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TF SWETNAM

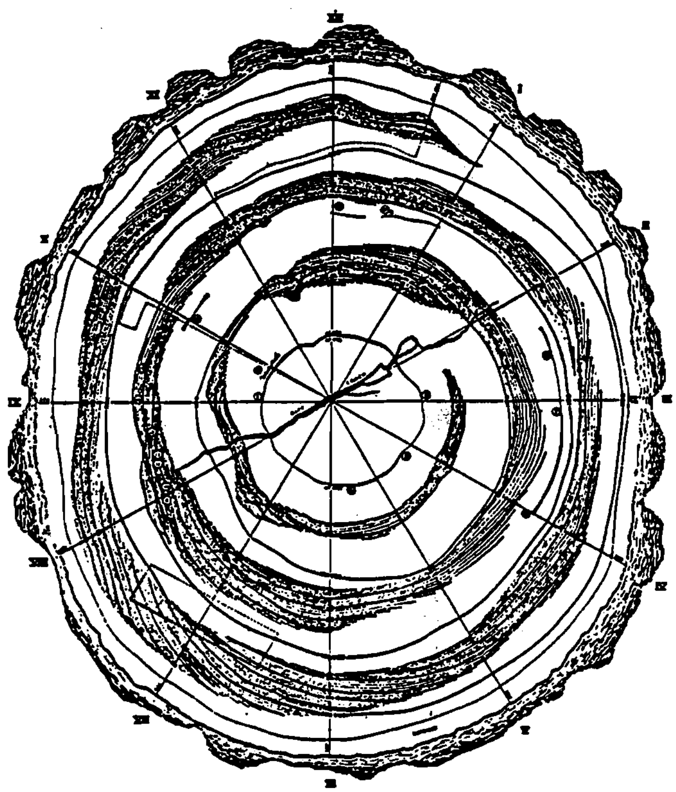
FIRE HISTORY

AND

DENDROCLIMATIC STUDIES

IN COAST REDWOOD

Final Report to
Redwood National Park
P.O. No. 8480-6-0875



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ABSTRACT

Cross section and increment core samples of coast redwood, Sequoia sempervirens (D. Don) Endl., from Prairie Creek and Jedediah Smith State Parks, California were dendrochronologically analyzed. Crossdating was observed in five out of 15 cross section samples, while none of 36 increment core samples could be confidently crossdated. Discontinuous (partial) rings were the primary reason that specimens were not crossdatable. Samples from positions high on redwood stems (above 6 m) appeared to have fewer ring distortions and partial rings. Cross sections permitted the researcher to locate partial ring anomalies and this facilitated the dating process.

Evidence of a severe fire in late 1715 or early 1716 at Prairie Creek included a dated fire scar followed by rapid growth release in many of the sampled redwood trees, and germination and establishment of an understory of Douglas-fir (Pseudotsuga menziesii [Mirb.] Franco). Rings with traumatic resin ducts were also found to be a useful indicator of past fire events. Future fire scar studies using crossdating techniques are feasible, but will require improvement and extension of accurately dated redwood chronologies for dating control.

A 235-year ring-width index chronology, 1750-1984, was developed from dated redwood specimens. This chronology crossdated with two other chronologies developed by Edmund Schulman (1940). Climatic response function studies, using Eureka, California climate data, showed that redwood growth is influenced by temperature and precipitation during most of the growing season (April to August), but especially during the month of July. The observed growth synchrony of the redwood chronologies, and

results of the response function study, suggest that coast redwood has good potential for further dendroclimatic investigations. This species may provide an unusually long record of climatic change (exceeding 1,000 years) in the coastal area of northern California.

INTRODUCTION

Coast redwoods are among the worlds largest and oldest living trees. The great longevity of redwood, exceeding 2,000 years in some trees, has stimulated a number of dendrochronological investigations into the potential for deriving environmental information from measurements of the annual growth rings (Douglass 1928, MacDougal 1936, Schulman 1940). Useful information has been provided through the study fire scars (Stuart 1987), age and size relationships (Viers 1980), and studies of ring growth fluctuations in relation to geomorphic processes (LaMarche 1966, LaMarche and Wallace 1972), however, there has been limited success in developing accurately dated ring-width chronologies which are essential for certain dendroclimatic and dendroecologic investigations.

