To Tom —
Thanks.
Elaine

THE EFFECTS OF FIRE EXCLUSION ON GROWTH IN MATURE PONDEROSA PINE IN NORTHERN ARIZONA

by

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ABSTRACT

Dendrochronological techniques were used to assess the effect of fire exclusion on the radial growth of two age classes (approximately 150 and 300 years old) of mature ponderosa pine. Decline in average radial growth in both classes is coincidental with the establishment of a large ponderosa pine seedling crop in 1919 that has since become an extensive stand of stagnant, overcrowded saplings.

F and t tests of tree ring indices comparing the time period before and after 1920 show that growth has significantly declined since 1920 in both age classes. F and t tests comparing the two age classes suggest that growth was similar before 1920, but the older age class shows a significantly stronger growth decline than the younger age class. Spearman Rank Correlation tests indicate that in both groups there was no trend or a trend toward increasing tree ring indices before 1920 in both age classes, but that after 1920 there was a strong, significant trend toward decreasing tree ring indices in both groups, and that the trend is stronger in the older age class. These results suggest that the older trees are experiencing a more pronounced growth suppression effect than the younger trees.

October and July Palmer Drought Severity Indices from 1931 to 1976 were tested for trend toward drought using the Spearman Rank Correlation. There was no trend toward drought during these months, which have the most significant climatic relationship to ponderosa pine growth in northern Arizona. Therefore the growth decline at Chimney Spring may not be attributed to climate.

No environmental factor has changed at Chimney Spring, other than fire exclusion and subsequent seedling establishment. Competition for soil moisture and nutrients, reduced nutrient cycling and soil moisture losses from litter interception may all be factors contributing to the growth decline in the mature ponderosa pines at Chimney Spring.

Key words:

age classes

competition

dendrochronology

"dog-hair" thickets

fire exclusion

forest

northern Arizona

Pinus ponderosa

radial growth

10-year index:

- declining radial growth in mature pondeosa pine
- difference in growth rates between age classes
- dendrochronological techniques to analyze growth rates
- fire exclusion effects on radial growth rates
- Palmer Drought Severity Index and radial growth
- reduced soil moisture from competition by young trees and from litter interception

INTRODUCTION

The United States Forest Service has used fire exclusion as a silvicultural tool in U.S. forests for more than 60 years. Among the forest types managed under this policy is interior ponderosa pine forest. Ponderosa pine (Pinus ponderosa Laws.) is fire-resistent, and before Euro-American settlement ponderosa forests were subject to low-intensity fires every 2 to 10 years (Dieterich, 1980).

Although there has recently been research dealing with the effect of fire and fire exclusion on fuel buildup (Biswell et al., 1973) increasing undergrowth (Weaver, 1943; Arnold, 1950; Cooper, 1960; Habeck and Mutch, 1973) and nutrient cycling (Behan, 1970; Wright and Heinselman, 1973; Kilgore, 1973) there has been little, if any, research dealing with the effect of fire and fire exclusion on tree growth and productivity.

If a growth effect attributable to fire exclusion exists, it would be an important consideration to both ecologists and foresters interested in the productivity of the millions of hectares of ponderosa pine forests in western North America.

The purpose of this study is to use dendrochronological techniques to quantify the relationship between fire exclusion and long term radial growth in two age classes of mature ponderosa pine trees growing in northern Arizona.

SITE DESCRIPTION

The study area is within a 36 hectare section of the Chimney Spring Prescribed Burn Piot, Fort Valley Experimental Forest. This area lies within the Coconino National Forest, 11 km northwest of Flagstaff, Arizona at latitude 35° 16'N and longitude 111° 45'W. The dominant forest type of the Chimney Springs area is interior ponderosa pine (SAF Forest Type no. 237; Eyre, 1980). The site is located on a southwest-facing slope 8.8 km directly south of the San Francisco Peaks, with elevations at the site ranging from 2240 to 2286 meters. Soils are a basaltic clay loam.

Average annual precipitation is about 560 mm, and daily mean temperatures range from -5°C to 16.7°C (Sackett, 1980). The site was selected because the area's pre- and post-settlement fire history, and record of human-related forest disturbance are known. The last fire recorded as a scar on a tree at Chimney Springs was in 1876, and previous to that, the composite fire interval was 2.4 years (Dieterich, 1980).

