663-1987	325	9	18	16	3277
40	DBN	PN	1769-1987	219	19	26	20	3229
41	MHP	PP	1714-1987	274	12	24	20	3508
TOTALS					889	1747	1150	283582

PN = Pinus edulis
PP = Pinus ponderosa
WP = Pinus strobiformis
DF = Pseudotsuga menziesii
WF = Abies concolor

coniferous forests, were summarized by Graybill (1982). He also updated and refined the basic computer software that is widely used for chronology development (1979 a,b, 1982). Those programs, RWLIST, INDEX and SUMAC, were used in this research.

After tree-ring series were assigned annual calendar dates the ringwidths were measured to the nearest .01 mm. These values are printed and plotted by program RWLIST. Inspection of this output and of line plots of the series permitted initial determination of the best potential model that might be used to remove the biological growth trend and standardize each series. Some of the most salient points that arise in any consideration of chronology development concern the nature of the variation that might be included or excluded by the standardization process. The primary purpose of standardization is to remove signals from a series of ringwidths that may either completely confound or obscure those of interest. The biological growth trend (B_t), like that evident in the top three series in Figure 12, is most universally removed from individual series before they are averaged. If these trends were not removed and the nonstationary ringwidths were averaged, then a mean value function chronology of ringwidths would evidence nonstationary variation due simply to differences in ring age and average growth rate of the different series (see the fourth plot, Figure 12).

Removal of the biological growth trend from ringwidth series was primarily accomplished by fitting simple models that are either negative exponentials or straight lines. It was possible for us to apply the deterministic models in most cases because the nature of ringwidth series here coupled with our sampling strategies minimized the numbers of series with disturbance signals. In a limited nunber of cases where we were forced to use a cubic spline due to apparent disturbances it was kept relatively stiff and we do not think that the signals of interest were lost after inspecting final index results.

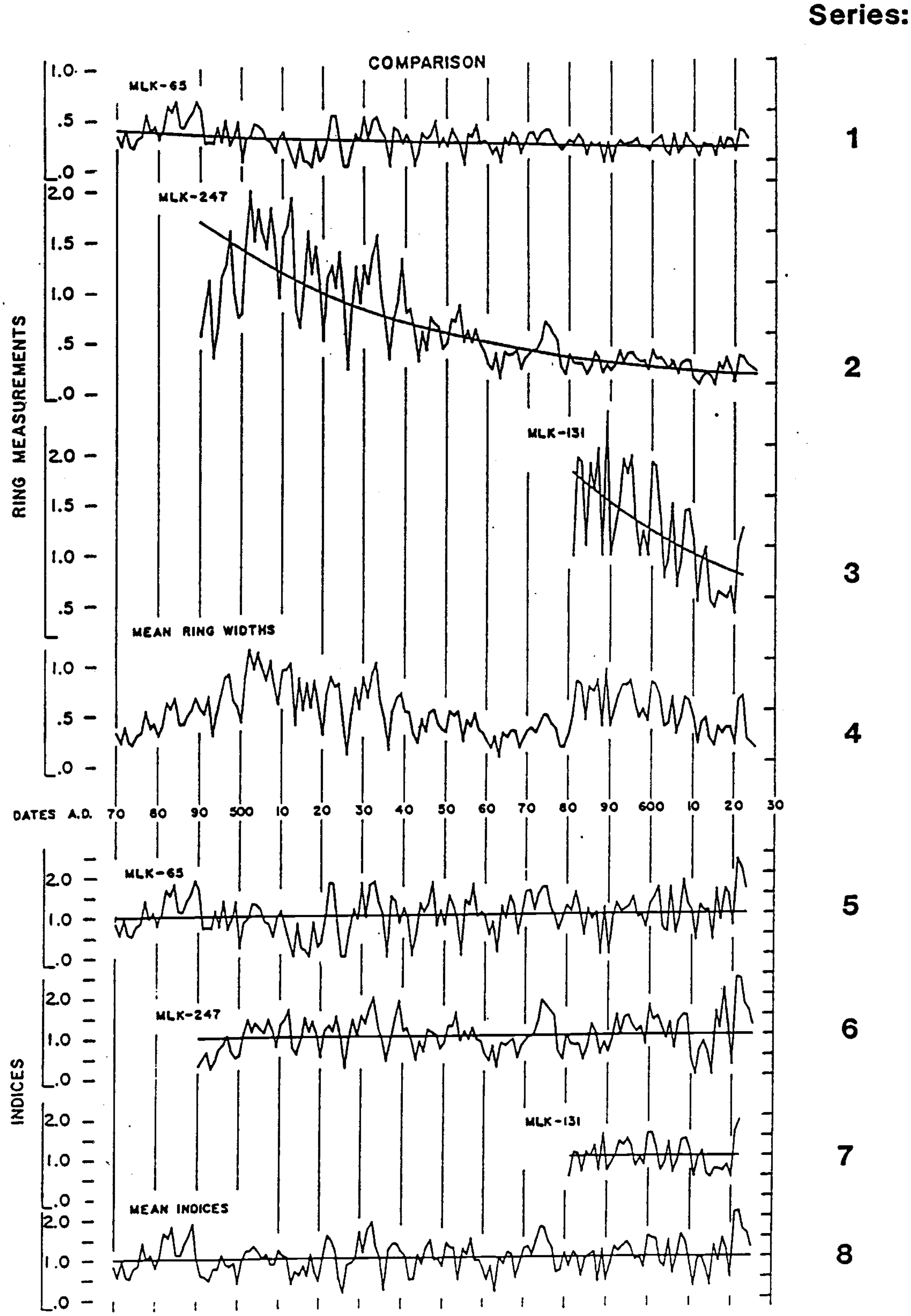
Application of the curve fitting procedure via program INDEX to a ringwidth series R_t results in a new time series of tree-ring indices (I_t) that is computed as

$$I_t = R_t / Y_t$$

where Y_t is the expected yearly growth determined from the fitting procedure. This scales the variance so that it is less heteroscedastic than in the ringwidth series, scales the mean to near 1.0, and reduces autocorrelation due to biological growth trend (Figure 12, series 5-7).

Once the indices for individual ringwidth series had been developed (program INDEX) they were then averaged to form a mean value function index chronology (I_t) that is the basis for

Figure 12. Ring measurements and standardized indices.



continuing analysis (as in Figure 12 bottom series). The averaging procedure is accomplished by program SUMAC and is a simple unweighted average of the individual series index values per year. This process has the effect of reducing the unique error (E_t) associated with each component series, although this can never be totally eliminated in a final index chronology. The tree-ring index chronologies are plotted in Figure 13.

6.1 Variation In Stand Chronologies

Most chronologies represent an average of the measured and indexed series from a single stand. There are two kinds of exceptions. In the dating process we found that a moderate to substantial portion (up to about 50 percent in some sites) of the series from ponderosa pine in several stands could not be dated after times ranging from about 1920 - 1950 to the final date of collection in 1986. This was due to extreme suppression of growth particularly in the post 1950 time period. In some cases more than 40 rings are absent from our samples during the period of 1920 - 1987.

The stands exhibiting this are primarily in the southern part of the region in the Rincons (collections 32,34,38), the Chiricahuas (collection 20) and Ord Mountain near Phoenix (collection 21). In the northern area only the Mule Tank forest interior collection demonstrated this.

For exploratory purposes we divided the series into those from trees that we could date through to the collection year and those that we could not. Separate chronologies for the stands in question were then developed and examined in various analyses described below. For recognition and coding purposes, the third character of the chronology code was designated as 'E' (easy - datable) or 'T' (tough - undatable). Note that the final 'T' in two collection codes - numbers 11 and 14 - does not signify this dichotomy.

A second kind of exception to single chronologies per stand is represented by separate 'older' and 'younger' series that were developed from the GPNA (number 31) and Mule Tank (number 5) forest interior site collections. Younger trees at the former site are about 70 years old while the older individuals average about 300 years. At the latter site the younger individuals average about 125 years and the older ones about 200 years. The third character of the chronology codes are either 'Y' or 'O' to signify the respective age classes.

Final chronology statistics computed in SUMAC and presented in Tables 4 and 5 provide a basis for evaluating the nature of the common signal in each index chronology. The variability in a chronology can be partitioned into a number of sources using analysis of variance (Fritts 1976:282-293; Stockton 1975,

Table 4. Analysis of variance, 1850-1986.

					VARIANCE COMPONENTS			
No.	Code	SPP	#Trees	#Series	Sides of Trees	Trees	Common	Cores
1	RMP	PP	12	24	.562	37.086	44.951	17.402
2	WDF	DF	7	14	.000	18.794	50.898	30.308
3	PDF	DF	8	16	3.318	36.701	29.037	30.944
4	SMP	PP	13	26	.000	22.724	63.634	13.642
5	MTP	PP	08	16	1.405	50.710	18.390	29.495
6	SGP	PP	10	20	.119	17.075	69.689	13.117
7	GRP	PP	13	26	.177	19.494	60.235	20.094
8	DCP	PN	10	20	.000	18.719	61.774	19.507
9	RGP	PP	7	14	.728	15.586	61.434	22.252
10	GRS	PP	12	24	1.179	14.284	61.651	22.886
11	GMT	PP	9	18	.000	32.542	41.894	25.565
12	SRH	DF	11	22	.841	13.986	53.350	31.823
13	PCD	DF	10	20	.000	5.037	43.779	51.184
14	PST	DF	11	22	.000	19.139	33.889	46.973
15	NOO	PP	12	12	--[2]	46.468	53.532	--[2]
16	BCR	PP	16	32	.691	29.397	43.082	26.830
17	GMF	DF	8	16	2.110	25.088	44.464	28.338
18	BWF	DF	9	18	3.898	37.979	31.374	26.749
19	RCF	DF	14	28	.306	20.689	52.355	26.650
20	RPE	PP	8	16	.364	17.430	43.202	39.004
21	ORD	PP	9	18	.000	32.611	43.218	24.171
22	BRF	DF	11	22	.248	23.618	47.536	28.598
23	BKF	DF	10	20	.000	24.093	53.776	22.131

Table 4. (Continued) Analysis of variance, 1850-1986.

					VARIANCE COMPONENTS			
No.	Code	SPP	#Trees	#Series	Sides of Trees	Trees	Common	Cores
24	BKP	PP	10	20	.000	33.695	46.040	20.265
25	MJN	PN	10	20	.078	22.653	55.854	21.415
26	AFN	PN	9	18	.000	16.685	70.994	12.321
27	GCP[1]	PP	--	--	--	--	--	--
28	RPP	PP	11	22	.000	12.194	66.848	20.957
29	EPN	PN	9	18	.730	18.491	56.593	24.186
30	WCP	PP	10	20	.000	30.936	50.318	18.746
31	GPO	PP	16	32	.000	24.312	50.390	25.298
32	HDE	PP	7	14	3.507	25.431	49.364	21.698
33	HDW	WP	9	18	1.663	26.239	41.783	30.315
34	NSE	PP	6	12	.814	31.193	36.690	31.302
35	NSW[3]	WP	6	12	.000	34.809	46.498	18.693
36	NSF	DF	9	18	.000	22.413	46.654	30.933
37	NSA	WF	7	14	.298	25.183	48.035	26.483
38	TSE	PP	13	26	1.029	22.422	42.821	33.729
39	TSW	WP	4	8	.000	18.715	46.547	34.738
40	DBN	PN	9	9	--[2]	54.776	45.224	--[2]
41	MHP	PP	8	16	.000	30.809	47.038	22.154

1) Inadequate constant specimen depth during 1850-1986 ANOVA period. ANOVA not calculated.

2) Not available in single core ANOVA

3) ANOVA period begins in 1860

Table 5. Chronology signal strength.

No.	Code	SPP	1850-1986 Period # Series	Signal:Noise	90% Signal Point # Series	Year[2]
1	RMP	PP	24	26.965	6	1657
2	WDF	DF	14	20.530	4	1686
3	PDF	DF	16	9.767	7	1812
4	SMP	PP	26	61.684	3	1655
5	MTP	PP	18	6.169	10	1787
6	SGP	PP	20	60.870	3	1639(4)
7	GRP	PP	26	46.315	4	1675
8	DCP	PN	20	40.070	4	1650
9	RGP	PP	14	32.474	3	1698(5)
10	GRS	PP	24	46.951	4	1727
11	GMT	PP	18	19.681	6	1633
12	SRH	DF	22	29.888	5	1638
13	PCD	DF	20	18.903	6	1668
14	PST	DF	22	17.278	7	1633
15	NOO	PP	12	15.456	4	1783
16	BCR	PP	32	30.335	7	1596
17	GMF	DF	16	17.358	5	1707
18	BWF	DF	18	11.282	8	1675
19	RCF	DF	14	27.190	3	1630
20	RPE	PP	16	14.122	6	1660
21	ORD	PP	18	17.145	6	1600
22	BRF	DF	22	25.682	6	1603
23	BKF	DF	20	34.499	4	1522(5)
24	BKP	PP	20	29.130	5	1610

Table 5. (Continued) Chronology signal strength.

No.	Code	SPP	1850-1986 Period # Series	Signal:Noise	90% Signal Point # Series	Year[2]
25	MJN	PN	20	30.678	4	1661
26	AFN	PN	18	53.448	3	1510
27	GCP[1]	PP	--	--	--	--
28	RPP	PP	22	52.667	2	1678(3)
29	EPN	PN	18	28.501	4	1685
30	WCP	PP	20	26.239	5	1601
31	GPO	PP	32	39.448	6	1583
32	HDE	PP	14	18.564	4	1711
33	HDW	WP	18	16.861	6	1737
34	NSE	PP	12	9.456	6	1777
35	NSW[3]	WP	12	13.853	5	1711
36	NSF	DF	18	19.067	6	1710(7)
37	NSA	WF	14	18.390	5	1790
38	TSE	PP	26	24.041	7	1715
39	TSW	WP	8	8.637	4	1680
40	DBN	PN	9	7.968	5	1770
41	MHP	PP	16	17.650	5	1776

[1] Inadequate constant specimen depth during 1850-1986 period. Signal information not calculated.

[2] Numbers in parentheses signify number of cores available for 90% signal point year, if greater than number of series actually required.

[3] Signal strength data based on 1860-1986 period.

Graybill 1982:25-28). Annual variability among trees in a region is generally identified as resulting from limiting macroclimate factors. In chronology development we normally wish to maximize this component. Interstand differences result from such factors as variation in soil properties, slope, and each community's interaction with the environment. Differences among trees in a stand may be due to variations in tree vigor, competition, and operational environment. This value tends to increase as heterogeneity of site characteristics such as substrate, soil, slope or drainage characteristics increases. Variability within a tree can be due to differential growth in major roots and shoots, local microclimate, and factors controlling the operational environment of different tissues and organs.

The total variation in each of the chronologies used in this study is broken down into the sources mentioned above and presented in Table 4: yearly differences in indices (common), index differences between trees (trees), differences between cores within a tree (sides of trees), and, differences in individual core chronologies (cores). The ANOVA used in this report is a specific sums-of-squares partitioning procedure for tree-ring indices developed by Harold Fritts at the Laboratory of Tree-Ring Research (Fritts 1976:282-293). It requires a balanced and replicated sampling design and all samples must include the same growth interval; all trees must have the same number of cores, and; if there is more than one group, each must have the same number of trees. In the present analysis all samples minimally include the years 1850-1986, trees are usually represented by 2 cores, and if there is more than 1 group, the categorization is based on age (old vs. young), ease of crossdating (easy vs. tough), or forest interior vs. forest exterior. Years, core classes, and groups are assumed to be fixed, not selected randomly. The ANOVA technique also assumes variables and errors are independent, with the error normally distributed with a mean of zero and constant variance. In dendrochronology the component variances are generally expressed as percentages (e.g. Table 4) to facilitate comparisons among individual series.

Because various assumptions of the ANOVA model are confounded by the autocorrelation problem, the ANOVA results are normally not used for hypothesis testing. Instead the results are viewed as useful descriptive statistics that provide one of several bases for chronology evaluation and for refining future sampling strategies (Graybill 1982:25).

If autocorrelation is high and positive, the variance component due to annual variability will tend to be inflated. For example, almost half of the variability in series 3 (Peaks Douglas fir) can be explained with an autoregressive moving average model, described below. The 29% variance component in the common category (Table 4) for series 3 is thus an overestimate. A large percentage variance component due to differences among tree chronologies indicates each tree sampled adds new information to the total sample. A good example of this characteristic is series 5 from Mule Tank, where 50% of the variability can be relegated to differences among trees. Similarly, a large variance component due to core classification (e.g., by side of the tree sampled) shows annular nonconformity and provides significant differences in core chronologies. This variance component is small or nonexistent for the chronologies developed in this project. In some cases differences in individual core chronologies, listed in the last column in Table 4, can be relatively high in relationship to the other components (e.g. series 13, Pinery Canyon). In these situations in can be concluded that irregularities of crown size, competition, and distribution of food and growth controlling substances produced a large amount of ring-width variability within the trees of the site. Alternatively, if there is a large amount of variance in common within and among trees, only a little is lost in the averaging process and a large amount remains in the year by year site chronology. In this case it is inferred a large scale factor, such as macroclimate, varies annually and affects growth similarly on different sides of all trees in different sites.

The variance component information for any of the series in Table 4 can be interpreted in a similar manner. With the exception of the variance component due to the sides of trees, values of the different components exhibit a considerable range of variability. Analysis of variance was not run for the Gila Cliff Dwellings ponderosa pine (series 27) because the specimen depth during the 1850 - 1986 period was not constant. Single core ANOVA's were computed for series 15 and 40, Noon Creek ponderosa and Devils Bathtub pinyon respectively, because there were not enough paired cores for the 1850 - 1986 period. For these two sites there are no variance components associated with "sides of trees" or "cores". Sufficient paried core samples were obtained from both of these sites, but age of trees and abberrant growth in some specimens mitigated against a balanced experimental design.