This study was undertaken with the objective of determining if crossdating of ring-width series could be achieved within and between individual redwood trees using increment core and cross section samples. Additional work has concentrated on development of an accurately dated ring-width index chronology of coast redwood, dating of fire scars on crossdated samples, and analysis of correlation between index chronologies and instrumented climatic records.

Recommendations for future fire history and dendroclimatic investigations in this forest type are also presented. An opportunity exists for obtaining additional tree-ring samples from stumps remaining from old growth redwood stands that were harvested over the past 100 years within and around the present boundaries of National and State Parks. These stumps are generally well preserved because the heartwood of redwood is usually resistant to decay fungi. In some areas there is an urgent need to secure samples from remnant stumps before they are removed, as in the case of the current road construction of the California State Highway 101 bypass around Prairie Creek State Park.

Past tree-ring studies of coast redwood have been frustrated by anomalous growth characteristics. Discontinuous rings, sometimes associated with compression wood, are recognized as a major source of error in ring counts on increment cores. For example, Fritz (1940) found differences in ring counts exceeding 100 rings from one radius to another on the same tree. Fritz and Averill (1924) described and illustrated the phenomenon of discontinuous rings (or ring "wedging"), where one, and sometimes groups of rings, pinch down to smaller and smaller widths until they are completely absent along portions of the stem.

Because of the ring dating problems in redwood, fire history studies based only on ring counting of fire scarred trees must be considered less than reliable. Researchers have derived more complete information on past fire regimes in this type by obtaining evidence from a variety of sources, including dated fire scars, ages of basal sprouts which are known to be stimulated by past fires, and post-fire establishment of understory cohorts of Douglas-fir (*Pseudotsuga menziesii* [Mirb.] Franco) and western hemlock (*Tsuga heterophylla* [Raf.] Sarg.) (Viers 1980, Abbott 1987, Stuart 1987).

Despite the problem of discontinuous rings, Schulman (1940, n.d.) was able to successfully crossdate about half of more than 100 cross section and increment core samples that A. E. Douglass collected in the 1920s from throughout the redwood region of northern California. Schulman also studied the vertical uniformity of rings in redwood stems and found that specimens from positions high on the stem (sometimes exceeding 30 m) had fewer anomalous growth patterns than specimens from near the base, and were therefore more useful for crossdating and developing accurately dated chronologies. Schulman (n.d.) developed a mean index chronology from seven trees from the Willits-Fort Bragg area of California that exhibited the most consistent and reliable crossdating. He also developed another chronology from four trees from the Weott area. The Willits-Ft. Bragg and Weott chronologies have apparently never been published. Schulman stated that trees from the northern redwood groves (area of the present study) typically exhibited the poorest crossdating.

Schulman compared his chronologies with measurements of total hours of fog by month from several points along the Pacific Coast in the redwood region, but he did not observe any consistent relationship. However, he did note a strong association with seasonal precipitation, especially the co-occurrence of severe drought years (e.g., 1924, 1913, 1918) and small growth rings. He did not analyze temperature records.

METHODS

Collection Areas

Tree-ring samples were collected in 1986 from two areas - Prairie Creek and Jedediah Smith State Parks. Locations are: Prairie Creek - township 12 N, range 1 E, section 25; Jedediah Smith - township 16 N, range 1 E, section 16. The Prairie Creek stand is approximately 5.6 km east of the Pacific Ocean and the Jedediah Smith area is approximately 13.7 km northwest of Crescent City, California and the Pacific Ocean. The topography of the sampled areas is highly weathered and eroded terrain composed of low rounded ridges and benches rising to the east.

Ridge tops are typically 100 to 250 m higher than adjacent major drainage bottoms. The tree-ring samples came from gentle slopes (5 to 10%). The aspect of the slope at the Prairie Creek area is northwest, while it is generally to the north-northwest in the area of the Jedediah Smith collections. Elevation at the two collection areas ranges from approximately 150 to 300 m above mean sea level.

The stand in the Prairie Creek area has an overstory of large redwoods and a mixture of Douglas-fir and western hemlocks in the understory. The Jedediah Smith area is in the upper elevation range of redwood, and Douglas-fir is the most common tree in the over and understory, with fewer hemlocks and redwoods dispersed in the stand.