SITE HISTORY

The Flagstaff area was settled in the 1870's by Euro-American, including loggers, cattle and sheep ranchers, and their families (Faulk, 1970). In 1901, a forest survey was conducted by the United States Geological Survey in what was then called the San Francisco Mountain Forest Reserve, located around the Flagstaff area (Leiburg, Rixon and Dodwell, 1904). This survey included the area that became the Fort Valley Experimental Forest. The ponderosa pine forests in the area were described as "open, continuous stands. . . . The stands surround and enclose many areas entirely devoid of arborescent growth so called 'parks' " (Leiburg et al., 1904). Ponderosa pine was and is a valuable timber resource, and early foresters were concerned about the apparent lack of saplings and young trees in the forests (Pearson, 1918). Leiburg et al. noted: "Reproduction of the yellow (ponderosa) pine is, generally, extremely deficient as regards seedling and young sapling growth. . .apparently there has been an almost complete cessation of reproduction over very large areas during the last 20 or 25 years, and there is no evidence that previous to that time it was at any point exuberant". Fire, grazing and climatic change were postulated as the cause of the lack of ponderosa pine reproduction.

The Fort Valley Experimental Forest was established in 1908. Although the Chimney Spring area had not been logged and the forests were described by Pearson (1933) as virgin, grazing did occur. In 1918, Pearson discussed the general absence of reproduction at Fort Valley, but in 1933 he reported that in 1919 there occurred over much of the Southwest a heavy ponderosa pine seed crop as well as the climatic conditions necessary for a record seed germination and seedling survival. Heavy grazing since Euro-American settlement probably created good, extensive seedbeds by reducing grass cover (Arnold, 1950). However, Pearson (1933) recognized that heavy grazing also contributed to high seedling mortality. In order to preserve the seedlings, grazing at Fort Valley was substantially reduced in 1921, and eliminatd by 1926. The Chimney Spring area was undisturbed by human activity from 1926 to 1976, when the Chimney Spring Burn Plots were established.

METHODS

Sampling technique and laboratory preparation

Tree ring samples were collected from the Chimney Spring site in August 1981 and May 1982. At least two increment core samples were taken from each of 27 mature ponderosa pines. Only trees with no visible fire scars or mistletoe infestation were sampled.

After the increment cores were air-dried, they were glued into grooved sticks and sanded until individual tracheid cells were visible under microscopic examination. The cores were crossdated using a graphical technique called skeleton plotting (Stokes and Smiley, 1968). The cores were independently crossdated by another worker as a dating check. In 10 of the trees dating could not be established because there were too many locally absent rings in the cores. These cores were removed from the data set. Ring-widths in the remaining cores were then measured to 0.01 millimeter on the Henson/microcomputer measuring system (Robinson and Evans, 1980). These measurements were also independently checked for accuracy (see Fritts, 1976).

Analysis

As trees grow older and increase in circumference, the ring widths and ring width variation tend to decrease at a rate specific to each tree. In order to compare radial growth between trees of different size and ages or at different time periods within the same tree, it is necessary to remove the biological growth trend. This process, called indexing, is accomplished by fitting a curve to each raw ring width series and dividing the raw ring width of a given year by the expected growth for that year predicted by the calculated curve. The resulting series are called ring-width indices (Fritts, 1976). Each indexed series has an approximately normal distribution, and a mean of about 1.0 (0.0 is the lowest possible index value) (Stockton and Fritts, 1971). The raw ring-width series from Chimney Spring were indexed using the simplest expected growth models (a straight line or a negative exponential curve, whichever fitted best) using the computer program INDEX (Graybill, 1979; Graybill et al., 1982).

Growth trends are a form of low frequency variance in tree ring series. The expected growth functions were chosen so that the residual index series retained as much low frequency variance as possible. It was not possible to index the ring-width series of four trees in the data set using simple expected growth functions because the outer three or four decades were highly suppressed. More complex growth functions such as polynomial or spline functions may have successfully been used to index these ring-width series, however use of these functions would not have been appropriate in this case since they remove much of the low frequency variance. Consequently, the ring-width series of the four trees were removed from the data set.

The trees were divided into two groups based on approximate tree age to determine if there were any temporal differences in radial growth. The first group was composed of trees with an average chronology length of 291 years, and the second group had an average chronology length of 156 years. Hereafter, the older group will be referred to as Group 1, and the younger group as Group 2.

For both groups, individual indexed radial series were summarized into site chronologies using the program SUMAC (Graybill, 1979). In SUMAC, tree chronologies are calculated from the average of the two core chronologies, and a site summary chronology is calculated from the average of all tree chronologies. Individual differences between samples are smoothed by the averaging procedure so that the summary chronology reflects tree growth response to common site conditions with time. Descriptive statistics including the mean, standard deviation and first order autocorrelation coefficient were also calculated in SUMAC.

Based on the visual inspection of the plotted summary chronologies, and the historically documented stand history, the chronologies were divided into two subperiods: the beginning of each summary chronology to 1919, and 1919 to 1976. Although the cores were collected in 1981, the second subperiod was terminated in 1976 to coincide with the beginning of the prescribed burning experiment in 1976.

Histograms were plotted to visually compare the class frequencies of indices 1) between time periods, for each group, and 2) between groups, for each time period. F and t tests were performed to determine the statistical significance of differences in the variance and mean in the above treatments. The degrees of freedom for the tests of significance were reduced using the first-order autocorrelation coefficient as suggested by Mitchel et al. (1965) to adjust for dependence between successive indices.