Additional information produced in the chronology development analyses describes how well the average of a finite number of time series (the core index series averaged to produce a chronology) represents the population average, and how well a subset of series (index series for different numbers of cores) represent the average of the complete chronology. Wigley, Briffa, and Jones (1983:201-213) have studied the average value of correlated time series used in dendroclimatology and hydrometeorology, and they refer to the former characteristic as the expressed population signal (EPS) and the latter as the subsample signal strength (SSS). Information pertaining to the EPS and SSS of the tree-ring index chronologies developed in this study is presented in Table 5. The first set of values presented for each chronology pertain to the EPS, which we refer to as the signal-to-noise ratio, for the 1850 - 1986 ANOVA period, and the number of cores on which the calculation is based. It should be noted that the signal-to-noise ratio presented in

Table 5 is based on the calculations of Wigley et. al. 1983, and is somewhat different but strongly related to the signal-to-noise ratio discussed by Dewitt and Ames (1978), Graybill (1982), and Cropper (1982).

Chronology signal-to-noise ratio has been used to evaluate the relative strength of the common variance signal in tree-ring chronologies from different regions. Common climate forcing is probably the major contributing cause of common variance, but it cannot be interpreted solely in climatic terms, since common variance can arise from other factors - management, pests, disease, pollution, etc. However, in the chronologies from most of the sites included in this study climate probably is the most realistic cause of common variance. The signal-to-noise ratio for the chronologies in Table 5 ranges from a minimum of about 6.0 (series 5, Mule Tank ponderosa) to a maximum of about 62 (series 4, Slate Mountain ponderosa).

The other set of values in Table 5 pertain to subsample signal strength (SSS). The earliest sections of chronologies are normally based on fewer cores than the more recent sections. As the number of cores becomes smaller as one goes back in time, the comparison among the chronologies composed of reduced numbers of cores and the chronology composed of all the cores becomes more disparate. That is, the earliest parts of chronologies have variability (error) due simply to sample size, and not some common forcing function such as climate. Prior to undertaking any time series analysis, we wanted to determine the point in each chronology where a subsample of cores would contain 90% of the signal expressed in a chronology composed of all the cores. For each series, Table 5 lists the number of cores required to meet the 90% signal strength threshold and the year in which that minimum number of cores is first achieved. For example, even though series 11 (Green Mountain ponderosa pine) begins in the early 1400's, it is not until 1633 and a specimen depth of 6 cores that the 90% point is reached.

Core samples were collected from both young and old ponderosa at sites 5 and 31, Mule Tank and Gus Pearson Natural Area. An analysis of variance was calculated for both the young and old trees at each location during years of common overlap. At site 31 (Gus Pearson) the years of overlap were from 1930 to 1985, and there were 16 trees in each group, with two cores per tree. In both the young and old trees the amount of variance due to core classification was zero. The common variance component was 55.93% for the old trees and 28.36% for the young trees, indicating that an external limiting factor, most likely macroclimate, was more limiting to growth in older trees than younger trees. The variance component for tree chronologies is somewhat larger in the younger than older trees (21.32% vs. 15.07%), while the component for core chronologies is much larger (50.32% vs. 29.00%). The larger tree component suggests that site factors are slightly more important to the younger trees, possibly because the older trees are more established. The extreme differential in the variance component due to core chronologies indicates a great amount of variance is contributed by differences among the core chronologies from the different trees. This suggests competition and factors influencing food-and-growth controlling substance introduce a great amount of variability among cores.

At the Mule Tank ponderosa site analysis of variance calculations were based on six young and ten old trees, with two cores per tree. The years of common overlap between the young and old specimens were 1869 to 1986. As with the Gus Pearson site, the core class variance component was essentially zero (1.59% for the older trees and .04% for the younger trees). The common variance component was smaller for the older trees (18.81%) in comparison to the younger specimens (27.28%), while the tree component was larger for the older trees (49.99% vs. 33.56%). The variability due to core chronologies was smaller for the older trees (29.62% vs. 39.12%). The larger value for the common variance component for the younger trees indicates that they are more limited by an exogenous factor(s) than the older trees, while the larger tree component for the older specimens suggests that site factors such as slope, orientation, soils, etc. exert more of an influence on their growth than on the younger trees. The younger trees also exhibit a greater variance contribution due to core chronologies than the older trees, similar to the specimens from the Gus Pearson site. Factors controlling the distribution of food-and-growth controlling substances, and which introduce variability within and between trees, are also important at the Mule Tank location.

The Douglas-fir chronologies from the San Francisco Peaks (series 3) and Walnut Canyon sites (series 2) provide a convenient example of differences between chronologies from more mesic forest interior sites (series 13) and arid lower forest border locations (series 2) in the same general area. The Peaks chronology contains a 29% common variance component (Table 4), while the series from Walnut Canyon possesses a 51% value. It could thus be inferred that macroclimate exerts more of a control on the growth of the trees included in the Walnut Canyon chronology than those used in building the Peaks chronology. Neither of the series has a significant variance component due to sampling cores from different sides of a tree, and the core chronology variance components from both sites are virtually the same (approximately 30%). The similar values for the core chronology components indicate that factors such as irregularity of crown size, competition, and distribution of food-and growth-controlling substances produces similar amounts of ring-width variability at both locations. The variance for tree chronologies is larger for the Peaks site (37%) than the Walnut Canyon site (19%). The higher value for the tree component at the Peaks site in comparison to Walnut Canyon suggests that site factors at the former location exert a greater control in affecting the ring-width chronology somewhat differently in each tree.

Given the obvious mid-late 20th century growth decline of some but not all ponderosa pine in several stands, we investigated the possibility that this might represent a long-standing pattern of growth differential. Analysis-of-variance comparisons were made between chronologies developed from "easy" and "tough" to date specimens at six sites: 5 (Mule Tank), 20 (Rhyolite Canyon), 21 (Ord Mountain), 32 (Helen's Dome), 34 (North Slope) and 38 (Tucson Side). The comparisons were based on common years of overlap among the two groups for the longest possible time period, that the data would permit, prior to the onset of growth decline. The core classification variance component is not treated here because it was not part of the original sampling design.

Comparisons between the Mule Tank tough (MTT) and easy (MTP) chronologies were made for the 1840 - 1920 interval using 2 cores/tree from 8 trees in each group. The largest differences between the two chronologies were in the common variance component, which was 31.77% for MTP and 45.28% for MTT, and in the tree component, which was 41.29% for MTP and 26.04% for MTT. There were no major differences between the two sites in the variance components due core chronologies (25.89% for MTP and 27.48% for MTT).

ANOVA comparisons between the Rhyolite Canyon easy (RPE) and tough (RPT) chronologies were made for the 1840 - 1940 period using 2 cores/tree from 8 trees in each group. Again, the chronology based on tough-to-date specimens had more variance in the common component than the series developed from easy-to-date specimens (46.72% for RPT vs. 41.55% for RPE). The variance components ascribable to differences among tree chronologies were similar (23.10% for RPT vs. 21.23% for RPE), however, the chronology of tough-to-date specimens had less variance in the core chronology component (30.18%) than the series composed of easy-to-date cores (36.24%).

Analysis-of-variance comparisons for the ponderosa chronologies developed from the North Slope site were made from 1815 - 1920 using 2 cores/tree from 6 easy-to-date trees and 7 tough-to-date trees. There was basically no difference in the values of any variance components between the two groups. The common variance component was 41.39% for NSE and 38.73% for NST and the tree component was 27.09% for NSE and 30.53% for NST. There were not any differences between the two groups in the core chronology components (30.52% for NSE vs. 29.88% for NST).

At the Helen's Dome site comparisons between the easy (HDE) and tough (HDT) chronologies was made for the years 1821 - 1920 using 2 cores/tree for 8 trees for HDE and 5 trees for HDT. The common variance components were basically the same (44.12% and 42.11% for HDE and HDT respectively), as were the tree variance components (29.69% for HDE and 25.48% for HDT). Considerable difference exists between the variance components due to core chronologies. The HDT group had 32.41% variance in this component, while the value for HDE was 21.54%.

Analysis of variance comparisons for the Mt. Ord site were made for the period from 1812 - 1900 using 2 cores/tree for 9 trees from the easy-to-date group and 5 trees from the tough-to-date group. Significant differences are apparent in the common variance components, with 50.44% for the "easy" chronology and 41.80% for the "tough" chronology. The tree component variances are essentially the same (27.56% for ORD and 25.97% for ORT), but the component variances due to difference between core chronologies are considerable. The "easy" chronology has less variance in this component (22.00%) than the "tough" series (31.47%).

The final set of comparisons to be made are for the Tucson Side site, for the 1841 - 1920 period. Two cores/tree from 13 trees in the easy-to-date group and from 7 trees in the tough-to-date group were used in the analysis. None of the variance components from the TSE and TST groups exhibit large differences. The variability ascribed to the common component was 45.61% for TSE and 41.74% for TST. The tree component variances were 27.29% for TSE and 25.90% for TST, while the core chronology variance components were 27.10% and 32.11% for TSE and TST respectively.

The analysis of variance comparisons described above were undertaken in general consideration of the null hypothesis that there were no major differences in the growth of trees designated as easy-to-date and those that were tough-to-date, prior to the period of obvious growth decline. Overall, there was no apparent pattern of relationships among the variance components. Only at the Mule Tank, Helen's Dome, and Ord Mountain sites were major differences exhibited in any of the variance components between the "easy" and "tough" chronologies. Differences in the common variance components were present at the Mule Tank and Ord Mountain sites, with the tough-to-date chronology having a larger value at Mule Tank but a lower value at Ord Mountain. The core chronology variance component was largest in the tough-to-date chronologies from both Helen's Dome and Ord Mountain.

Overall, the results of these analyses do not contradict the null hypothesis stated in the last paragraph. However, the possibility that the individuals in the "decline" and "non-decline" groups have different intrinsic (genetic) tolerances and had different responses to the climatic stresses of the 20th century will ultimately require further consideration.

9.0 The Persistence Component

The persistence, or autocorrelation, structure is one additional characteristic of tree-ring index chronologies that now requires consideration. This component must be identified and treated appropriately before moving to some stages of analysis. Temporal persistence in a tree ring chronology is present when successive values in the series are not independent, that is, when they can be partially predicted from past observations (Chatfield 1980:6). The presence of significant persistence in time series that are being used in regression-based procedures results in a number of adverse consequences, i.e., the regression statistics are not reliable. The dependency structure exhibited by tree-ring index values is stochastic (Meko 1981, Rose 1983, Graybill 1985, 1986, Monserud 1986), therefore the following discussion precludes deterministic relationships.

Temporal persistence in tree ring chronologies is commonly defined with Box-Jenkins autoregressive - moving average (ARMA) modelling techniques (Box and Jenkins 1976, McCleary and Hay 1980, Hoff 1983). A series (chronology) that has had its persistence removed is frequently said to be prewhitened, by optical analogy. Box-Jenkins ARMA modeling involves using a sample realization (the tree ring index series) to build a model of the underlying probabilistic generating process. The technique requires decomposing a series into the autoregressive (AR) and moving average (MA) components, using an iterative process of model identification, parameter estimation, and diagnostic checking. The integrated component (I) discussed by Box and Jenkins in building ARIMA models can be dispensed with, since the series are weakly stationary.

An autoregressive (AR) process of order <u>p</u> can be modeled using <u>p</u> lagged observations of the time series (z_{t-1}, z_{t-2}, ... z_{t-p} to predict the current observation (z_t), that is,

$$z_t = \emptyset_1 z_{t-1} + \emptyset_2 z_{t-2} + \ldots + \emptyset_p z_{t-p} + a_t$$

The <u>p</u> $\emptyset$ (phi) terms are the autoregressive coefficients associated with previous years tree-ring index values. The a_t are serially random inputs or shocks that drive the tree growth system, as reflected in the tree rings. An autoregressive process is realized as an exponentially weighted sum of all past shocks, though the impact of an individual shock rapidly diminishes.

In contrast to the autoregressive process, a moving average process is characterized by a finite persistence of the random shock. It enters the system, persists for <u>q</u> observations, and then vanishes entirely. A portion of the preceding random shock is already lost along with all prior random shocks back into the distant past. A moving average process of order <u>q</u> is written as:

$$z_t = a_t - \theta_1 a_{t-1} - \theta_2 a_{t-2} - \ldots \quad \theta_q a_{t-q}$$

The <u>q</u> θ (theta) terms are the moving average coefficients associated with the previous years error terms.

The general autoregressive moving average (ARMA) model of orders p and q combines the two models described above and is written as:

$$z_t = \phi_1 z_{t-1} + \dots + \phi_p z_{t-p} + a_t \quad \theta_1 a_{t-1} - \dots \theta_q a_{t-q}$$

ARMA(1,1) models have frequently provided the most parsimonious representations of the persistence structure of western North American conifers (Rose 1983, Monserud 1986, Graybill 1985,1986), with the best competing models falling in the AR(1-3) classes.

10.0 The Baseline Periods

Treating persistence in the project chronologies first involved consideration of the appropriate time span for model evaluation. Two variables were of concern. First, it was desirable to use a time period for model fitting that was thought to precede any period of probable abnormal growth. In this case we decided that the ambiguity of evidence for any clear cut normal/abnormal growth period would best be served by using two time reference frames as terminal dates - 1950 and 1960. Although arbitrary in some ways, they provide a beginning frame or window of post World War II expansion and pollution production as it may or may not be relevant in affecting tree growth in this region. A second concern was with the potential stability of a time series model for any particular chronology due to decreasing sample size in terms of the numbers of series represented in its early years. Thus, the first year that was used for model fitting procedures was selected as that where the subsample signal strength was nearest 90 percent (see Table 5 above).

The persistence components of the tree-ring index chronologies were then identified using the standard protocol of model identification, parameter estimation, and diagnostic checking described by Box and Jenkins (1976) for the baseline periods defined by the criteria noted above. Once the models were derived then the coefficients were applied to the total length of the chronology in question to develop final residual or prewhitened series.

The ARMA models per chronology and respective time period are summarized in Table 6. In all but three cases the most parsimonious model fit for the period ending in 1950 is identical to the model for the interval ending in 1960. The three exceptions are series 8, 32, and 36, where the AR_2 model was judged the best fit for the first period while an AR_1MA_1 model provided the best fit for the later interval. The AR and ARMA models represent only minor differences in explained variance, and they are competing models in each respective situation. The amount of variance accounted for by the time series models ranges from about seven percent in the

Table 6. ARMA modelling summary.

No.	Code	SPP	First year -1950 1960 model period	Best fit to 1950	% Var.	Best fit to 1960	% Var.
1	RMP	PP	1657	AR_2	18.083	AR_2	19.954
2	WDF	DF	1686	AR_2	35.686	AR_2	36.506
3	PDF	DF	1812	AR_1MA_1	48.094	AR_1MA_1	48.253
4	SMP	PP	1655	AR_2	44.076	AR_2	44.366
5	MTP	PP	1787	AR_2	28.793	AR_2	28.457
6	SGP	PP	1639	AR_2	31.091	AR_2	31.678
7	GRP	PP	1675	AR_2	22.941	AR_2	23.406
8	DCP	PN	1650	AR_2	21.701	AR_1MA_1	20.763
9	RGP	PP	1698	AR_2	42.134	AR_2	42.792
10	GRS	PP	1727	AR_2	21.110	AR_2	21.670
11	GMT	PP	1633	AR_1MA_1	18.818	AR_1MA_1	20.683
12	SRH	DF	1638	AR_1	23.382	AR_1	24.469
13	PCD	DF	1668	AR_1	12.994	AR_1	13.610
14	PST	DF	1633	AR_2	23.665	AR_2	21.996
15	NOO	PP	1783	AR_1	14.560	AR_1	19.215
16	BCR	PP	1596	AR_1MA_1	20.569	AR_1MA_1	20.294
17	GMF	DF	1707	AR_2	16.862	AR_2	17.590
18	BWF	DF	1675	AR_1	25.105	AR_1	24.985
19	RCF	DF	1630	AR_1	8.638	AR_1	9.136
20	RPE	PP	1660	AR_1MA_1	11.291	AR_1MA_1	11.383
21	ORD	PP	1600	AR_1MA_1	16.903	AR_1MA_1	17.448
22	BRF	DF	1603	AR_2	16.443	AR_2	15.671
23	BKF	DF	1522	AR_1MA_1	14.785	AR_1MA_1	15.302

Table 6 (Continued) ARMA modelling summary.

No.	Code	SPP	First year -1950 1960 model period	Best fit to 1950	% Var.	Best fit to 1960	% Var.
24	BKP	PP	1610	$AR_{1,4}$	8.502	$AR_{1,4}$	9.950
25	MJN	PN	1661	AR_1MA_1	6.780	AR_1MA_1	8.853
26	AFN	PN	1510	$AR_{1,4}$	20.483	$AR_{1,4}$	22.322
27	GCP	PP	1850[1]	$AR_{1,4}$	17,795	$AR_{1,4}$	20.016
28	RPP	PP	1678	AR_1MA_1	29.192	AR_1MA_1	30.623
29	EPN	PN	1685	AR_1	16.006	AR_1	15.285
30	WCP	PP	1601	AR_2	26.366	AR_2	26.112
31	GPO	PP	1583	$_AR^2$	23.040	AR_2	22.566
32	HDE	PP	1711	AR_2	35.059	AR_1MA_1	37.116
33	HDW	WP	1737	AR_1MA_1	21.555	AR_1MA_1	25.799
34	NSE	PP	1777	$AR_{1,4}$ MA_1	31.939	$AR_{1,4}$ MA_1	31.206
35	NSW	WP	1711	AR_1MA_1	22.350	AR_1MA_1	25.819
36	NSF	DF	1710	AR_2	34.964	AR_1MA_1	36.283
37	NSA	WF	1790	$AR_{1,4}$	25.323	$AR_{1,4}$	23.900
38	TSE	PP	1715	AR_2	24.199	AR_1MA_1	26.981
39	TSW	WP	1680	AR2	20.023	AR_2	19.987
40	DBN	PN	1770	AR_2	23.106	AR_2	20.839
41	MHP	PP	1776	AR_1MA_1	18.118	AR_1MA_1	20.681

[1] Starting date of 1850 for GCP is not based on ANOVA results, due to poor specimen depth.

[2] Neither of the models for ORD produces a Q-statistic with an associated probability value 70.05, indicating that the autocorrelation function is characteristic of a random series.

model for Mimbres Junction pinyon (series 25) to approximately forty-eight percent in both of the models for Peaks Douglas fir (series 3). On the average 22.99% of the variance in the chronologies is explained by the time series models for the period ending in 1950, while 23.76% of the variance is accounted for in the interval ending in 1960. In general similar amounts of variance are explained in each period.