Since the standardization and summarization procedures produce a series of indices varying around 1.0, a growth trend would be visible as a series of indices greater or less than 1.0. To test for trends in each summary chronology, the Spearman Rank Correlation test was applied to each chronology as a whole, and to each subperiod.

Since climate is a major growth-limiting factor in ponderosa pine (Fritts, 1976), summary index chronologies were compared with the climatic record to relate any growth trends to long-term climatic fluctuations. The interaction of precipitation and temperature affect soil moisture and ultimately ponderosa pine growth. The Palmer Drought Severity Index (PDSI) is a monthly estimate of available soil moisture. Reliable monthly PDSI values were only available for 1931-1981 (National Climatic Center, Palmer Drought Severity Index Divisional for 1931-present, 1982). This period lacks the first 12 years of the second subperiod (1920-1976), but should be of sufficient length to discern any long term climatic trends in the time PDSI record comparable to a trend in the summary chronologies.

In order to evaluate the importance of temperature and precipitation of a given month to tree growth, Fritts (1974) performed response function analysis on forest interior ponderosa pine at the Fort Valley Experimental Forest, and found that precipitation and temperature of the September and October previous to the growing season, and the June and July of the growing season were significantly related to ring width growth. Since the PDSI value has month-to-month persistence, only October and July PDSI values were chosen for comparison to ponderosa pine growth at Chimney Spring. The October and July PDSI values were tested for trend using the Spearman Rank Correlation to compare the results to those of the summary chronologies.

RESULTS

Plots of the summary chronologies for both groups are shown in Figure 1. In both cases, the summaries show no long-term deviations from the mean until about 1905, when tree ring indices show a strong, sustained (about 15 years long) increase in mean values. From the Flagstaff precipitation record that began in 1897, it is evident that from 1905 to about 1915 there was a period of unusually high precipitation. This increase in moisture probably caused an increase in radial tree growth and resulted in the high index values visible in Figure 1. Another striking feature of both summary chronologies is that beginning in the 1920's or 1930's there is a steady decline in index value. There is no value greater than 1.0 in Group 1 after 1935, and only five values slightly greater than 1.0 after 1935 in Group 2. This trend indicates that the trees are experiencing a decrease in radial growth that is greater than would be expected due to bole geometry and age alone.

Descriptive statistics from the summary chronologies of each group are given in Table 1. The mean index values for both groups in Table 1 are the expected values for well-standardized chronologies (about 1.0), and the standard deviations are within the norm compared to the values presented by Fritts and Shatz (1975) for 21 ponderosa pine chronologies. These statistics indicate that the summary chronologies at Chimney Spring are not strongly different from other ponderosa pine chronologies from the western United States. The first-order autocorrelation coefficient is an estimate of the dependence of a tree ring index for the year t on the index value of the preceding year, year t-1 (Fritts, 1976). Both summary chronologies show high autocorrelation compared to the chronologies studied by Fritts and Shatz (1975). According to Fritts and Shatz this result indicates that there may be nonclimatic factors influencing growth at Chimney Spring since climatic influence tends to be reflected in the high frequency variance components of tree ring series in this semi-arid environment.

If there is no difference in the distribution of the indices due to time periods then the distributions should be the same in both time periods, in either group. The histograms in Figure 2 show that the overall distribution of indices is approximately normal in both groups. In both groups, indices of the first time period (pre-1920) are slightly skewed toward large values. This is a result of the precipitation anomaly of 1905-1919 (see above). During the second subperiod (1920-1976), however, index values are notably distributed in the lower ranges. This distribution is particularly evident in the Group 1 indices (Figure 2a).

The results of the F and t tests for both groups for differences of variance and mean between the two subperiods are shown in Table 2. It was necessary to adjust the degrees of freedom because autocorrelated data have dependence between successive values. To perform tests of significance, data must be independent. The null hypothesis in both cases was that there was no significant change in the variance or mean with time. According to the results, there was no significant change in variance between time periods in either group but there was a significant change in mean index value between time periods in both groups (99.5% confidence level). The indices of both groups have significantly decreased since 1920.

If there is no difference in the distribution of the indices due to age differences, then the distributions should be the same in both groups, in both time periods. The histograms in Figure 3 show that the indices of both groups are distributed similarly in the subperiod 1795 to 1919 (Figure 3a) but in the second subperiod (Figure 3b) more of the indices of Group 1 tend to be distributed in the smaller index classes than Group 2. The results of the F and t tests for differences between groups in common time periods are given in Table 3. The null hypothesis was that there was no difference in the variance or mean between groups. In both time periods, there was no change in variance between groups. However while there was no difference in the mean indices of Group 1 and Group 2 during the comon time period 1979 to 1919, the indices of Group 1 are significantly less (99.5% confidence level) than those of Group 2 during 1920 to 1976. This result suggests that although both groups experienced a decline in index value in the second subperiod, the decline in the older trees is greater than that in the younger trees.