An interesting time series characteristic of the chronologies in this study is the preponderance of autoregressive models (29 series) as opposed to AR_1MA_1 models (12 series). Of the 29 autoregressive series, six are first order, 19 are second order, and four are fourth order with null second and third order terms. Several earlier studies of the time series characteristics of tree-ring chronologies in the western United States have recognized the primacy of the AR_1MA_1 model (Rose 1983, Monserud 1986, Biondi and Swetnam 1988, Graybill 1985, 1986). This study is the first to usethe 90% variance cut off point in the chronology as the first year to begin time series modeling (see Table 5). That is, the first year of the interval for which the time series model is identified is the point at which the set of a few cores have 90% variance in common with the chronology made up of all the specimens. In other words the error is minimal.

The other time series modeling studies mentioned above have considered chronologies that have weaker specimen depth in the earliest years and hence they probably have more noise. In these cases the MA component may be capitalizing on capturing the variability expressed by the error component. Most of the competing models to the AR_1MA_1 are autoregressive models, especially AR_2. In the present study there is a preponderance of autoregressive models over AR_1MA_1 models; this may be a reflection of the dominance of the year-to-year dependence of the actual values over the error component. The competing models to the AR_1MA_1 are autoregressive in most cases, and the differences in explained variance are usually small, so it is not an object of major concern. The only point to be made is that the observed dominance of the AR models over the ARMA models was made on objective and replicable grounds, and any explanations of real-world ecophysiological behavior accounting for the statistical regularities must recognize the possibility of a numerical artifact.

One way to test the AR vs. ARMA hypothesis would be to model series from the 90% cut-off point to the present (or some other suitable criterion indicative of chronology strength) and then over the full length. In ARMA and AR competing model situations the ARMA models would be expected to dominate over the full series length while the AR models should predominate over the shorter lengths based on the 90% cut off. Dendrochronologists should at least be cognizant of the possibility that the year in which a model begins, in relationship to the strength of the series, may exert some effect on the most parsimonious representation developed.

11.0 Climate-Tree Growth Relations

The approach described in Section 4.2 of the original proposal for this research (Graybill and Swetnam 1987) was implemented to develop reliable predictions of natural tree growth variation from climatic variation over a baseline period that is thought to be free of major anthropogenic pollution inputs. In dendroclimatic research these kinds of relationships are commonly evaluated with regression models of varying complexity depending on the number of dependent and independent variables used. Assumptions of these models as well as goodness of fit statistics associated with them are treated by a number of sources and they will not be repeated here (Neter, Wasserman and Kutner 1985, Draper and Smith 1981, Snedecor and Cochran 1979, Cook 1977, Graybill 1976).

In this study we established predictive relationships of tree-ring growth and climate over a baseline period from 1897 to 1950 and again from 1897 to 1960, using the residual series created in the time series modeling process. Once a predictive relationship was established for each baseline period it was then used to estimate tree-growth during the most recent period, from either 1951 or 1961 to 1986. If there has been no major change in the climate-tree growth relationship then the estimated growth should be reasonably similar to actual growth in the recent interval. The means of the predicted and actual growth should not be significantly (alpha = .05) different, the covariance between the predicted and actual growth should be similar to that of the model calibration period, and there should not be any anomalous trend in the actual growth that is not present in the predicted growth. Differences of means and central tendency are tested with the t test and the Wilcoxon matched pairs signed ranks test, covariance is evaluated with Pearson's correlation coefficient and its square, the coefficient of determination, and trends are tested with a sign test.

Alternatively, there (1) may be a significant difference between the means of the actual and the predicted, (2) the actual and predicted series may not exhibit significant covariance, or (3) there may be a trend in the residuals. Inability to reject any of the alternative hypotheses indicates that the actual and predicted growth empirically differ in some manner. It does not 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 still remain to be demonstrated.

12.0 Calibration and verification - baseline period.

Statistical models were established between divisional climate and tree-growth for the baseline period over two subintervals. That is, the intervals from 1897 to 1950 or 1960 were divided into halves. The first interval was initially used for calibration while the second interval was used for verification. 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 in an attempt to test for time stability of the climate - tree-growth system. Only after the split period results were evaluated was the final calibration established with the full baseline period data set. This exercise was necessary and prudent because the climatic data available during the baseline period is only 45 to 55 years in length. All of the data were used to insure that the final calibration model was developed on the fullest possible range of data covariation.

A summary of the final calibration results is presented in Table 7. The calibration heading in the table refers to results for the final model, from 1897 to 1950 or 1960, while the verification heading refers to the 1951 or 1961 to 1986 interval. The amount of variance explained in the residual tree ring series is presented under the r-squared heading. This is the amount of variance explained in the tree-ring index series after persistence has been removed. The null hypothesis is that the covariation is not significant. The few instances in which this hypothesis cannot be rejected are indicated by an 'R' next to the numerical value.

The _t_ test null hypothesis is that the means are not significantly different. Acceptance of this hypothesis is indicated by an 'A' in the table, rejection is indicated by an 'R'. When the null hypothesis is rejected a lower case 'd' indicates that the mean of the actual residual series is less than the mean of the residual series predicted from the divisional climate data. An 'i' indicates the actual mean is greater than the mean of the residual series. In addition to the _t_ test the nonparametric Wilcoxon matched pairs signed ranks test was computed. The null hypothesis is that there is essentially no difference in central tendency between the actual and predicted residual tree-growth series. Its acceptance and rejection is indicated in the same manner as the _t_ test. The _t_ and Wilcoxon tests are not presented for the calibration interval because the means of the actual and predicted series are the same.

The F test for the verification period involves the variances of the actual and predicted series. The null hypothesis is that the variances of the two series are not significantly different. Its acceptance is indicated by an 'A', while rejection is denoted by

Table 7. Summary of calibration and verification results. r^2 is variance in residual tree-ring series explained by climate (square of correlation), t is difference of means test, F is ratio of variances, and W is Wilcoxon matched pairs signed ranks. A indicates null hypothesis accepted, R indicates rejection.

			CALIBRATION		VERIFICATION				
	CODE		r^2	sign test	r^2	t	F	W	sign test
1	RMP	A[1]	.40	A	.37	Ri	Ri	R	A
		B[2]	.39	A	.31	A	Ri	R	A
2	WDF	A	.38	A	.52	A	Ri	R	A
		B	.39	A	.53	A	Ri	A	A
3	PDF	A	.35	A	.45	A	Ri	A	A
		B	.37	A	.41	A	Ri	A	A
4	SMP	A	.37	R	.50	Rd	Ri	R	A
		B	.43	A	.46	Rd	Ri	R	A
5	MTP	A	.16	A	.00R	A	Ri	A	R
		B	.18	A	.00R	A	Ri	A	R
6	SGP	A	.48	A	.48	Rd	Ri	R	A
		B	.50	A	.46	Rd	Ri	R	A
7	GRP	A	.43	A	.19	A	A	A	A
		B	.47	A	.09R	A	A	A	R
8	DCP	A	.51	A	.50	A	Ri	A	A
		B	.47	A	.59	A	A	A	A
9	RGP	A	.45	A	.34	Rd	Rd	R	A
		B	.46	A	.34	Rd	Rd	R	A
10	GRS	A	.50	A	.30	A	Ri	A	A
		B	.28	A	.47	A	Ri	A	A
11	GMT	A	.27	A	.12	Rd	A	R	A
		B	.23	A	.16	Rd	A	R	A
12	SRH	A	.42	A	.41	Rd	Rd	R	A
		B	.40	A	.50	Rd	Rd	R	A
13	PCD	A	.37	A	.45	Rd	Ri	R	A
		B	.40	A	.43	Rd	Ri	R	A
14	PST	A	.29	A	.33	Rd	Ri	A	A
		B	.25	A	.43	Rd	Ri	A	A

			CALIBRATION		VERIFICATION				
	CODE		r^2	sign test	r^2	t	F	W	sign test
15	NOO	A	.33	A	.27	Ri	Rd	A	A
		B	.31	A	.22	Ri	Ri	R	R
16	BCR	A	.13	A	.41	A	Ri	A	A
		B	.18	A	.35	A	Ri	A	R
17	GMF	A	.35	A	.22	Rd	A	R	A
		B	.31	A	.31	Rd	A	R	A
18	BWF	A	.23	A	.09R	A	Ri	A	R
		B	.16	A	.18	A	Ri	A	R
19	RCF	A	.41	A	.50	Rd	Ri	R	A
		B	.43	A	.46	Rd	Ri	R	A
20	RPE	A	.23	A	.31	Rd	Ri	R	A
		B	.26	A	.32	Rd	Ri	R	A
21	ORD	A	.30	A	.20	Rd	Ri	R	A
		B	.28	A	.20	Rd	Ri	R	A
22	BRF	A	.43	A	.54	A	Ri	A	A
		B	.46	A	.51	A	Ri	A	A
23	BKF	A	.43	A	.54	Rd	A	R	A
		B	.44	A	.60	Rd	A	R	A
24	BKP	A	.37	A	.58	A	Ri	A	A
		B	.40	A	.58	A	Ri	A	A
25	MJN	A	.25	A	.64	A	Ri	R	A
		B	.33	A	.57	A	A	A	A
26	AFN	A	.42	A	.45	Rd	A	R	A
		B	.43	A	.44	Rd	A	R	A
27	GCP	A	.35	A	.42	Rd	Ri	R	R
		B	.40	A	.35	A	Ri	A	R
28	RPP	A	.41	A	.33	Rd	A	A	A
		B	.40	A	.32	A	A	A	A
29	EPN	A	.37	A	.17	A	A	A	A
		B	.33	A	.20	A	A	R	A
30	WCP	A	.55	A	.49	Rd	Ri	A	A
		B	.59	A	.42	Rd	Ri	A	A

			CALIBRATION		VERIFICATION				
	CODE		r^2	sign test	r^2	t	F	W	sign test
31	GPO	A	.31	A	.33	Rd	Ri	R	A
		B	.36	A	.34	Rd	A	R	A
32	HDE	A	.10	A	.03R	Rd	Ri	R	R
		B	.07	R	.01R	Rd	Ri	R	R
33	HDW	A	.24	A	.34	A	Ri	R	A
		B	.24	A	.30	Rd	Ri	A	A
34	NSE	A	.17	A	.09R	Rd	Ri	R	R
		B	.16	A	.06R	Rd	Ri	R	R
35	NSW	A	.37	A	.48	Ri	Ri	A	A
		B	.36	A	.51	Ri	Ri	A	A
36	NSF	A	.25	A	.24	Rd	A	R	A
		B	.24	A	.25	Rd	Rd	R	R
37	NSA	A	.36	A	.51	A	A	A	A
		B	.37	A	.48	A	A	A	A
38	TSE	A	.25	A	.14	Rd	A	R	R
		B	.22	A	.09	A	A	A	R
39	TSW	A	.16	A	.26	A	Ri	A	R
		B	.17	A	.19	A	Ri	A	A
40	DBN	A	.09	A	.09R	A	Ri	R	R
		B	.11	A	.06R	A	Ri	R	R
41	MHP	A	.29	A	.30	A	Ri	A	A
		B	.29	A	.27	Rd	Ri	A	R

d Indicates value for actual tree-ring index residual series is less than corresponding value for series reconstructed from August-July total precipitation.

i Indicates value for actual tree-ring index residual series is greater than corresponding value for series reconstructed from August-July total precipitation.

1 A in code heading indicates calibration from 1897 - 1950, verification from 1951 - 1986.

2 B in code heading indicates calibration from 1897 - 1960, verification from 1961 - 1986.

an 'R'. The 'd' and 'i' indicate that the variance of the actual series is less than that of the reconstructed series, while an 'i' indicates the opposite. Normally it is expected that the variance of the actual series is greater than that of the reconstructed series, since in none of the calibrations is 100% of the variance in the tree-growth series predicted from the climate data. The few cases where the variance of the actual series is less than that of the reconstructed suggests a marked reduction in the variance of actual tree-growth has occurred from the calibration period.

The sign test demonstrates whether there are any differences between the actual and reconstructed series in the change of sign from one year to the next. That is, the change in sign from one year to the next is tabulated separately for the actual and reconstructed series. The null hypothesis is that there is not a significant difference between the series in the changes of sign from one year to the next. If the actual and reconstructed series are behaving in a similar manner the matches of sign between the series will be high. Alternatively, if one series shows annular changes of sign that are not similar to the other series the number of mismatches will be high and the null hypothesis will be rejected.

Significant predictive relationships between divisional climatic data (August to July total precipitation) and residual tree-growth were developed for every chronology (Table 7) during the baseline period. These relationships were also usually significant during the 1951 or 1961 to 1986 period, but in a few cases the covariation was not significant. Chronologies with non-significant covariation include Mule Tank ponderosa (series 5), Girls Ranch ponderosa (series 7, 1961-1986 period), Bear Wallow fir (series 18, 1951-1986 period), Helen's Dome ponderosa (series 32), North Slope ponderosa (series 34), and Devil's Bathtub pinyon (series 40). In many cases (e.g. Devil's Bathtub pinyon) the predictive relationship established during the calibration period, while significant, did not result in a large amount of explained variance. In other cases, such as Girl's Ranch ponderosa, the variance explained in the calibration period is reasonably large, and the decrease in the verification interval may signal that some factor(s) have caused the nature of the climate-tree-growth system to be altered.

For most chronologies the amount of explained variance remains relatively stable between the calibration and verification periods, indicating the climate - tree-growth relationship remains about the same. Other support for the similarity in direction of year to year growth in pairwise comparison of the actual and predicted series is found in the results of the non-parametric sign test (Table 7). In general, the lowest calibration and verification variance values (less than .3 - .4) and most hypothesis rejections based on the sign test are associated with chronologies to the south of the Mogollon Rim.

The differences between the reconstructed and actual means are a different matter. Both the t test and the Wilcoxon test indicate many instances where the two means, or central tendency, are significantly different, with the mean of the actual tree growth usually being less than that predicted from climate (denoted by a 'd'). For a few chronologies the means of actual growth are greater than predicted.

Figures 14 and 15 show the chronologies and species with significant differences of means in the 1951 to 1986 period (denoted by a dot next to the number or species designation), while Figures 16 and 17 convey the same information for the 1961 to 1986 period. Dark dots indicate actual growth is less than predicted, while open dots denote situations where actual growth is greater than that predicted from August to July divisional precipitation. There are some notable differences ina actual and predicted growth levels on a spatial basis. This involves consideration of sites in and near the Mogollon Rim (northern sector) vs those in the southern Basin and Range area. Across all species, from 58% (1951-1986) to 63% (1961-1986) of the series in the southern area show mean growth decrease. These figures are somewhat less in the northern area - 41% for 1951-1986 and 36% for 1961-1986 evidence growth decrease. On a species basis the north-south differences are more striking. During the 1951-1986 oeriod, five of seven (71%) ponderosa pine chronologies in the south evidence less growth than expected while six of fouteen (43%) in the north demonstrate this. For the period of 1961-1986 these differences are similar (71% with decline in the south and 29% in the north). For Douglas-fir chronologies, six of seven (86%) in the south but only one of four in the north have less growth than expected for the period of 1951-1986. Again, for the 1961-1986 period this difference is similar with five of seven (71%) series in the south and only one (25%) in the north demonstrating significant declines in mean growth.

In terms of other species, the only white fir chronology in the collection, North Slope fir (series 37), does not show a difference of means. It also has a large amount of explained variance during the verification period. Additionally, only one of the five pinyon chronologies (Agua Fria, series 26) and only one of the southwestern white pine series (North Slope, series 35) have a difference between the predicted and actual mean growth.

13.0 Summary

Forty-one crossdated and well-replicated tree-ring index chronologies from Arizona and southwestern New Mexico were developed in the present study. They were derived from a variety of sites ranging from the arid lower forest border to mesic forest interior locations. This set of chronologies represents 1747 core samples taken from 889 different trees. All of the core samples were crossdated, and 1150 of them were also measured and subjected to normal standardization procedures. Over a quarter of a million tree rings (283582) are represented in the 41 chronologies.

The ring width series comprising each chronology were subjected to independent measurement and quality control checks before being standardized with programs INDEX and SUMAC. Analysis of variance calculations for the final chronologies partition the sums-of-squares in the series into components that are (1) held in common among all trees and cores, (2) related to differences between paired cores within a tree, (3) caused by differences among trees, and (4) due to variation among core chronologies.

Each tree-ring index chronology was subjected to standard Box-Jenkins ARMA modeling techniques to remove the persistence (serial correlation) usually ascribed to biological, as opposed to climatic, causes. All of the chronologies contain significant amounts of persistence. Removal of the persistence from each series resulted in residual chronologies with no significant autocorrelation, which in turn were calibrated with divisional climate data over the 1897 to 1951 or 1961 baseline periods. Prior to using the full baseline period data set, the data was evenly split into two segments, with separate calibrations and verifications established for each segment in an attempt to verify the temporal stability of the model. Only then was the full data set used to establish a climate - tree-growth predictive relationship. For each chronology, the model developed for the baseline period was applied to divisional climatic data to yield estimates of tree growth, which was then compared to actual growth.

Comparisons of actual to predicted growth were made on the basis of several criteria. Covariation between climate and tree-growth was measured with the coefficient of determination, and only a few chronologies fail the verification process. In the absence of a poor calibration, it is suggested that some factor or factors has intervened to change the climate - growth relationship. For most chronologies the covariation remains reasonably similar between the calibration and verification periods.

In most cases the variance of the tree growth series estimated from divisional climate data was less than the variance of the actual tree growth. This is to be expected if the calibration relationship remains stable, since the amount of explained variance never reaches 100%. Differences between the variances of the actual and estimated tree growth series were tested with the F-ratio. When the variance of the actual series is less than that of the predicted series, it may be inferred that some factor has significantly impacted the tree-growth - climate relationship.

Differences of means and central tendency were measured with t and Wilcoxon tests. Many chronologies exhibit significant differences between actual and predicted growth, with most series showing a decrease in actual growth relative to that predicted from climate. A substantially higher proportion of the ponderosa pine and Douglas-fir chronologies from the mountains of the Basin and Range area of southern Arizona evidenced mean growth decrease in the 20th century than did chronologies of the same species in the northern areas of the study.