Mitchell et al. (1965) consider the Spearman Rank Correlation test for trend to be appropriate in time series analysis because the power of this non-parametric test is not reduced by autocorrelation and because the share of the trend is unknown. That is, the Spearman test does not depend on linearity of the trend as, for example, linear regression does. The results of the Spearman Rank Correlation of mean indices with time are given at the top of Table 4. Before 1920 in both groups there was a significant trend toward increasing indices (Group 1, r = 0.1212, 97.3% confidence level; Group 2, r = 0.2707, 99.9% confidence level). After 1920, both groups show a significant trend towards decreasing indices (Group 1, r = -0.7125, 99.9% confidence level; Group 2, r = -0.4766, 99.9% confidence level). When the series were tested for a trend during the entire length of the summary chronologies, there was still a significant trend toward decreasing indices in the first group, but not the second group. These results, and the value of the Spearman r suggest that both groups have a significant trend toward decreasing indices in their summary chronology in the recent subperiod, and that in the older group, this trend is stronger than in the younger group. The trend toward increasing indicies in the first subperiod is the result of the high precipitation anomaly, since it disappeared when the first subperiod was truncated to 1905 and tested for trend (Table 4).

If the decreasing growth trend apparent in the summary chronologies is the result of an increasing climatic trend toward drought, then the PDSI series (an indication of soil moisture) should have a trend toward negative values. The PDSI is calculated from nonlinear combinations of precipitation and temperature to estimate actual and potential evapotranspiration, and it takes into account the persistence of climatic conditions over a period of months. The PDSI values vary between -7 and +7, where negative values indicate drought conditions and positive values indicate nondrought conditions (Palmer, 1965). The PDSI has been found to be highly correlated with tree-ring indices by Julian and Fritts (1968), who believed that the PDSI was a better, more simple predictor of the climate/tree physiology relationship than precipitation or temperature singly. Because climatic records do not exist in the Flagstaff area before 1897, it is necessary to assume that because the tree-ring indices show no long-term deviation from 1.0 in the first subperiod, no long-term climatic trend occurred. It is not possible to make a direct comparison between climate and the summary chronologies in the first subperiod.

For visual comparison, the Group 1 summary chronology was plotted above the October and July PDSI values for 1931-1976 (Figure 4). The strong relationship between year to year variation in the summary chronology and the PDSI values is apparent, but there is no apparent trend in the PDSI values comparable to that in the summary chronology. The results of the Spearman Rank Correlations are given in the bottom of Table 4. There is no significant trend in either of the PDSI series. Climatic trend is not the apparent source of the declining growth trend in the summary chronologies at Chimney Spring.

DISCUSSION

Since the observed decline in tree growth at Chimney Spring is not the result of a climatic trend and the decline is common among the trees, an alternative growth-limiting factor must be responsible for the decline.

At Chimney Spring, it is clear from the reports of the early foresters (Leiburg et al., 1904; Pearson, 1918) that the Fort Valley area had almost no seedlings or saplings from the time of Euro-American settlement until the 1919 seedling crop. The "dog-hair" thickets at Chimney Spring post-date 1919, and it is clear from the plots and from the trend analyses of the summary chronologies that the growth decline also post-dates 1919. That is, the growth decline at Chimney Spring is concurrent with the establishment of the dog-hair thickets. The thickets may be directly or indirectly associated with the growth-limiting factor causing the decline since they are wide-spread throughout the site. Their presence and the exclusion of fire are the most obvious environmental changes to the site in the last 100 years.

In 1943 Harold Weaver predicted, but did not test for, a declining growth rate in mature ponderosa pines attributable to understory competition, particularly from dense thickets of young ponderosa pine trees, for soil moisture. Cooper (1960) noted Weaver's hypothesis in a visual survey of radial growth of mature ponderosa pines in central Arizona growing in dense understory conditions. He did not observe a growth decline in those trees but did not quantitatively analyze growth rates. Alternatively, Van Sickle and Hickman (1959) analyzed growth rates of ponderosa pines growing in Oregon on either side of a fire line, thirty years after an intense fire. They found that in the third decade after the fire, the trees in the burned area were on the average growing 66 percent faster than those in the unburned area. The lower growth rate in the unburned area was attributed to the greater density of undergrowth, which was stated to be competing with the trees for soil moisture.

Direct competition from the thickets for soil moisture may not be the only growth-limiting factor associated with the growth decline at Chimney Spring. According to Wells (1978) heavy undergrowth and litter contribute to precipitation interception, and reduce soil moisture content. After the first fire at Chimney Spring in 100 years, Sackett (1980) found that the dead fuel loading was overall reduced by 62 percent from 35.8 metric tons/hectare to 13.7 metric tons/hectare. This implies that during the pre-settlement period when the mean fire frequency interval was 2.4 years, there was much less fuel on the ground than had accumulated by 1976. Thus, the thickets and litter may have contributed to precipitation interception and subsequent reduction of soil moisture content.

Reduced nutrient availability may be another contributing factor to the growth decline at Chimney Spring. Kilgore (1973) found that fire plays an important role in returning mineral nutrients to the soil in all Sierran conifer forests, including ponderosa pine forests. The exclusion of fire, and continual mineral absorption by undergrowth is a nutrient drain upon the soil (Behan, 1970; Wright and Heinselman, 1973), reducing nutrient availability to all plants including the mature ponderosa pines.

In Arizona alone there are 620,000 hectares of ponderosa pine forest with dog-hair thicket conditions (Schubert, 1974). If the decline in productivity at Chimney Spring is representative of dog-hair thicket conditions, then the ponderosa pine forests may be potentially more productive than at present if the thickets could be reduced. The re-introduction of fire by prescribed burning into these forests has been advocated as a way to facilitate 1) reduction of high-intensity wildfire damage by reducing fuel loadings, 2) improvement of wildlife habitat and ranges, 3) preparation of seedbeds, and 4) thinning of the dense thickets of young ponderosa pine (Sackett, 1980). The productivity and vigor of the ponderosa pine forests is an item that should be added to the list.

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Table 1. Descriptive statistics of the Group 1 and Group 2 summary chronologies.

Number of trees	Chronology length	Mean Age	First-order Autocorrelation	Mean Index Value	Standard Deviation
Group 1:					
8	1586-1981	291	0.569	1.001	0.394
Group 2:					
6	1795-1981	156	0.607	1.019	0.318

Table 2. F and t tests: 2-tailed testing of both Group 1 and Group 2 for a difference in summary indices with time

	Group 1		Group 2	
Time period:	1586-1919	1920-1976	1975-1919	1920-1976
No. years	334	57	125	57
Adjusted degrees of fredom	91.7	15.7	30.6	13.9
Average index	1.057	0.706	1.045	0.896
Variance	0.1365	0.0983	0.116	0.0499
F-test:				
F	1.387;NS		2.32;NS	
T-test:				
t	6.7437;*		5.9127;*	

NS = not significant; * = significant, 99.5% confidence level

Table 3. F and t test: 2-tailed testing for difference in summary indices between groups in both time period

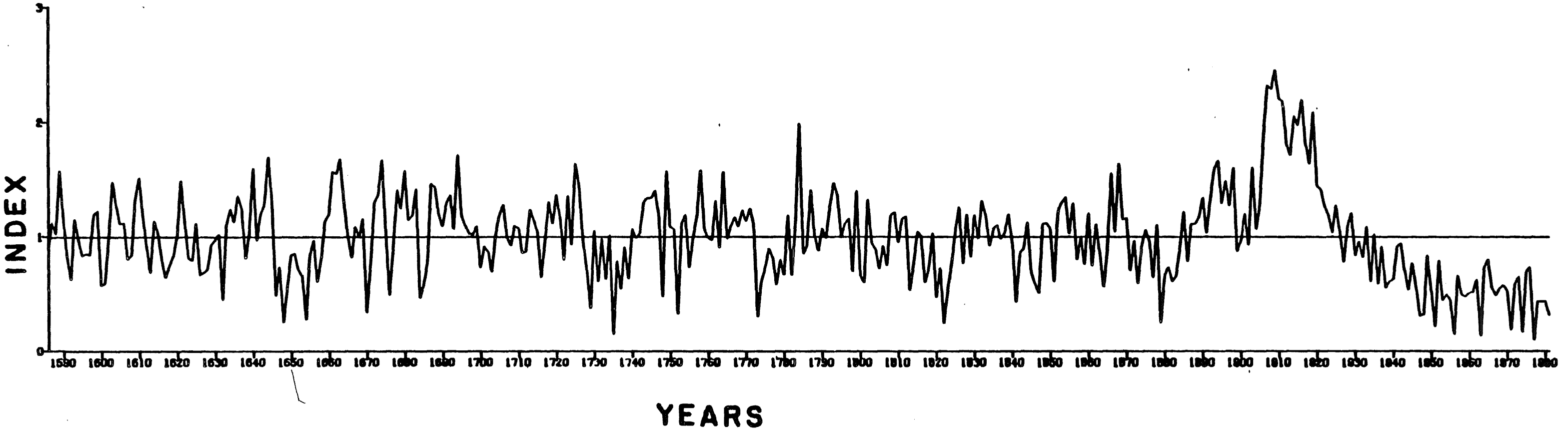
Time Period:	1975-1919		1920-1976	
	Group 1	Group 2	Group 1	Group 2
Average index	1.1167	1.045	0.706	0.896
Variance	0.2025	0.116	0.0983	0.0499
Adjusted degree of freedom	30.1	30.1	13.9	13.9
F-test:				
F	1.7456;NS		1.9699;NS	
t-test:				
t	1.2834;NS		-3.686;*	