14.0 Other Approaches

Several of the stands that we sampled are in National Monuments. This is part of a cooperative effort with Dr. K. Stolte of the N.P.S.

National Monument	Conifer type	N of chronologies
Gila Cliff Dwellings, N.M.	ponderosa pine	1
Chiricahua, AZ.	ponderosa pine	1
	Douglas-fir	1
Saguaro East, AZ	ponderosa pine	3
	southwestern white pine	3
	pinyon pine	1
	Douglas-fir	1
	white fir	1
Walnut Canyon, AZ	ponderosa pine	1
	Douglas-fir	1

All of the ponderosa pine were evaluated for foliar damage and other morphological characteristics indicative of stress in 1987 through Stolte's program by Mr. D. Duriscoe of Eridanus Research Associates. In addition, substantial numbers of increment cores were taken from ponderosa pine in all stands for elemental analyses at Los Alamos National Laboratory (Dr's E. Gladney and R. Farenbaugh).

A second evaluation of the foliage of all tree-ring series that had been dated and measured from the Rincon sites was made by Duriscoe in late June, 1988. This was done for two reasons. First, there was some concern that the 1987 evaluations in October might be biased in terms of needl-retention characteristics because it was after the violent summer monsoon storms (July-August) that may have removed needles mechanically. A second concern was to evaluate the foliage and other characteristics of dated and measured individuals of other species and genera in the Rincons. With minor exceptions, these do not evidence the severe mid-late 20th century growth decline found in some of the ponderosa pine. This is useful simply as baseline data but it also provides another set of controls for making comparisons of inter-species growth differences. Additionally, increment cores were collected in June of 1988 by Stolte's group from some of the Douglas-firs, white firs and white pines that we developed chronologies from. These will be used in elemental analysis, thus providing a multiple species/genera set of controls and perspectives.

At the current date of writing (July 12, 1988), the 1988 Duriscoe survey data are not yet available and the 1987 survey data have not yet been exhaustively compared with the tree-ring series. However, outside of the Rincon unit, ponderosa in all other monuments evidence essentially no foliar damage that might clearly be ascribed to pollution. Based on a tally of the 1987 data, about 23 percent (11 individuals) of the ponderosa evaluated in the Rincons demonstrate some ozone damage. Only three of those individuals appear to have growth decline in their recent years.

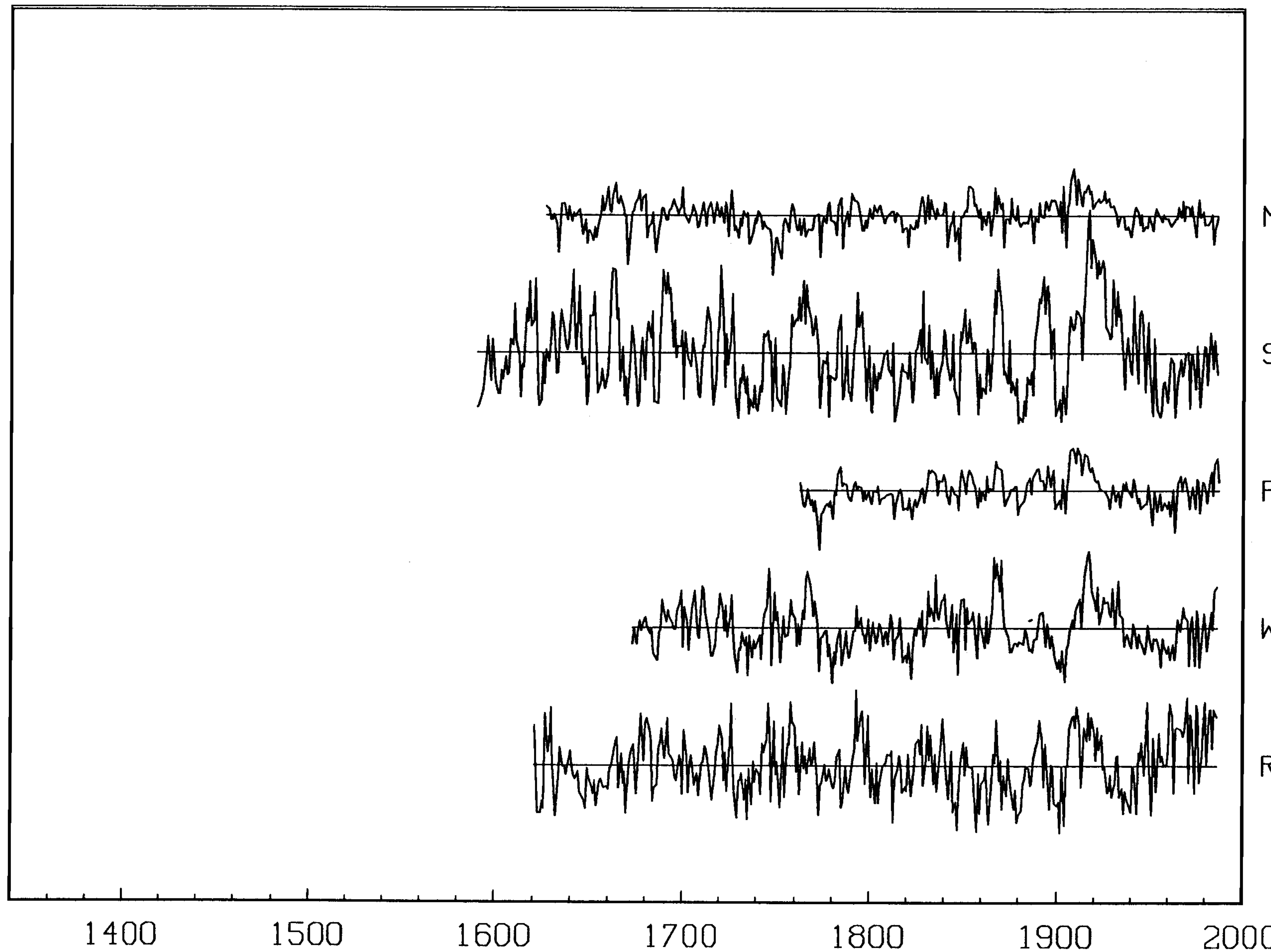
Graybill will review all of the 1988 and 1987 Duriscoe survey data with respect to stand and tree chronology data in the Fall of 1988, developing a document that summarizes all pertinent covariation found. Elemental analyses will not be undertaken until Fall of 1988 and this data will be sought for integration as it becomes available. Another kind of information will also be avaialable for at least some of the stands, and that is briefly summarized here.

14.1 Competition Indices

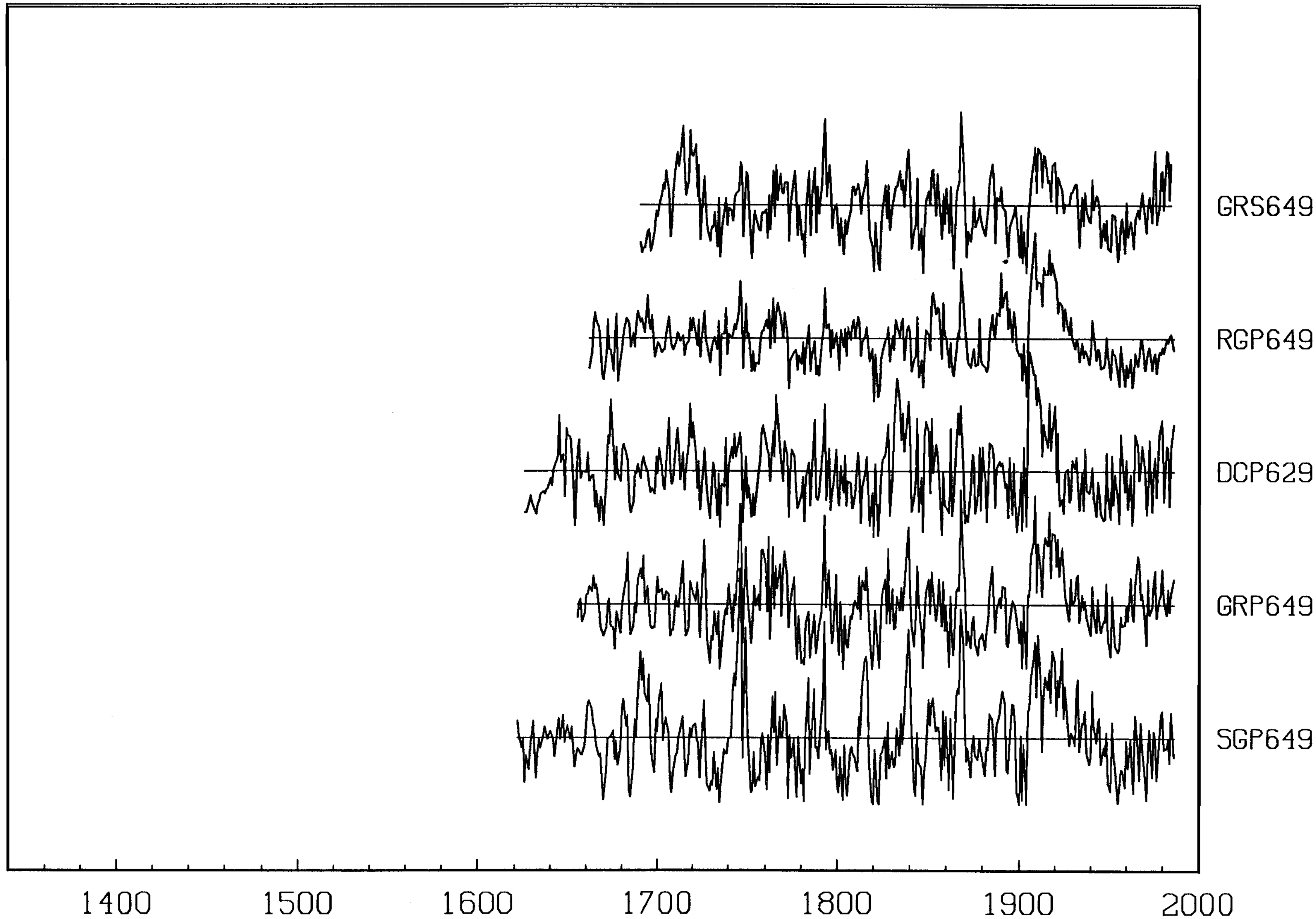
One hypothesis that needs to be considered in potential explanation of growth decline in some trees in the mid-late 20th century is that increasing competition is responsible. Relatively wet conditions in the early 20th century may have encouraged the establishment of a substantial number of trees and during the succeding 30-60 years they may have provided serious competition with older individuals for water, soil nutrients and finally, light. We have therefore initiated a study to develop a competition index for trees in various stands. At present we have raw competition data measurements for ponderosa pine in the Chiricahuas and for all species and sites in the Rincons. Depending on our funding, we hope to collect more of this information in other stands with apparent growth decline as well as from a number of others in various settings and without growth decline in order that we might better understand the character and dynamics of all stands. Analysis of whatever information we are able to collect will be integrated with other survey or elemental analysis data in time for inclusion in the June 1989 report on western forest conditions.

Figure 13. Original tree-ring index chronologies (not prewhitened) from Arizona and New Mexico. First three letters of label associated with each chronology correspond to code listed in Table 1.

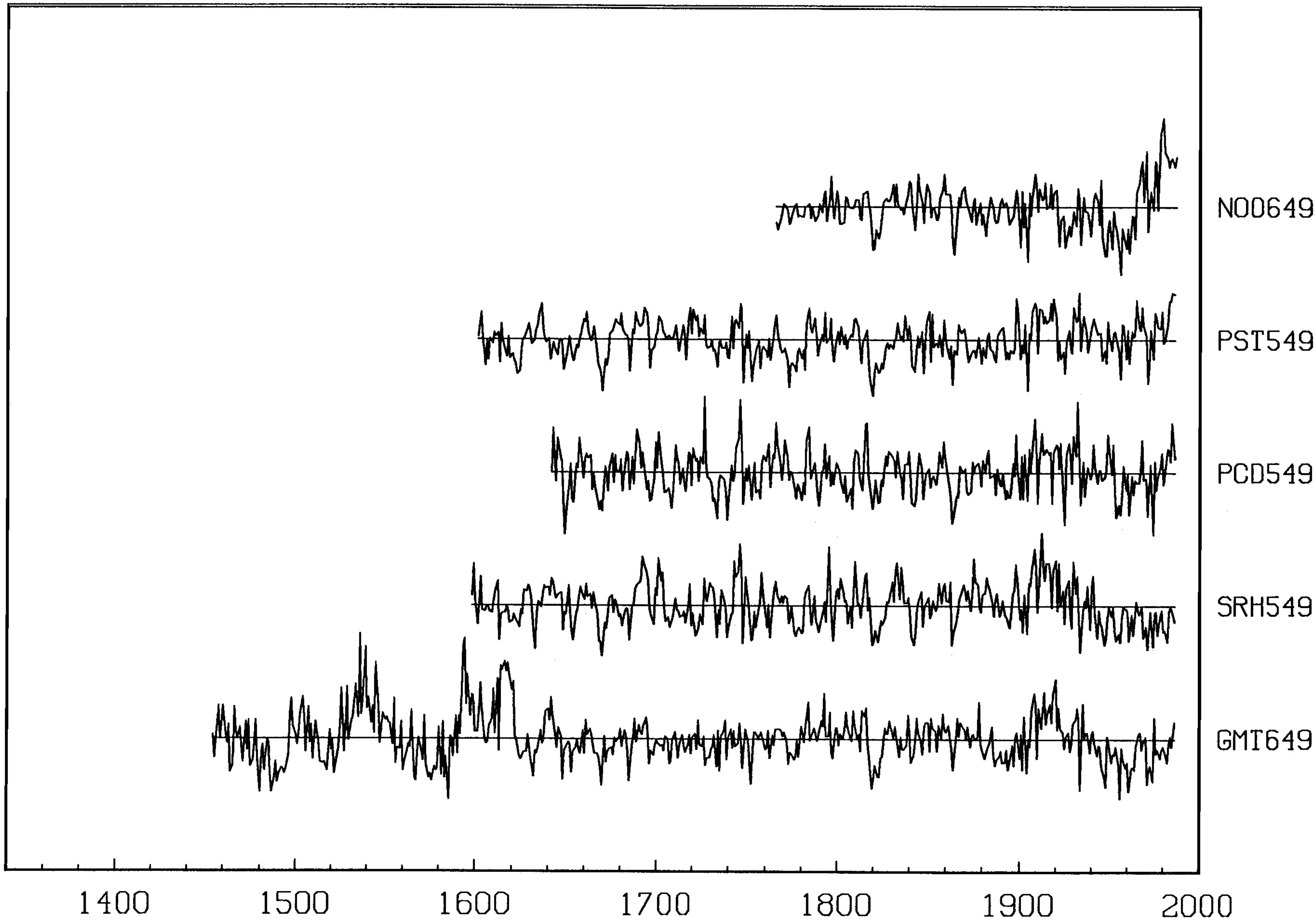
CHRONOLOGIES RMP, WDF, PDF, SMP, MTP



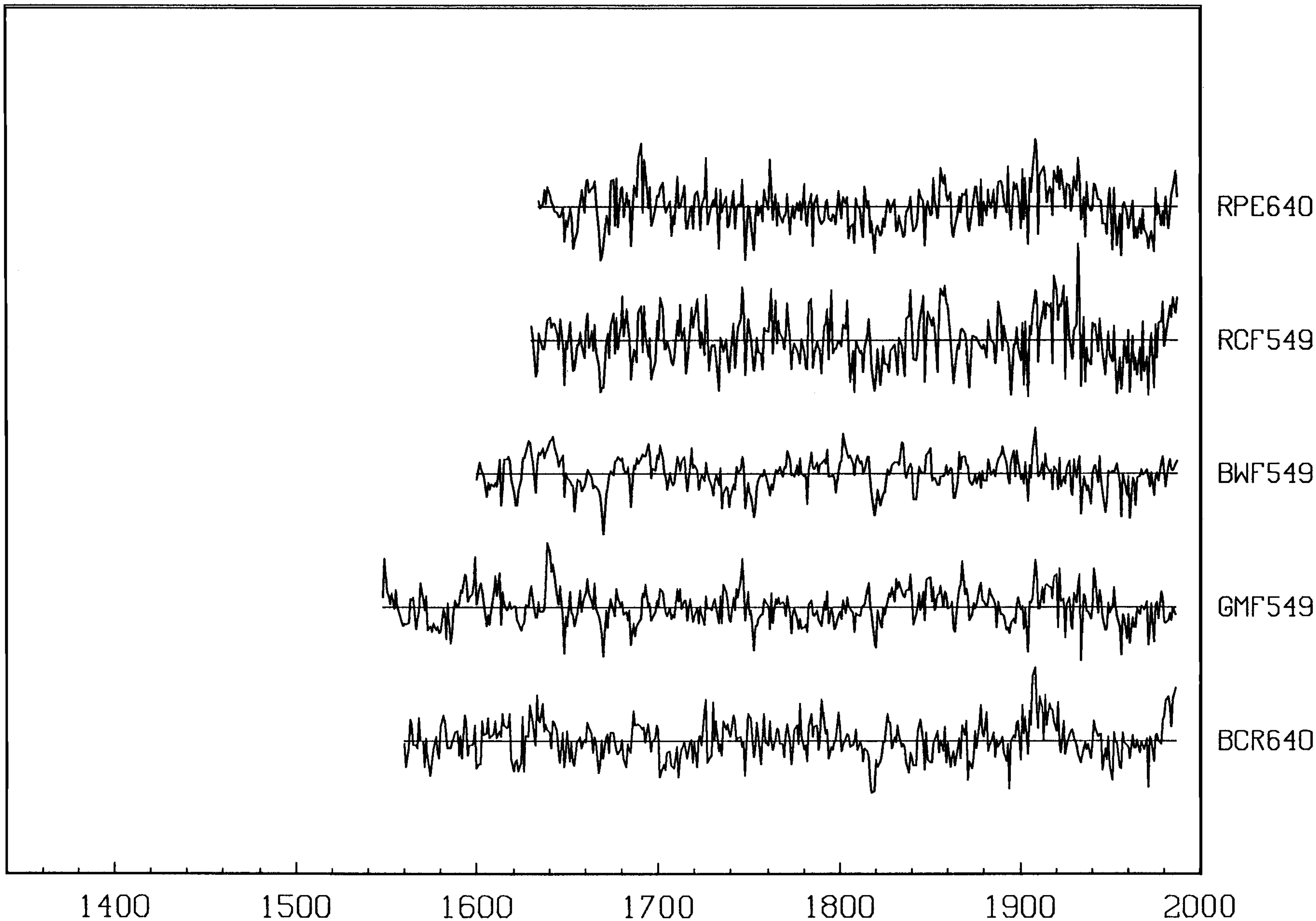
CHRONOLOGIES SGP, GRP, DCP, RGP, GRS



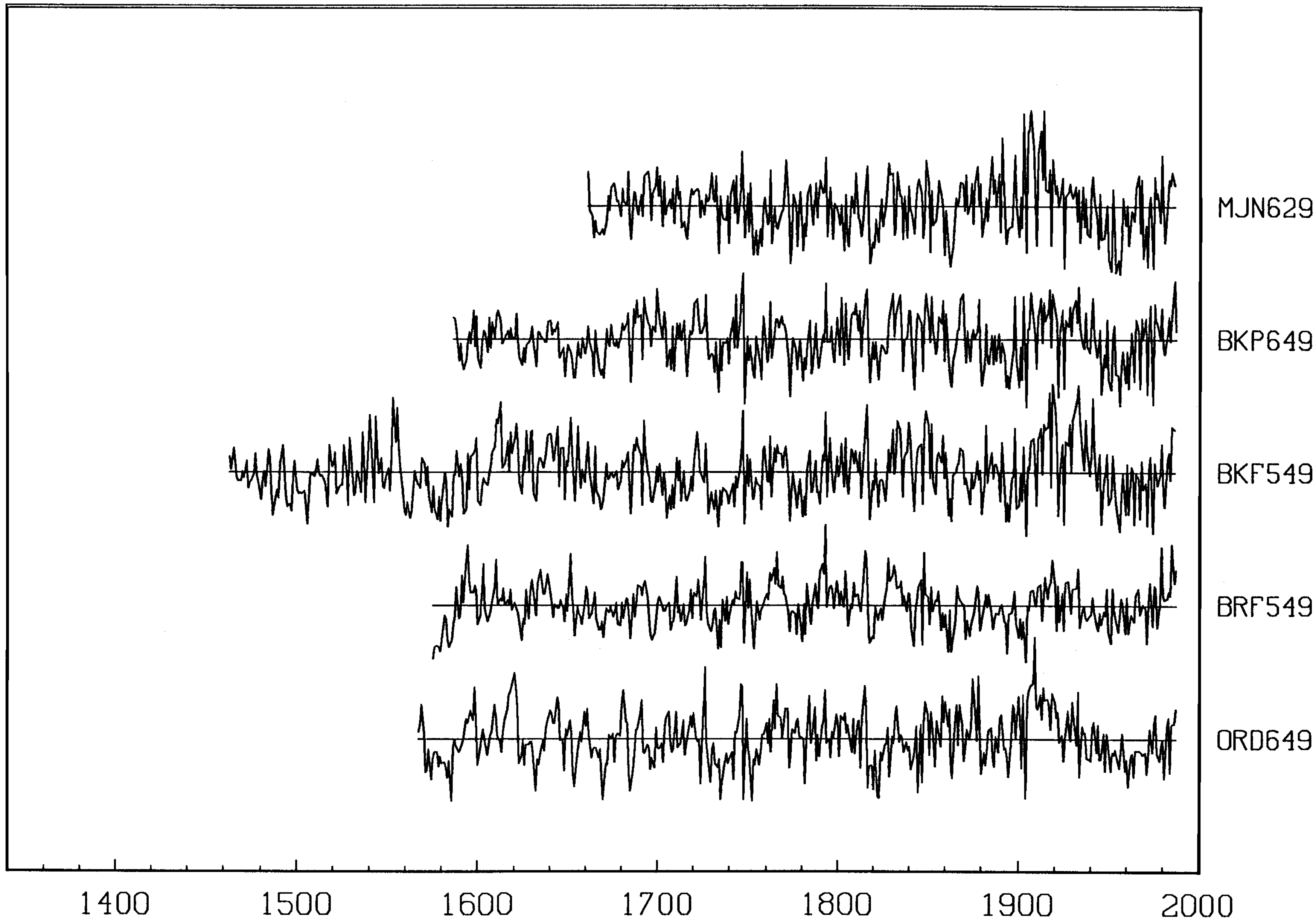
CHRONOLOGIES GMT, SRH, PCD, PST, NOO



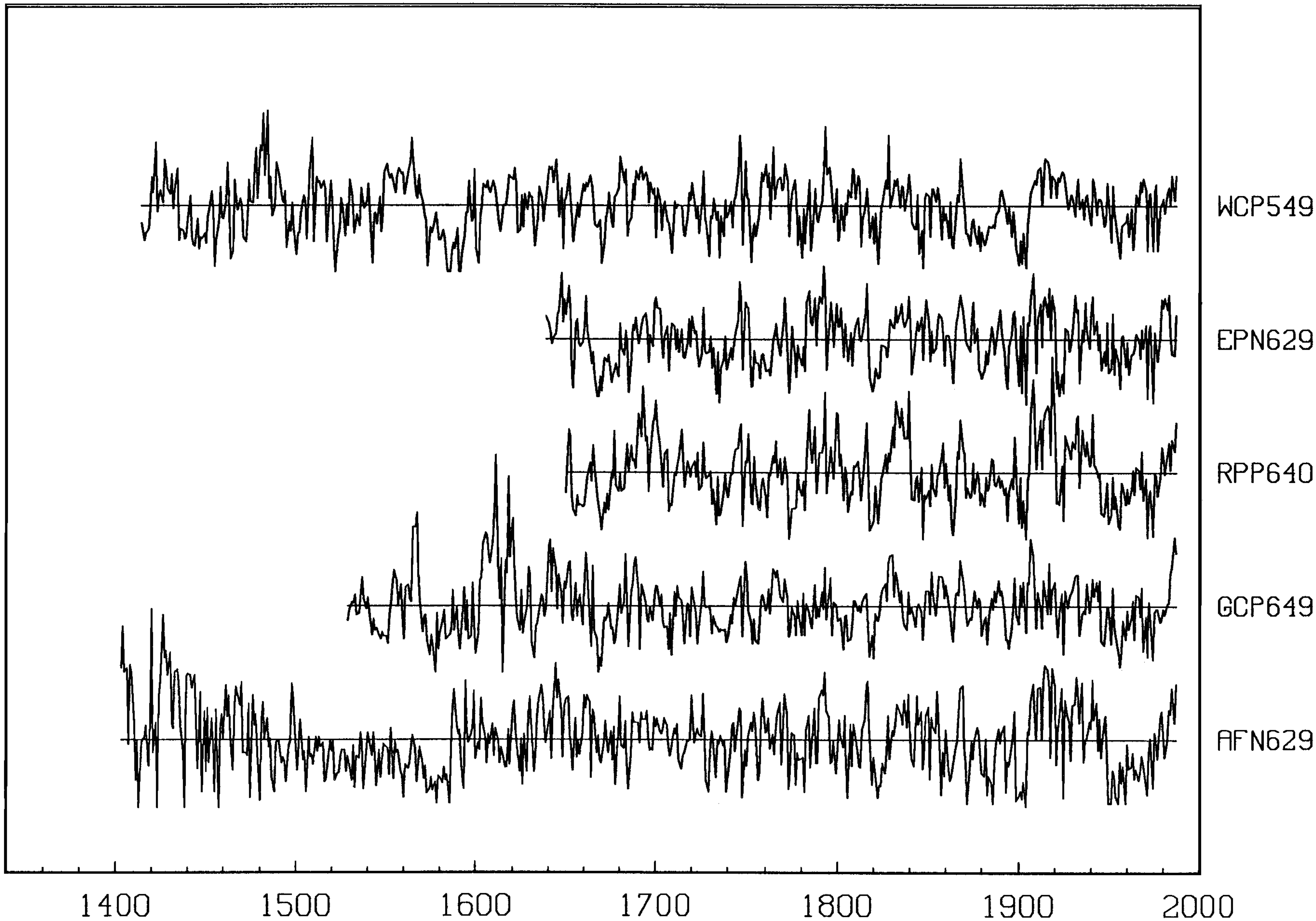
CHRONOLOGIES BCR,GMF,BWF, RCF, RPE



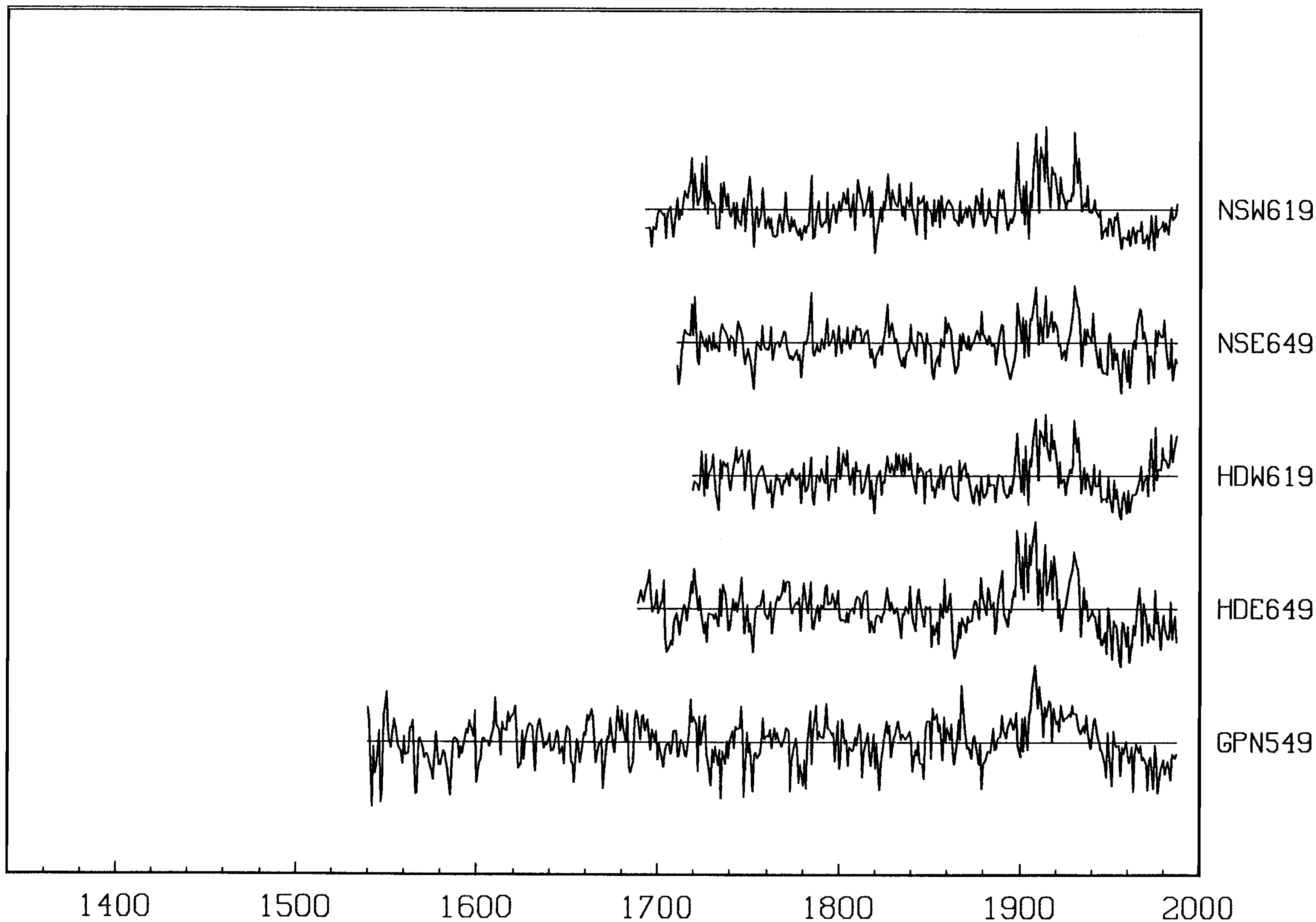
CHRONOLOGIES ORD, BRF, BKF, BKP, MJN



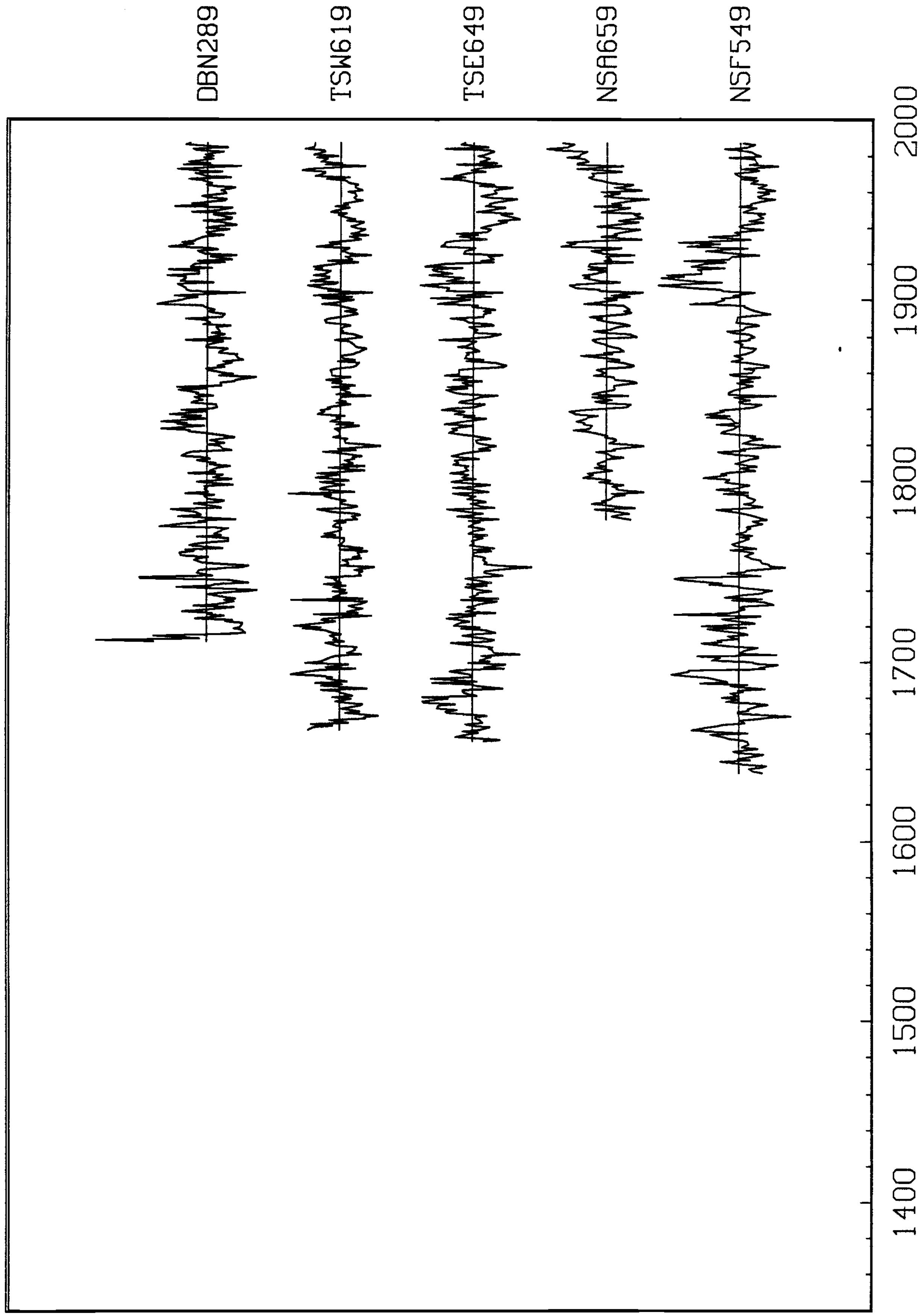
CHRONOLOGIES AFN, GCP, RPP, EPN, WCP



CHRONOLOGIES GPN, HDE, HDW, NSE, NSW



CHRONOLOGIES NSF, NSA, TSE, TSW, DBN



CHRONOLOGY MHP

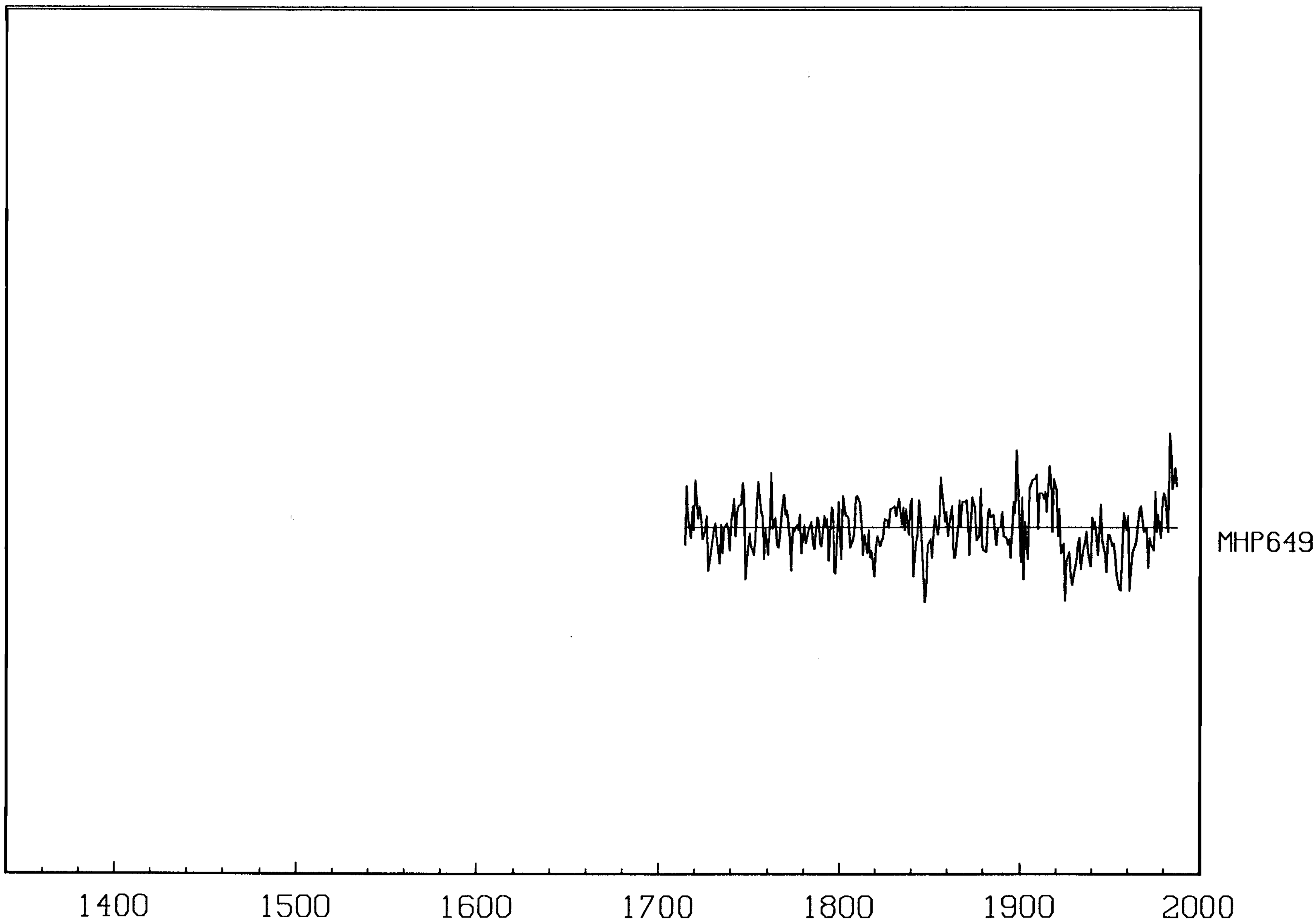


Figure 14. Locations of chronologies corresponding to entries in Table 1. A dark circle indicates a significant decrease in actual growth compared to predicted growth, while an open dot indicates a significant increase in actual growth over predicted growth. Applies to 1951 to 1986 period.