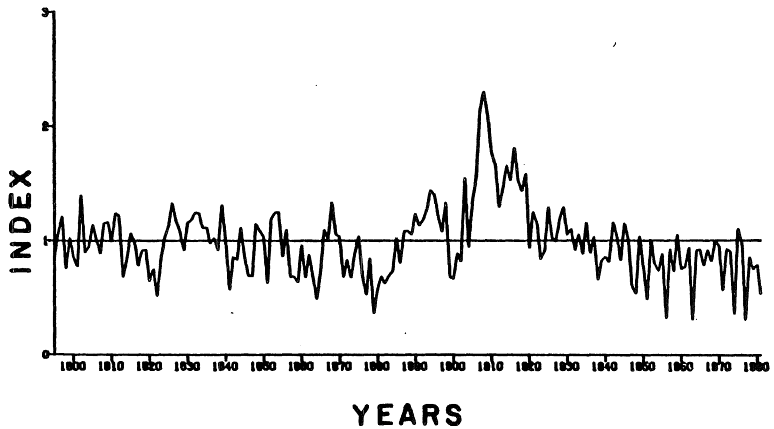
NS = not significant; * = significant, 99.5% confidence level.

Table 4. Spearman Rank Correlation Coefficients

Series	Time Period	r	N
A. Summary Chronologies			
Group 1 indices	1586-1976	-0.1682;*	391
	1586-1919	0.1212;**	334
	1920-1976	-0.7125;*	57
	1586-1905	0.0017;NS	120
Group 2	1795-1976	-0.1136;NS	182
	1795-1919	0.2707;*	125
	1920-1976	-0.4766;*	57
	1975-1905	-0.0346;NS	111
B. PDSI SERIES			
October	1931-1976	-0.586;*NS	46
July PDSI's	1931-1976	0.0021;NS	46

NS = not significant
* = significant, 99.5% confidence level
** = significant, 97.3% confidence level