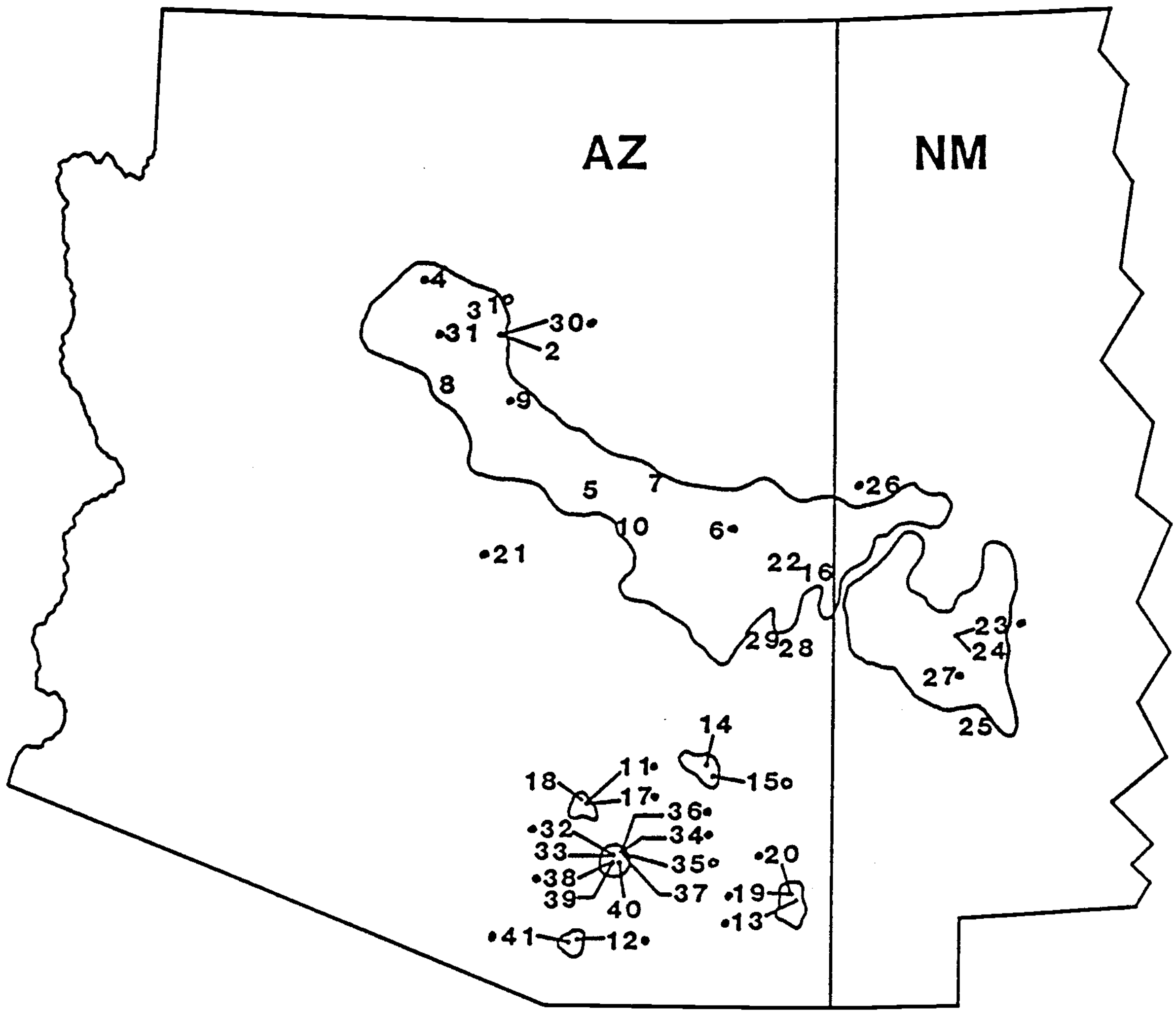
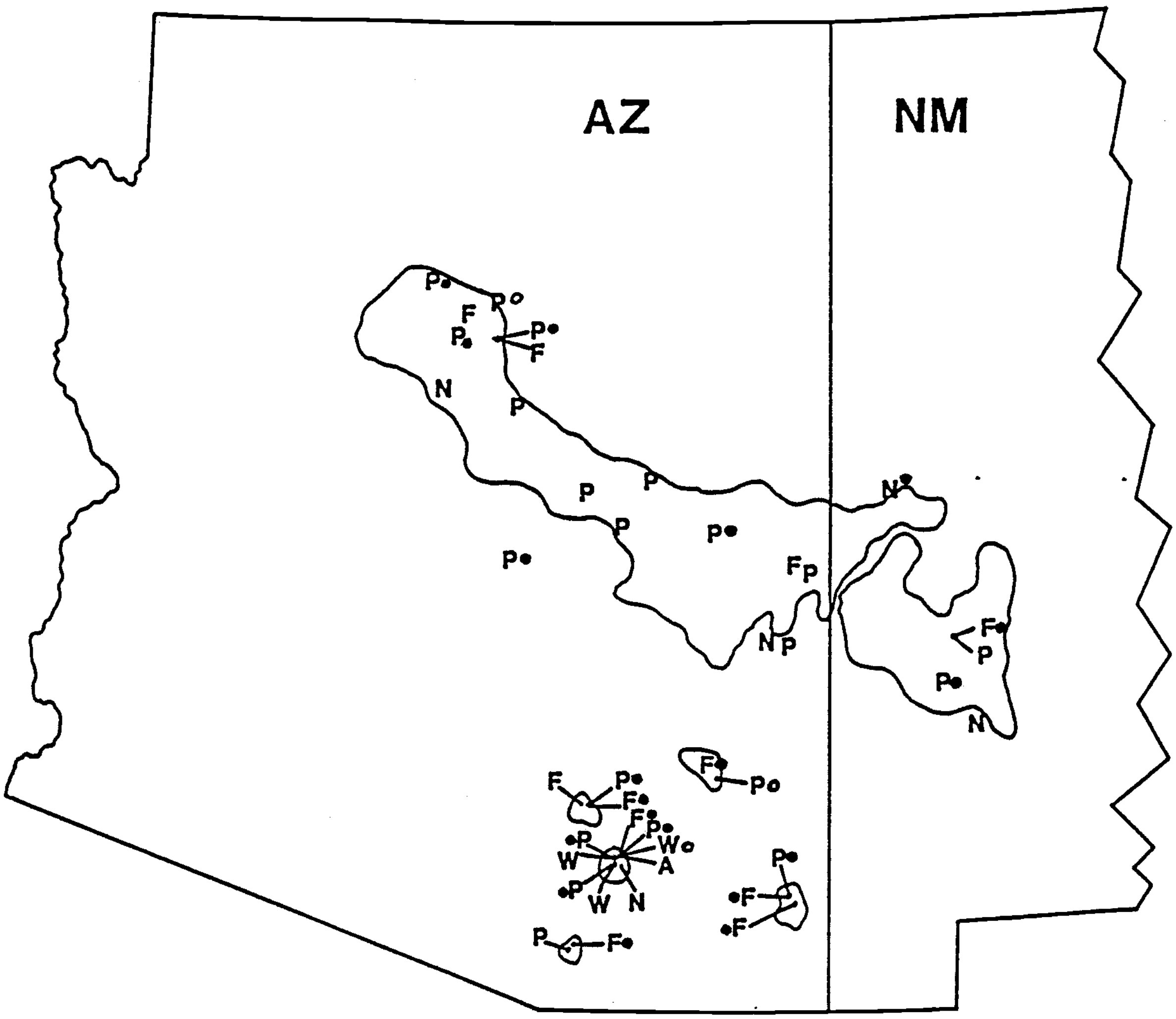


Figure 15. Locations of species corresponding to entries on Figure 14. A dark circle indicates a significant decrease in actual growth compared to predicted growth, while an open dot indicates a significant increase in actual growth over predicted growth. Applies to 1951 to 1986 period.



P - Ponderosa pine

F - Douglas fir

N - Pinyon pine

W - Southwestern white pine

A - White fir

Figure 16. Locations of chronologies corresponding to entries in Table 1. A dark circle indicates a significant decrease in actual growth compared to predicted growth, while an open dot indicates a significant increase in actual growth over predicted growth. Applies to 1961 to 1986 period.

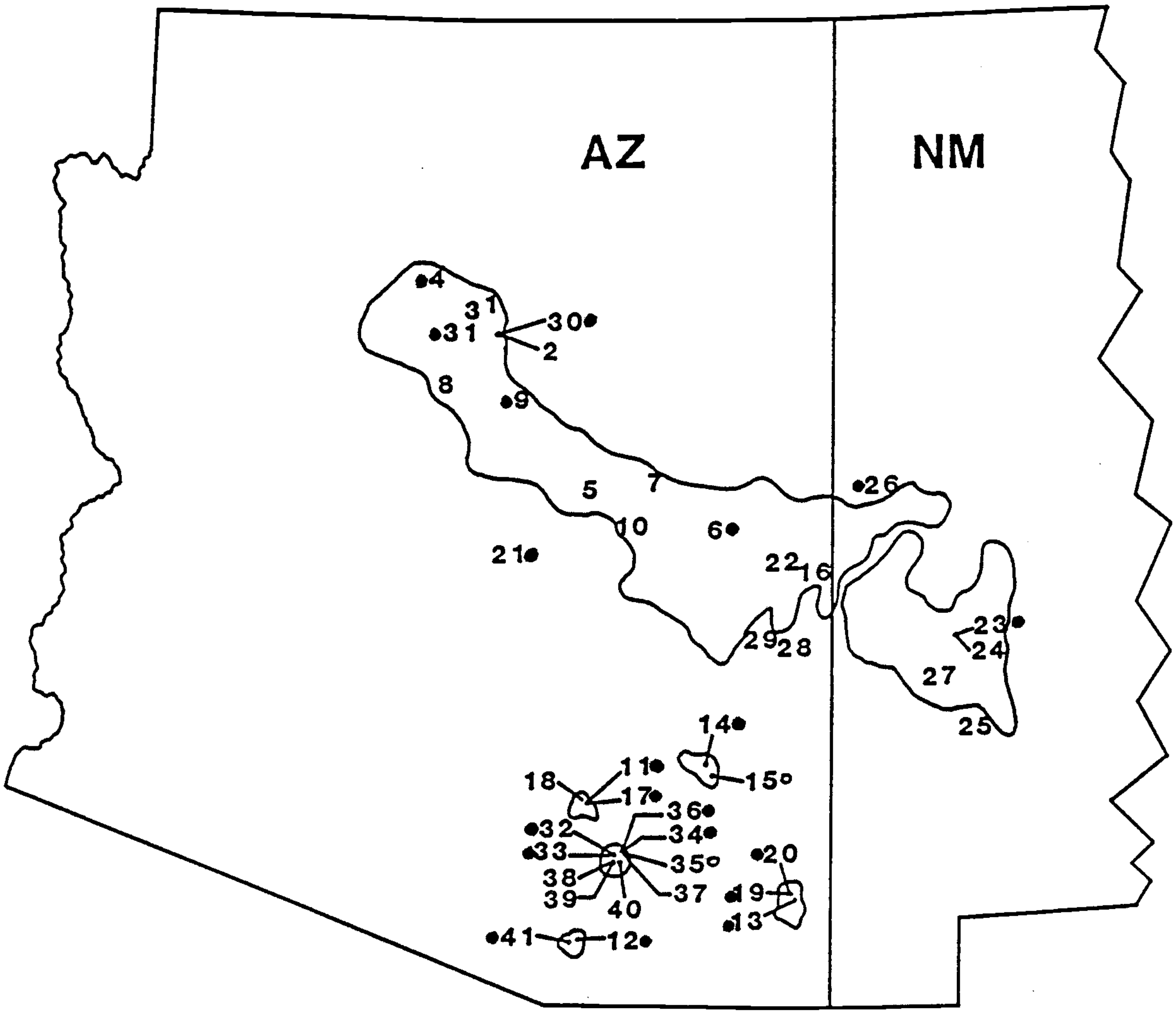
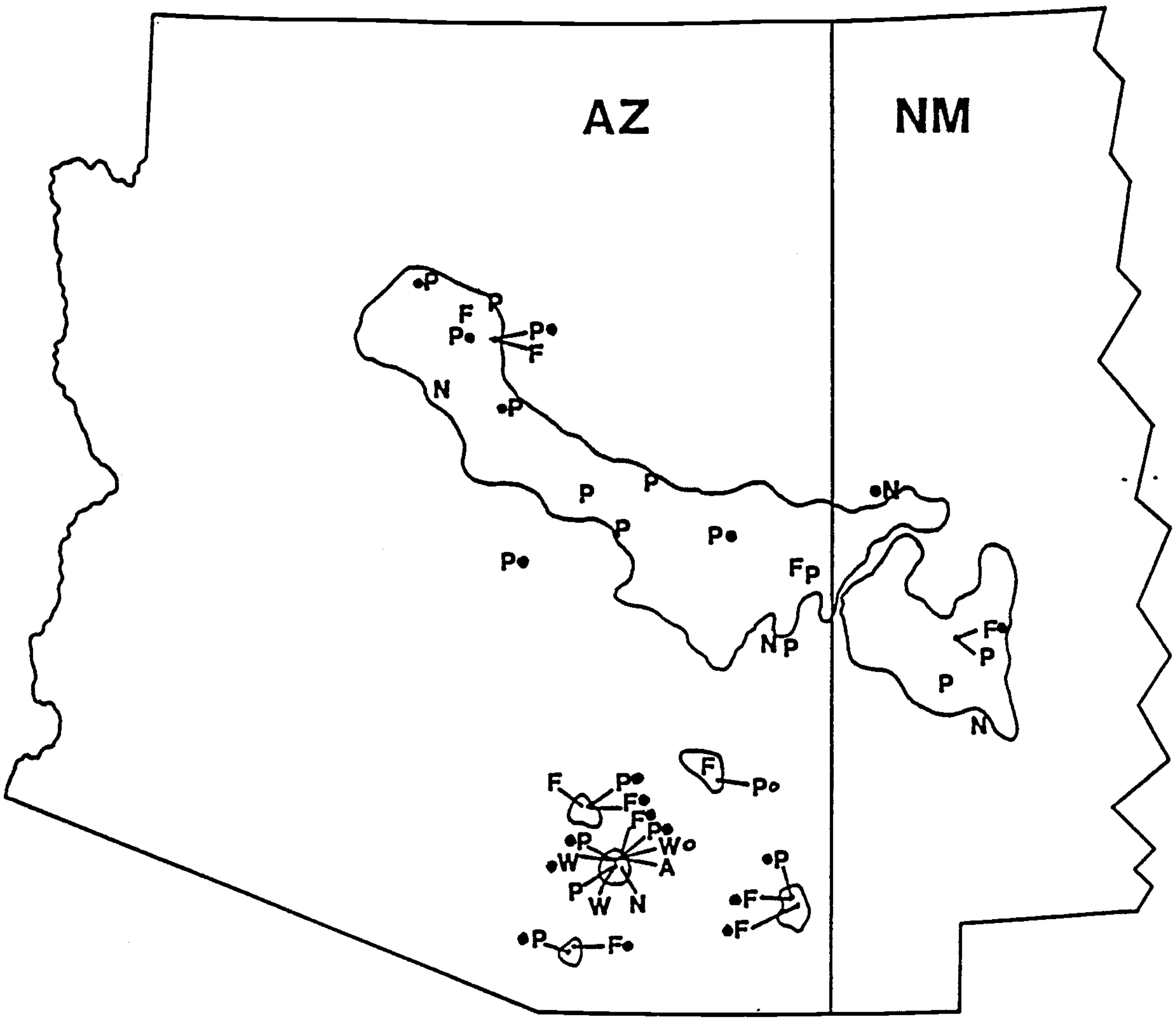


Figure 17. Locations of species corresponding to entries on Figure 16. A dark circle indicates a significant decrease in actual growth compared to predicted growth, while an open dot indicates a significant increase in actual growth over predicted growth. Applies to 1961 to 1986 period.



P - Ponderosa pine

F - Douglas fir

N - Pinyon pine

W - Southwestern white pine

A - White fir

15.0 Appendix 1. Site Attribute Information

Most of the categories pertaining to site descriptions on the following pages require no explanation. However, a brtief note on the soil classifications is included for general information.

Soil types specified here are based in part on generalized state and county soils maps. The mapping units reflect the major soil types found within each map unit and may or may not represent the actual soil series at each site.

The New Mexico series are based on maps prepared by New Mexico College of Agriculture and Mechanical Arts (1957) and by Maker and others (1974). The Arizona types were obtained from the Arizona General Soils Map (Jag and others 1983) and from the U.S. Soil Conservation Service soils maps of Arizona counties (Miller, 1969,1970; Miller and James 1967; Richmond 1971,1973a,1973b; Richardson 1971; Richardson and Miller 1974; Vogt and Richardson 1974; and Wendt 1969). For convenience these references are listed separately after the other references for this document.

Site Information

Site Name: Robinson Mountain (RMP)

Collection Date: 19 JUL 87

Species collected: *Pinus ponderosa*

Associated Species: Grass, thistles

State: AZ

County: Coconino

Latitude: 35°23'45"N

Longitude: 111°32'00"W

Elevation: 7200-7400'

Map reference: O'Leary Peak, AZ (USGS 7-1/2')

Slope Direction: NE-NW

Slope Angle: 45°

Parent Material(s) of soils: Basalt cinders

Soil Classification: Moderately deep, cold subhumid soil from cinders
Sponseller-Ess-Gordo Association

Site Information

Site Name: Walnut Canyon (WDF)

Collection Date: 20 JUL 87

Species collected: *Pseudotsuga menziesii*

Associated Species: *Pinus ponderosa, P. edulis, Robinia neomexicana, Juniperus, Quercus, Yucca*, grass

State: AZ

County: Coconino

Latitude: 35°10'N

Longitude: 111°31'W

Elevation: 6600-6700

Map reference: Flagstaff East, AZ (USGS 7-1/2')

Slope Direction: NW

Slope Angle: 35°-40°

Parent Material(s) of soils: Limestone

Soil Classification: Shallow, cool semiarid soil
Roundtop-Boysag Association

Site Information

Site Name: San Francisco Peaks (PDF)

Collection Date: 23 JUL 87

Species collected: *Pseudotsuga menziesii*

Associated Species: *Pinus strobiformis*, *P. ponderosa*, *Picea*, *Populus tremuloides*, shrubs

State: AZ

County: Coconino

Latitude: 35°19'N

Longitude: 111°43'30"W

Elevation: 8800'

Map reference: Humphrey's Peak, AZ (USGS 7-1/2')

Slope Direction: WNW

Slope Angle: 0-45°

Parent Material(s) of soils: Volcanic

Soil Classification: Shallow, cold subhumid soil
Sponseller-Ess-Gordo Association

Site Information

Site Name: Slate Mountain (SMP)

Collection Date: 22 JUL 87

Species collected: *Pinus ponderosa*

Associated Species: *Pinus edulis*, *Juniperus*, grass

State: AZ

County: Coconino

Latitude: 35°30'N

Longitude: 111°50'W

Elevation: 7200'

Map reference: Ebert Mtn, AZ (USGS 7-1/2')

Slope Direction: NE-NW

Slope Angle: 30°

Parent Material(s) of soils: Basalt

Soil Classification: Shallow, cold subhumid soil
Sponseller-Ess-Gordo Association

Site Information

Site Name: Mule Tank (MTP, MTD, MTY, MTT)

Collection Date: 27 JUL 87

Species collected: *Pinus ponderosa*

Associated Species: Grass, clover, composites, ferns, roses
No other tree species

State: AZ

County: Coconino

Latitude: 34°19'N

Longitude: 110°46'W

Elevation: 7550-7600'

Map reference: Woods Canyon, AZ (USGS 7-1/2')

Slope Direction: NW

Slope Angle: 0°-20°

Parent Material(s) of soils: Limestone

Soil Classification: Moderately deep, warm subhumid soil
Overgaard-Elledge-Telephone Association

Site Information

Site Name: Sitgreaves Gravel Pit (SGP)

Collection Date: 26 JUL 87

Species collected: *Pinus ponderosa*

Associated Species: *Quercus*, *Juniperus*, service berry, prickley pear, grass

State: AZ

County: Navajo

Latitude: 34°15'N

Longitude: 109°56'30"W

Elevation: 6800'

Map reference: Silver Springs, AZ (USGS 7-1/2')

Slope Direction: N-NE

Slope Angle: 30°-40°

Parent Material(s) of soils: Basalt

Soil Classification: Moderately deep, warm semiarid soil
Cabezon-Thunderbird-Springerville Association

Site Information

Site Name: Girl's Ranch (GRP)

Collection Date: 28 JUL 87

Species collected: *Pinus ponderosa*

Associated Species: *Juniperus*, *Quercus*, *Arctostaphylos*, *Rhus trilobata*, *Yucca*, grass, annuals

State: AZ

County: Navajo

Latitude: 34°23'30"N

Longitude: 110°25'W

Elevation: 6400-6520'

Map reference: Clay Springs, AZ (USGS 15')

Slope Direction: E-NW

Slope Angle: 0°-20°

Parent Material(s) of soils: Gravel of diverse composition

Soil Classification: Deep, gravelly, mesic subhumid soil
Soldier-Hogg-McVickers Association

Site Information

Site Name: Dry Creek (DCP)

Collection Date: 15-16 JUL 87

Species collected: *Pinus edulis*

Associated Species: *Cupressus arizonica, Juniperus, Arcostaphylos, Yucca,* berberis, grass, antelope bush

State: AZ

County: Yavapai

Latitude: 34°53′50″N

Longitude: 111°49′W

Elevation: 4480-4560′

Map reference: Wilson Mtn, AZ (USGS 7-1/2′)

Slope Direction: SW-NE

Slope Angle: 0°-45°

Parent Material(s) of soils: Sandstone, siltstone

Soil Classification: Shallow, cool semiarid soil
Tortugas-Purner-Jacks Association

Site Information

Site Name: Rocky Gulch (RGP)

Collection Date: 25 JUL 87

Species collected: *Pinus ponderosa*

Associated Species: *Quercus*, *Juniperus deppeana*, *Yucca*, cacti, grass, annuals

State: AZ

County: Coconino

Latitude: 34°43'45"N

Longitude: 111°30'30"W

Elevation: 6400-6500'

Map reference: Apache Maid Mtn, AZ (USGS 7-1/2')

Slope Direction: S-SW

Slope Angle: 20°-45°

Parent Material(s) of soils: Basalt, Limestone

Soil Classification: Shallow, cool semiarid soil
Cabezon-Thunderbird-Springerville Association

Site Information

Site Name: Grasshopper (GRS)

Collection Date: JUN 86

Species collected: *Pinus ponderosa*

Associated Species: *Quercus*, *Juniperus*, *Pinus edulis*, grass

State: AZ

County: Navajo

Latitude: 34°04'N

Longitude: . 110°37'W

Elevation: 5900'

Map reference: Chediski Peak

Slope Direction: NW-NE

Slope Angle: 0°-10°

Parent Material(s) of soils: Limestone

Soil Classification: Shallow to moderately deep, cool subhumid soil
Roundtop-Tortugas-Jacks Association

Site Information

Site Name: Green Mountain (GMT, GMF)

Collection Date: 15 NOV 86; 2, 21 APR 87, 6 MAY 87

Species collected: *Pinus ponderosa*, *Pseudotsuga menziesii*

Associated Species: *Pinus strobiformis*, *Quercus hypoleucoides*

State: AZ

County: Pima

Latitude: 32°23'30"N

Longitude: 110°41'30"W

Elevation: 7200'

Map reference: Mt. Bigelow, AZ (USGS 7-1/2')

Slope Direction: W

Slope Angle: 10°-25°

Parent Material(s) of soils: Granite, granite gneiss

Soil Classification: Shallow, cold Subhumid soil
Mirabal-Rock Outcrop Association

Site Information

Site Name: Santa Rita (SRH)

Collection Date: 28 APR 87

Species collected: *Pseudotsuga menziesii*

Associated Species: *Pinus ponderosa, Quercus gambelii*

State: AZ

County: Santa Cruz

Latitude: 31°43'30"N

Longitude: 110°50'45"W

Elevation: 7450-8300'

Map reference: Mt. Wrightson, AZ (USGS 7-1/2')

Slope Direction: East

Slope Angle: 20°-30°

Parent Material(s) of soils: Rhyolite

Soil Classification: Shallow, rocky, subhumid mountainous soil
Faraway-Barkerville Association

Site Information

Site Name: Pinery Canyon (PCD)

Collection Date: 19-21 AUG 87

Species collected: *Pseudotsuga menziesii*

Associated Species: *Pinus engelmannii*, *P. strobiformis*, *P. cembroides*, *Juniperus*, *Quercus* (Apache pine)

State: AZ

County: Cochise

Latitude: 31°56′

Longitude: 109°16′

Elevation: 7500′

Map reference: Rustler Park, AZ (USGS 7-1/2′)

Slope Direction: W to N

Slope Angle: 25°-30°N

Parent Material(s) of soils: Rhyolite

Soil Classification: Shallow mountainous soil
Luzena-Faraway Association

Site Information

Site Name: Post Creek (PST)

Collection Date: 12 JUN 87

Species collected: *Pseudotsuga menziesii*

Associated Species: *Pinus strobiformis, Abies concolor, Populus tremuloides, Picea, Acer*

State: AZ

County: Graham

Latitude: 32°41'30"N

Longitude: 109°53'45"W

Elevation: 8800-9120'

Map reference: Webb Peak, AZ (USGS 7-1/2')

Slope Direction: W

Slope Angle: 25°

Parent Material(s) of soils: Granitic

Soil Classification: Warm, subhumid mountainous soil, shallow
Barkerville-Moano-Faraway Association

Site Information

Site Name: Noon Creek Ridge (NOO)

Collection Date: 21 OCT 87

Species collected: *Pinus ponderosa*

Associated Species: *Pseudotsuga menziesii, Abies concolor, Quercus*

State: AZ

County: Graham

Latitude: 32°39'N

Longitude: 109°49'50"W

Elevation: 7700'

Map reference: Mt. Graham, AZ (USGS 7-1/2')

Slope Direction: E & S

Slope Angle: 20°-30°

Parent Material(s) of soils: Granitic

Soil Classification: Warm, subhumid mountainous soil, shallow Barkerville-Moano-Faraway Association

Site Information

Site Name: Beaver Creek (BCR)

Collection Date: 24 SEP 87

Species collected: *Pinus ponderosa*

Associated Species: --

State: AZ

County: Greenlee

Latitude: 33°42'30"N

Longitude: 109°14'30"W

Elevation: 7850'

Map reference: Blue AZ-NM (USGS 15')

Slope Direction: SW

Slope Angle: 10°-30°

Parent Material(s) of soils: Basalt

Soil Classification: Cold, Humid soil, shallow
Sponseller-Ess-Fluventic Camborthids Association

Site Information

Site Name: Bear Wallow (BWF)

Collection Date: 10, 17 SEP 87

Species collected: *Pseudotsuga menziesii*

Associated Species: *Abies concolor, Pinus ponderosa, P. strobiformis, Robinia neomexicana*

State: AZ

County: Pima

Latitude: 32°25'N

Longitude: 110°44'W

Elevation: 8000-8300'

Map reference: Mt. Bigelow, AZ (USGS 7-1/2')

Slope Direction: W, NW

Slope Angle: 15°-20°

Parent Material(s) of soils: Gneiss, metasediments

Soil Classification: Shallow, cold subhumid soil
Mirabal-Rock Outcrop Association

Site Information

Site Name: Rhyolite Canyon (RCF, RPE, RPT)

Collection Date:

Species collected: *Pseudotsuga menziesii, Pinus ponderosa*

Associated Species:

State: AZ

County: Cochise

Latitude: 32°0'N

Longitude: 109°20'W

Elevation: 6000'

Map reference: Cochise Head, AZ (USGS 7-1/2')

Slope Direction:

Slope Angle:

Parent Material(s) of soils: Rhyolite

Soil Classification: Shallow mountainous soil
Luzena-Faraway Association

Site Information

Site Name: Ord Mountain (ORD, ORE, ORT)

Collection Date: 8 OCT 87

Species collected: *Pinus ponderosa*

Associated Species: *Juniperus deppeana, Quercus*

State: AZ

County: Gila

Latitude: 33°54'N

Longitude: 111°24'30"W

Elevation: 7000'

Map reference: Reno Pass (USGS 7-1/2')

Slope Direction: N

Slope Angle: 20°

Parent Material(s) of soils: Granitic intrusives, schist

Soil Classification: Shallow, cool subhumid soil
Barkerville-Moano-Faraway Association

Site Information

Site Name: Black River (BRF)

Collection Date: 22-24 OCT 87

Species collected: *Pseudotsuga menziesii*

Associated Species: *Pinus ponderosa*, *Picea*, *Pinus strobiformis*, *juniperus communis*, grasses rose, *Ribes*

State: AZ

County: Apache

Latitude: 33°48'N

Longitude: 109°19'W

Elevation: 8000'

Map reference: Big Lake, AZ (USGS 15')

Slope Direction: S30°W

Slope Angle: 25°

Parent Material(s) of soils: Basalt

Soil Classification: Little or no soil present at all. Trees growing on steep basalt boulder slide area or on bare bedrock outcrops.

Site Information

<u>Site Name</u>: Black Mountain (BKP, BKF)

<u>Collection Date</u>: Summer 1987

<u>Species collected</u>: *Pinus ponderosa, Pseudotsuga menziesii*

<u>Associated Species</u>: *Quercus gambeli, Pinus strobiformis, Abies concolor, Juniperus deppeana, Populus tremuloides*

<u>State</u>: NM

<u>County</u>: Catron

<u>Latitude</u>: 33°23'

<u>Longitude</u>: 108°14'

<u>Elevation</u>: 8400'-9300'

<u>Map reference</u>: Black Mtn, NM (USGS 7-1/2')
Burnt Corral Canyon, NM (USGS 7-1/2')

<u>Slope Direction</u>: S to SW

<u>Slope Angle</u>: 0-45°

<u>Parent Material(s) of soils</u>: Basalt

<u>Soil Classification</u>: Mountainous shallow soil; bouldery
Argiborolls-Cryoborolls-Usorthents

Site Information

Site Name: Mimbres Junction (MJN)

Collection Date: 4 OCT 87

Species collected: *Pinus edulis*

Associated Species: *Juniperus deppeana, Pinus ponderosa, Agave*

State: NM

County: Grant

Latitude: 32°57'30"N

Longitude: 108°01'W

Elevation: 6400'

Map reference: Allie Canyon (USGS 7-1/2')

Slope Direction: SW to SE

Slope Angle: 20°-60°

Parent Material(s) of soils: Gila conglomerate

Soil Classification: Shallow, light-textured soils & rock outcrops
Haplustolls-Argiustolls-Rockland

Site Information

Site Name: Agua Fria Creek (AFN)

Collection Date: 6 OCT 87

Species collected: *Pinus edulis*

Associated Species: Grass, juniper, cacti, yucca

State: NM

County: Catron

Latitude: 34°13'40"N

Longitude: 108°37'29"W

Elevation: 7300'

Map reference: Largo Mesa, NM (USGS 7-1/2')

Slope Direction: N, S, W

Slope Angle: 0°-10°

Parent Material(s) of soils: Sandstone

Soil Classification: Medium-textured, moderately deep Haplargids

Site Information

Site Name: Gila Cliff Dwelling (GCP)

Collection Date: 3 OCT 87

Species collected: *Pinus ponderosa*

Associated Species:

State: NM

County: Catron

Latitude: 33°13'35"N

Longitude: 108°16'W

Elevation: 5800'

Map reference: Little Turkey Park, NM (USGS 7-1/2')

Slope Direction: NW

Slope Angle: 20°-40°

Parent Material(s) of soils: Sandstone

Soil Classification: Mountainous shallow soil & rock outcrops
Haplustolls-Argiustolls-Rocklands

Site Information

<u>Site Name</u>: Rose Peak (RPP)

<u>Collection Date</u>: 19 NOV 87

<u>Species collected</u>: *Pinus ponderosa*

<u>Associated Species</u>: *Pinus edulis, Juniperus, Quercus, Juglans, Nolina, Yucca*

<u>State</u>: AZ

<u>County</u>: Greenlee

<u>Latitude</u>: 33°25'N

<u>Longitude</u>: 109°22'W

<u>Elevation</u>: 7600'

<u>Map reference</u>: Rose Peak, AZ (USGS 7-1/2')

<u>Slope Direction</u>: NE

<u>Slope Angle</u>: 28°-40°

<u>Parent Material(s) of soils</u>: Basalt

<u>Soil Classification</u>: Very warm semi-arid soil, shallow
Cabezon-Thunderbird-Apache Association

Site Information

Site Name: Eagle Creek (EPN)

Collection Date: 20 NOV 87

Species collected: *Pinus edulis*

Associated Species: *Juniperus*, *Quercus*, *Yucca*, *Cercocarpus*, cactus, grasses

State: AZ

County: Greenlee

Latitude: 33°28'N

Longitude: 109°29'W

Elevation: 5560

Map reference: Robinson Mesa, AZ (USGS 7-1/2')

Slope Direction: South & East

Slope Angle: 11°

Parent Material(s) of soils: Basalt

Soil Classification: Very warm semi-arid soil, shallow
Springerville-Cabezon-Ziegler Association

Site Information

Site Name: Walnut Canyon (WCP)

Collection Date: OCT 87

Species collected: *Pinus ponderosa*

Associated Species:

State: AZ

County: Coconino

Latitude: 35°10'N

Longitude: 111°31'W

Elevation: 6750'

Map reference: Flagstaff East, AZ (USGS 7-1/2')

Slope Direction: Flat

Slope Angle: 0

Parent Material(s) of soils: Limestone

Soil Classification: Shallow, cool semi-arid soil

Site Information

Site Name: Gus Pearson Natural Area (GPN, O, Y)