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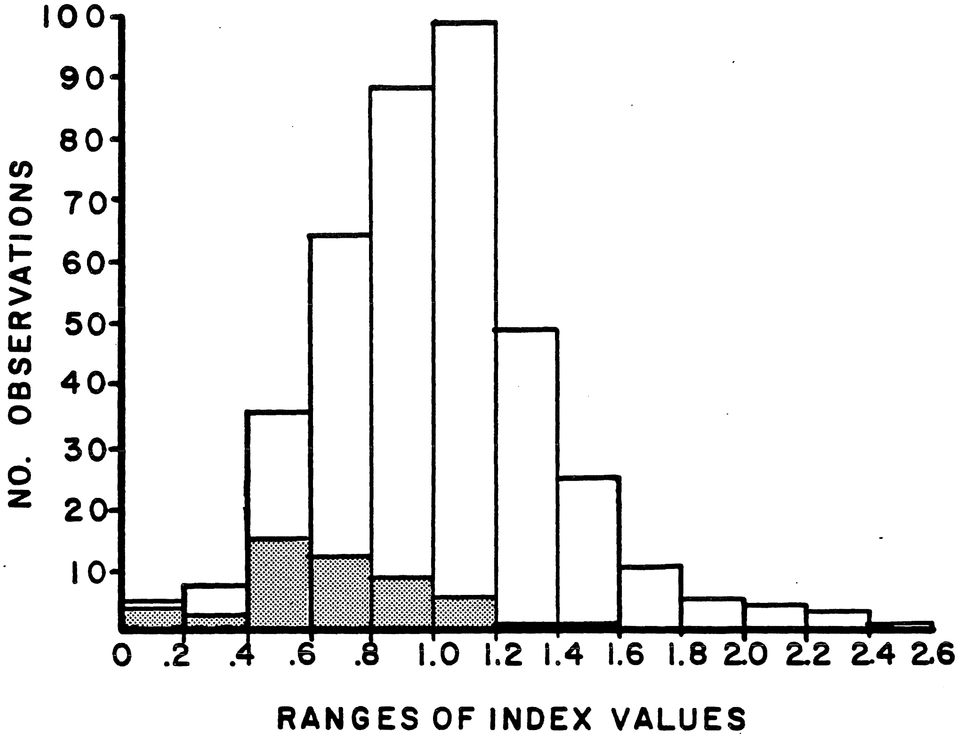
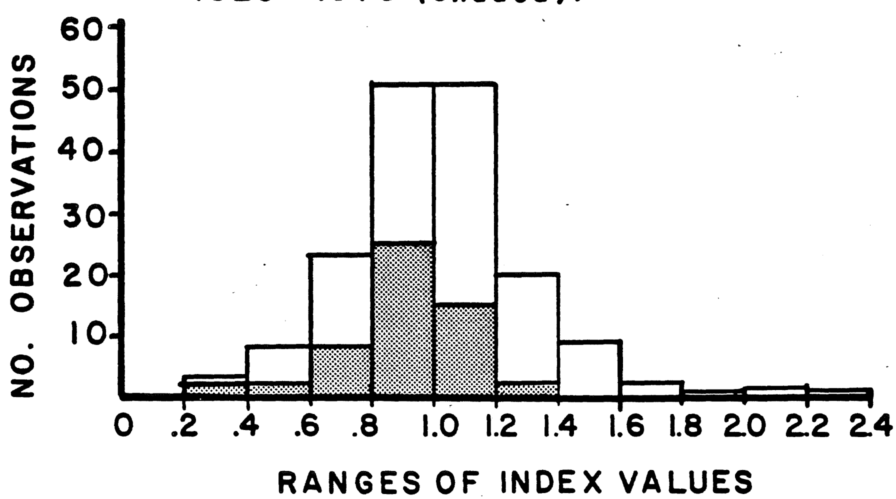
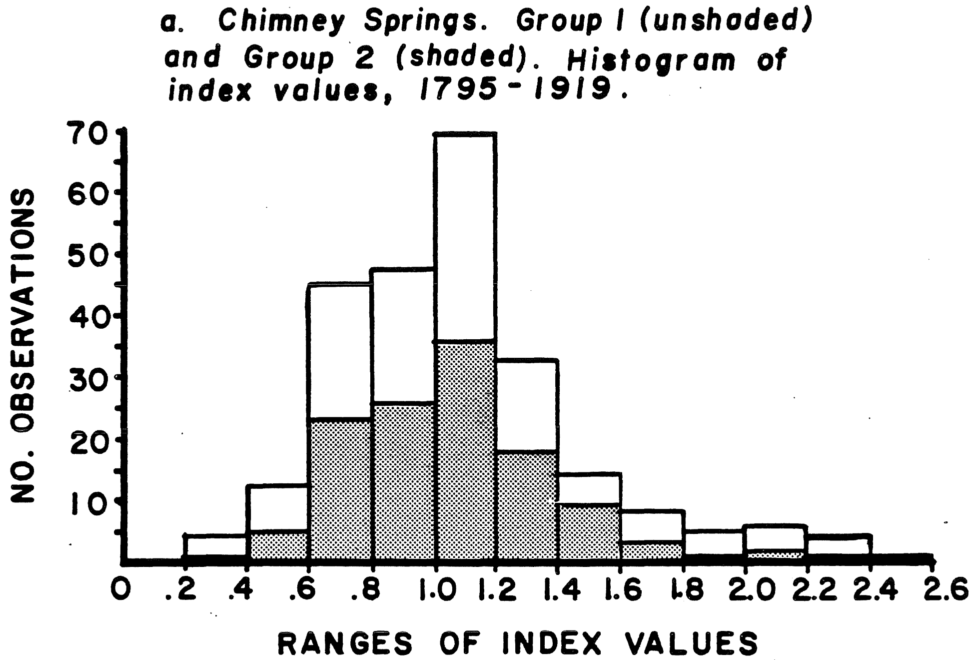
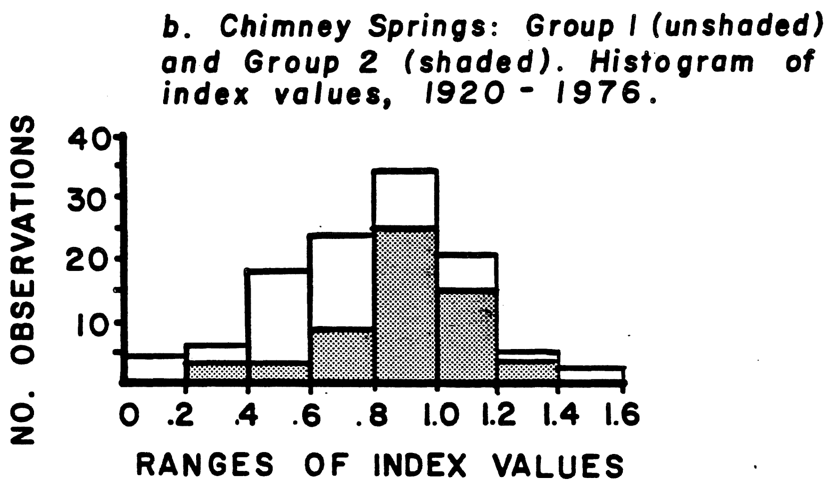
a. Chimney Springs Group 1. Histogram of index values: 1586 - 1919 (unshaded); 1920 - 1976 (shaded).