Collection Date: 5-6 NOV 87

Species collected: *Pinus ponderosa*

Associated Species: Pure ponderosa stand

State: AZ

County: Coconino

Latitude: 35°16'N

Longitude: 111°45'W

Elevation: 7400'

Map reference: Wing Mtn, AZ (USGS 7-1/2')
Humphreys Peak, AZ (USGS 7-1/2')

Slope Direction: Level

Slope Angle: Level - 5°

Parent Material(s) of soils: Basalt

Soil Classification: Moderately deep, cold, subhumid soil
Sponseller-Ess-Gordo Association

Site Information

Site Name: Helen's Dome (HDW, HDE, HDT)

Collection Date: 10 NOV 87

Species collected: *Pinus ponderosa*, *Pinus strobiformis*

Associated Species: *Quercus*, shrubs

State: AZ

County: Pima

Latitude: 32°13'N

Longitude: 110°33'30"W

Elevation: 8280-8360

Map reference: Mica Mtn, AZ (USGS 7-1/2')

Slope Direction: W, SW

Slope Angle: Flat to >25°

Parent Material(s) of soils: Gneiss

Soil Classification: Shallow, cool subhumid soil
Rock Outcrop-Barkerville-Faraway Association

Site Information

<u>Site Name</u>: North Slope (NSF, NSW, NSA, NSE, NST)

<u>Collection Date</u>: 11 NOV 87

<u>Species collected</u>: *Pseudotsuga menziesii*, *Pinus ponderosa*, *P. strobiformis*, *Abies concolor*

<u>Associated Species</u>: *Quercus gambelii*

<u>State</u>: AZ

<u>County</u>: Pima

<u>Latitude</u>: 32°13'30"N

<u>Longitude</u>: 110°33'W

<u>Elevation</u>: 7960-8040

<u>Map reference</u>: Mica Mtn, AZ (USGS 7-1/2')

<u>Slope Direction</u>: N, NE, NW

<u>Slope Angle</u>: Flat - >30°

<u>Parent Material(s) of soils</u>: Gneiss

<u>Soil Classification</u>: Shallow, cool subhumid soil
Rock Outcrop-Barkerville-Faraway Association

Site Information

Site Name: Tucson Side (TSW, TSE, TST)

Collection Date: 12 NOV 87

Species collected: *Pinus Ponderosa, P. strobiformis*

Associated Species: *Quercus hypoleucoides, Q. arizonica*, shrubs

State: AZ

County: Pima

Latitude: 32°12'20"N

Longitude: 110°33'45"W

Elevation: 7640-7880

Map reference: Mica Mtn, AZ (USGS 7-1/2')

Slope Direction: SW, SE, NE

Slope Angle: 5°-35°

Parent Material(s) of soils: Gneiss

Soil Classification: Shallow, cool subhumid soil
Rock Outcrop-Barkerville-Faraway Association

Site Information

Site Name: Devil's Bathtub (DBN)

Collection Date: 12 NOV 87

Species collected: *Pinus cembroides*

Associated Species: *Juniperus deppeana*, *Quercus*, *Yucca bacata*, *Arctostaphylos pungens*

State: AZ

County: Pima

Latitude: 32°12'N

Longitude: 110°33'W

Elevation: 7500'

Map reference: Mica Mtn, AZ (USGS 7-1/2')

Slope Direction: S

Slope Angle: 5-20°

Parent Material(s) of soils: Gneiss

Soil Classification: Shallow, cool subhumid soil
Rock Outcrop-Barkerville-Faraway Association

Site Information

Site Name: Mt. Hopkins (MHP)

Collection Date: 3 MAY 88

Species collected: *Pinus ponderosa*

Associated Species: *Pinus strobiformis, Quercus, Juniperus, deppeana*

State: AZ

County: Santa Cruz

Latitude: 31°42'N

Longitude: 111°52'W

Elevation: 7000'

Map reference: Mt. Hopkins, AZ (USGS 7-1/2')

Slope Direction: N

Slope Angle: 15°-30°

Parent Material(s) of soils: Granite

Soil Classification: Shallow, rocky, subhumit mountainous soil
Faraway-Barkerville Association

SOILS REFERENCES

Jay, J. E., Y. H. Havens, D. M. Hendricks, D. F. Post, and C. W. Guernsey.
1983 Arizona General Soils Map. National Cooperative Soil Survey, U. S. Department of Agriculture Soil Conservation Service, and University of Arizona Agriculture Experiment Station.

Maker, H. J., H. E. Dregne, V. G. Link, and J. U. Anderson
1974 Soils of New Mexico, with General Soil Map of New Mexico. New Mexico State University, Agricultural Experiment Station Report 285.

Miller, M. L.
1969 General Soil Map, Navajo County, Arizona. U.S.D.A. Soil Conservation Service.

Miller, M. L.
1970 General Soil Map, Apache County, Arizona. U.S.D.A. Soil Conservation Service.

Miller, M. L, and M. S. James
1967 General Soil Map, Coconino County, Arizona. U.S.D.A. Soil Conservation Service.

Richmond, D. L.
1971 General Soil Map, Cochise County, Arizona, U.S.D.A. Soil Conservation Service.

Richmond, D. L.
1973a General Soil Map, Greenlee County, Arizona, U.S.D.A. Soil Conservation Service.

Richmond, D. L.
1973b General Soil Map, Graham County, Arizona, U.S.D.A. Soil Conservation Service.

Richardson, M. L.
1971 General Soil Map, Santa Cruz County, Arizona, U.S.D.A. Soil Conservation Service.

Richardson, M. L., and M. L. Miller
1974 General Soil Map, Pima County, Arizona, U.S.D.A. Soil Conservation Service.

Vogt, K. D., and M. L. Richardson
1974 General Soil Map, Gila County, Arizona, U.S.D.A. Soil Conservation Service.

Wendt, G. E.
1969 General Soil Map, Yavapai County, Arizona, U.S.D.A. Soil Conservation Service.

New Mexico College of Agriculture and Mechanical Arts
1957 Soils Resource Map of New Mexico. Agricultural Experiment Station.

16.0 REFERENCES CITED

Arizona Department of Economic Security
1983 Arizona Occupational Profile. Arizona Department of Economic Security, Phoenix.

Avery, C. C., F. R. Larson, and G. H. Shubert
1976 Fifty-Year Records of Virgin Stand Development in Southwestern Ponderosa Pine. U. S. Forest Service, General Technical Report RM-22.

Baillie, M. G. L.
1982 Tree-Ring Dating and Archaeology. University of Chicago Press.

Bannister, B.
1969 Dendrochronology. In Science in Archaeology, ed. by D. Brothwell, E. Higgs and G. Clark, pp. 191-205. Thames and Hudson.

Beschta, R. L.
1976 Climatology of the Ponderosa Pine Type in Central Arizona. Agriculture Experiment Station Technical Bulletin 228. University of Arizona, Tucson.

Biondi, F., T. W. Swetnam
1987 Box-Jenkins Models of Forest Interior Tree-Ring Chronologies. Tree-Ring Bulletin, Vol. 47, pp. 71-96, Laboratory of Tree-Ring Research, University of Arizona, Tucson.

Box, G. E. P., and G. M. Jenkins
1976 Time Series Analysis: Forecasting and Control. Holden-Day, San Francisco.

Bryson, R. A.
1957 "The annual march of precipitation in Arizona, New Mexico and northwestern Mexico". University of Arizona Institute of Atmospheric Physics, Technical Reports on the Meteorology and Climatology of Arid Regions 6. Tucson, University of Arizona.

Chatfield, C.
1980 The Analysis of Time Series, 2nd ed. Chapman and Hall, London.

Cogbill, C. V.
1977 The Effect of Acid Precipitation on Tree Growth in Eastern North America. Water, Air, and Soil Pollution 8(1977):89-93.

Cook, E. R.
1985a A Time Series Analysis Approach to Tree-Ring Standardization. Unpublished Ph.D. Dissertation. University of Arizona, Tucson.

Cook, E. R.
1985b The Use and Limitations of Dendrochronology in Studying Effects of Air Pollution on Forests. Proceedings of NATO Advanced Research Workshop: Effects of Acidic Deposition on Forests, Wetlands, and Agricultural Ecosystems. 12-17 May, 1985, Toronto, Canada.

Cook, E. R., A. H. Johnson and T. J. Blasing
1986 Modelling the Climate Effect in Tree Rings for Forest Decline Studies. Paper presented at the Ninth North American Forest Biology Workshop, June, 1986, Oklahoma State University, Stillwater.

Cook, E. R.
1987 On the Decomposition of Tree-Ring Series for Environmental Studies. Tree-Ring Bulletin, Vol. 47, pp. 37-59. Laboratory of Tree-Ring Research, University of Arizona, Tucson.

Cook, R. D.
1977 Detection of Influential Observations in Linear Regression. Technometrics 19:15-18.

Cropper, J. P.
1982 Climate reconstructions from tree rings: comment. In Climate from Tree-Rings, M. K. Hughes, P. M. Kelly, J. R. Pilcher and V. C. LaMarche, Jr., eds, pp. 65-67, Cambridge University Press.

DeWitt, E. and M. Ames
1978 Tree-Ring Chronologies of Eastern North America, Chronology Series IV, Vol. 1, Laboratory of Tree-Ring Research, University of Arizona, Tucson.

Dixon, W. J. (Ed.)
1985 BMDP Statistical Software. University of California Press, Berkeley.

Douglas, A. V. and H. C. Fritts
1973 Tropical cyclones of the eastern North Pacific and their effects on the climate of the western United States. Final Report NOAA Contract 1-35241, Laboratory of Tree-Ring Research, University of Arizona, Tucson.

Draper, N., and H. Smith
1981 Applied Regression Analysis (2nd ed.). Wiley, New York.

Dunning, C. H. and E. H. Peplow, Jr.
1959 Rock to Riches. Southwest Publishing Co., Phoenix.

Eckstein, D., R. W. Aniol, and J. Bauch
1983 Dendroklimatologische Untersuchgen zum Tannensterben. European Journal of Forest Pathology 13:279-288.

Eckstein, D., K. Richter, R. W. Aniol, and F. Quiehl
1984 Dendroklimatologische Untersuchungen zum Buchensterben im sudwestlichen Vogelsberg. Forstwiss., Centralblatt 103:274-290.

Fritts, H. C.
1976 Tree Rings and Climate. Academic Press, London.

Fritts, H. C., D. G. Smith and M. A. Stokes
1965 The Biological Model for Paleoclimatic Interpretation of Mesa Verde Tree-Ring Series. American Antiquity 31(2)(Part 2):101-121.

Fritts, H. C. and T. W. Swetnam
1986 Dendroecology: A Tool for Evaluating Variations in Past and Present Forest Environments. Utility Air Regulatory Group, Acid Deposition Committee, Washington D. C. Hunton and Williams, Washington D. C.

Gibbons, J.D.
1976 Nonparametric Methods for Quantitative Analysis. American Sciences Press, Inc, Columbus, Ohio.

Graybill, D. A.
1979a Program Operating Manual for RWLIST, INDEX and SUMAC. Laboratory of Tree-Ring Research, University of Arizona, Tucson.

Graybill, D. A.
1979b Revised Computer Programs for Tree-Ring Research. Tree-Ring Bulletin 39:77-82.

Graybill, D. A.
1982 Chronology Development and Analysis. In Climate from Tree Rings, ed. by M. K. Hughes, P. M. Kelly, J. R. Pilcher, and V. C. LaMarche, Jr., pp. 21-28. Cambridge University Press, London.

Graybill, D. A.
1985 Western U. S. Tree Ring Index Chronology Data for Detection of Arboreal Response to Increasing Carbon Dioxide. No. 026 in the U. S. Department of Energy Green Book Reports on the Response of Vegetation to Carbon Dioxide series. Laboratory of Tree-Ring Research, University of Arizona, Tucson.

Graybill, D. A.
1986 The Reconstruction of Prehistoric Salt River Streamflow. Chapter 3 in The 1982-1984 Excavations at Las Colinas, Environment and Subsistence, ed. by C. A. Heathington and D. A. Gregory. Archaeological Series 162, Volume 5, Part 1, Cultural Resource Management Division, Arizona State Museum, University of Arizona, Tucson.

Graybill, D. A.
1987 A Network of High-Elevation Conifers in the Western United States for Detection of Tree-Ring Growth Response to Increasing Carbon Dioxide. Submitted for publication in a volume of proceedings of The International Symposium on Ecological Aspects of Tree-Ring Analysis, a meeting held in Palisades, New York, August 17-21, 1986.

Graybill, Donald A. and Thomas W. Swetnam
1987 Analysis of Growth Trends and Variation in Conifers from Central Arizona, Proposed Request for Federal Assistance from the U.S. EPA, Environmental Research Laboratories, Corvalis, Oregon. Laboratory of Tree-Ring Research, University of Arizona, Tucson.

Graybill, F. A.
1976 Theory and Application of the Linear Model. Duxbury Press, Scituate, Mass.

Green, Christine R. and William D. Sellers
1964 Arizona Climate. Tucson, University of Arizona Press.

Gunst, R. F. and R. L. Mason
1980 Regression Analysis and its Applications. Marcel Dekker, New York.

Hales, J. E.
1974 Southwestern United States summer monsoon source -- Gulf of Mexico or Pacific Ocean? Journal of Applied Meteorology 13:331-342.

Hirschbock, K. K.
1985 Hydroclimatology of Flow Events in the Gila River Basin, Central and Southern Arizona. M.S. Doctoral dissertation, University of Arizona, Tucson.

Hoff, J. C.
1983 A Practical Guide to Box-Jenkins Forecasting. Wadsworth, London.

Hughes, M. K., P. M. Kelly, R. J. Pilcher, and V. C. LaMarche,
1982 Jr. Climate from Tree-Rings. Cambridge University Press, Cambridge.

Hornbeck, J. W. and R. B. Smith
1985 Documentation of Red Spruce Growth Decline. Canadian Journal of Forest Research, 15:1199-1201.

Johnson, A. H., E. R. Cook, and T. G. Siccama
1988 "Climate and red spruce growth and decline in the northern Appalachians", Proceedings of the National Academy of Science, USA, Volume 85, Applied Biology, Washington, D. C.

LaMarche, V. C., Jr.
1982 Sampling Strategies, in Climate from Tree-Rings ed. by M. K. Hughes, P. M. Kelly, J. R. Pilcher and V. C. LaMarche, Jr., pp. 2-6. Cambridge University Press.

McCleary, R., and R. A. Hay, Jr.
1980 Applied Time Series Analysis for the Social Sciences. Sage Publications. Beverly Hills, California.

McLaughlin, S. B.
1984 FORAST: a Regional Scale Study of Forest Responses to Air Pollutants. In Proceedings of the Conference, Air Pollution and the Productivity of the Forest. Izaak Walton League, D. Davis, ed., pp. 241-253.

McLaughlin, S. B., T. J. Blasing, L. K. Mann and D. N. Duvick
1983 Effects of Acid Rain and Gaseous Pollutants on Forest Productivity: a Regional Scale Approach. Journal of the Air Pollution Control Association 33(11):1042-1049.

McLaughlin, S. B., D. J. Downing, T. J. Blasing, E. R. Cook, A. H. Johnson and H. S. Adams
1987 An analysis of climate and competition as contributors to decline of red spruce in high elevation Appalachian forests of the eastern United States. Oecologia 72:487-501.

Meko, D. M.
1981 Applications of Box-Jenkins Methods of Time Series Analysis to the Reconstruction of Drought from Tree Rings. Ph.D. Dissertation, University of Arizona, Tucson.

Mitchell, V. L.
1969 The regionalization of climate in the western United States, Journal of Applied Meteorology 15(9):920-927.

Monserud, R. A.
1986 Time Series Analyses of Tree-Ring Chronologies. Forest Science 32(2):349-372.

Neter, J., W. Wasserman, and M. H. Kutner
1985 Applied Linear Statistical Methods, Second Edition, Richard D. Irwin, Inc. Homewood, Illinois. 1127 pp.

Rose, M. R.
1983 Time Domain Characteristics of Tree-Ring Chronologies and Eigenvector Amplitude Series from Western North America. University of Arizona, Laboratory of Tree-Ring Research, Tucson, Technical Notes 25.

Rose, Martin R.
1988 Recent Forest Growth Trends in the Western United States: 1700-1985, report submitted to Southern California Edison & West Associates, Laboratory of Tree-Ring Research, University of Arizona, Tucson.

Roth, P., C. Blanchard, J. Harte, H. Michaels and M. T. El Ashry.
1985 The American West's Acid Rain Test. World Resources Institute and Energy and Resources Group, University of California, Berkeley.

Schweingruber, F. H., R. Kontic and A. Winkler-Seifert.
1983 Application of Annual Ring Analysis in Investigations of Conifer Die-Back in Switzerland. Swiss Institute of Forestry Research, Report No. 253, Aug. 1983, Birmensdorf, pp. 6-29. In German, with English abstract.

Sellers, William D.
1960 Precipitation trends in Arizona and New Mexico. Proceedings of the 28th Annual Snow Conference, Santa Fe, pp. 81-94.

Sellers, W. D. and R. H. Hill
1974 Arizona Climate, 2nd Edition, revised Tucson, University of Arizona Press.

Snedecor, G. W. and W. G. Cochran
1979 Statistical Methods. Sixth Edition. The Iowa State University Press, Ames, Iowa.

Stockton, C. W.
1975 Long-Term Streamflow Records Reconstructed from Tree Rings. Papers of the Laboratory of Tree-Ring Research, Number 5. The University of Arizona Press, Tucson.

Stokes, M. A. and T. L. Smiley
1968 An Introduction to Tree-Ring Dating. The University of Chicago Press, Chicago and London.

Swetnam, T. W.
1986 Radial Growth Losses in Douglas-fir and White Fir Caused by Western Spruce Budworm in Northern New Mexico: 1700 to 1983. U. S. Department of Agriculture, Forest Service, Southwestern Region Forest Pest Management Report R-3 86-2.

Western Conifers Research Cooperative
1987 1987 Research Plan. Western Conifers Research Cooperative, R.K. Olson, Manager. USEPA Environmental Laboratory, Corvallis Oregon.

White, P. S.
1979 Pattern, Process and Natural Disturbance in Vegetation. Botanical Review 45:229-299.