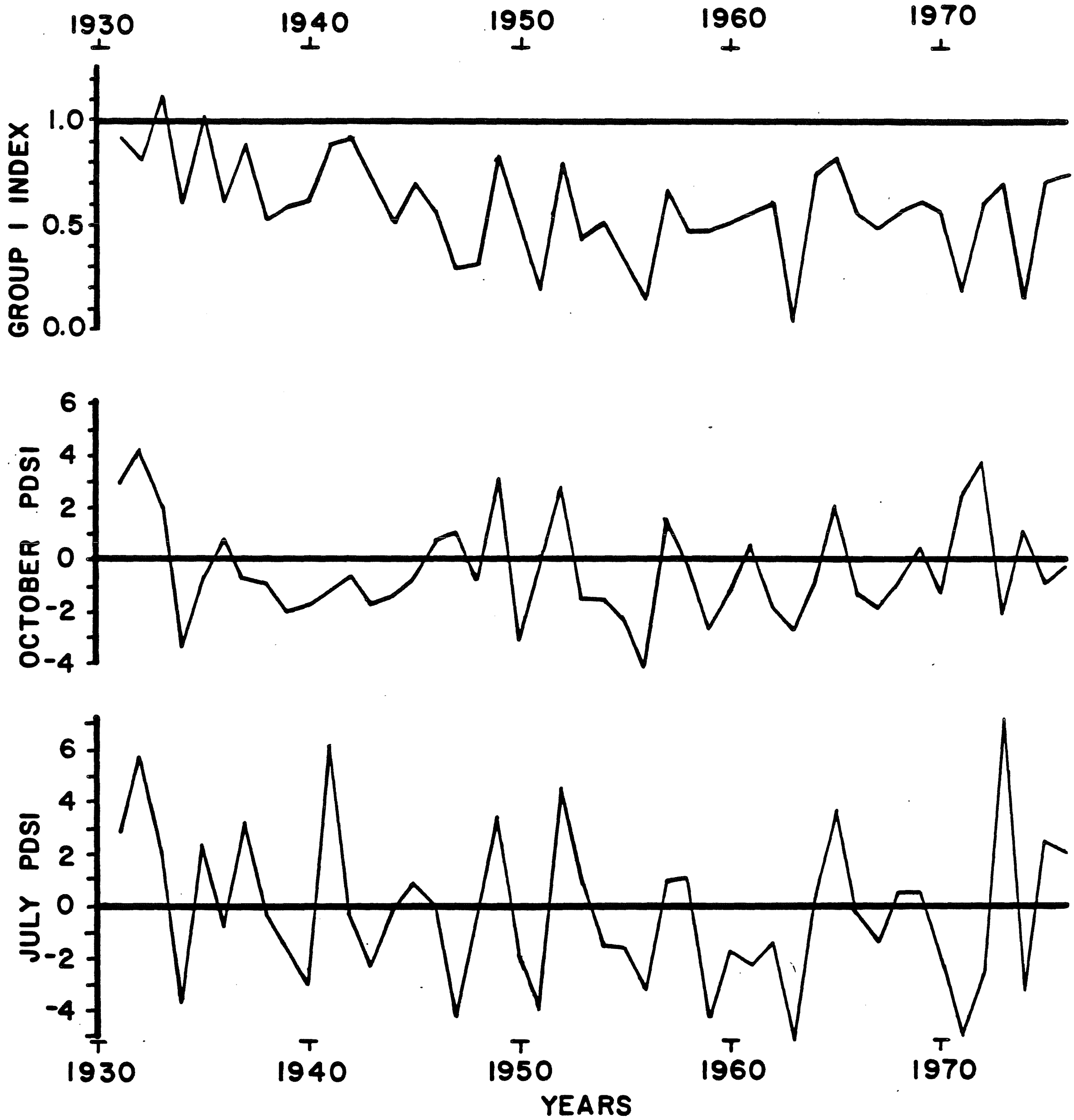


b. Chimney Springs Group 2. Histogram of index values: 1795 - 1919 (unshaded); 1920 - 1976 (shaded).




a. Chimney Springs. Group I (unshaded) and Group 2 (shaded). Histogram of index values, 1795 - 1919.
NO. OBSERVATIONS
70
60
50
40
30
20
10
0 .2 .4 .6 .8 1.0 1.2 1.4 1.6 1.8 2.0 2.2 2.4 2.6
RANGES OF INDEX VALUES


b. Chimney Springs: Group I (unshaded) and Group 2 (shaded). Histogram of index values, 1920 - 1976.
NO. OBSERVATIONS
40
30
20
10
0 .2 .4 .6 .8 1.0 1.2 1.4 1.6
RANGES OF INDEX VALUES



1930
1940
1950
1960
1970
GROUP I INDEX
1.0
0.5
0.0
OCTOBER PDSI
6
4
2
0
-2
-4
JULY PDSI
6
4
2
0
-2
-4
1930
1940
1950
1960
1970
YEARS