Samples

Partial cross section samples were obtained from two sites at the Prairie Creek area: near May Creek at the south end of the 101 bypass road which is currently under construction, and near an eastern corner of Prairie Creek State Park where the bypass road cuts through the edge of the old growth redwoods (NE 1/4 section 25) which are now protected in the State Park. These partial sections were obtained from stumps and logs of 15 different trees harvested in 1985 for the purpose of clearing the new roadway. Partial cross sections from the ends of logs were cut from varying heights on the stem (at least 6 m above the base). A chainsaw was used to excise radial pieces of wood from logs and stumps that included visible fire scars. Full cross sections were obtained from the stumps and logs of smaller, younger redwoods, Douglas-fir, and hemlocks up to approximately 1.5 m diameters.

An additional 13 living redwoods were sampled with 50 cm length increment borers at the Prairie Creek corner area along and near the road (within 100 m) passing through the William W. Eastman and J. Harold Peterson Memorial Groves, west of the 101 bypass road right-of-way. Two cores were taken from each tree on opposite sides of the lower stem. These trees ranged from approximately 1.5 to 5.0 m in diameter at breast height, thus, the cores included only the outer several centuries of ring growth. Five trees were cored in the Jedediah Smith grove in a similar manner. These cores were taken from trees along and up slope of the Little Bald Hills road.

Laboratory Analyses

The cross section samples were reduced to smaller more manageable pieces with a bandsaw. A beltsander was used to smooth the transverse surfaces for viewing the annual rings and fire scars. Increment cores were mounted in wooden holders and surfaced with sandpaper.

The annual rings were counted on the cross sections by carefully following the ring sequence along radii that appeared to have the least distortion due to scars or other growth suppressions and releases. Discontinuous rings (called "partial rings" here) were very common - as many as ten or more rings in a group were observed to wedge down to smaller and smaller widths until finally disappearing along a ring boundary (see Fritz and Averill 1924). In order to locate as many of the partial rings as possible, the transverse surface extending around the circumference of the section was searched. Wedging of rings was noted, and the additional rings counted. For many of the slower growing older specimens the ring counts probably do not include many rings that were not visible in the searched area but may have been present elsewhere on the specimen. Most of the younger specimens (less than about 300 rings) had larger rings and it was generally easier to locate partial rings, so these counts were likely to have included all or nearly all rings present on the specimen. All fire scars observable on the cross sections were noted and the number of rings to bark and/or pith were recorded.

Skeleton plots (Stokes and Smiley 1968, Swetnam *et al*. 1985) were produced from counted radii on the partial cross sections and from a selected set of the increment cores. Cores that appeared to have more "open" series (larger rings) and some "sensitivity" (variability in ring widths) were chosen for plotting. The skeleton plots were used to attempt to observe crossdating of ring-width patterns within and between trees.

The ring widths of all of the plotted (but undated) increment cores were measured on a Bannister incremental measuring bench interfaced with a micro-computer (Robinson and Evans 1980). A selected set of radii on the cross sections were also measured. These specimens were the most likely to have complete ring sequences because few partial rings (i.e., wedging) were noted, or the rings were generally large throughout the measured series so that partial rings were relatively easy to locate and include in the counted series. In the latter case, the partial rings found along another radius were included as zero values in the measurement file for the measured radius. Since none of the specimens (cores or sections) were crossdated prior to measurement, an arbitrary date of 3000 was assigned to the outermost ring and prior rings were dated successively 2999, 2998, 2997, etc.

Ring-width plots produced from the measurements were used for visual comparisons of within and between tree growth patterns and trends. Plots were overlaid on a light table for these comparisons. Low pass filters were also applied to the series and plots of the smoothed values were compared to observe similarities or dissimilarities in the long term trends among the series (Swetnam et al. 1985). After specimens were successfully crossdated using these graphical techniques the arbitrary ring dates were changed to the appropriate calendar year dates.

Crossdated series were processed through the program COFECHA (Holmes 1983) to statistically analyze the correlation among the samples. The crossdated series were standardized, i.e., ring indices were produced from the ring-width series, and averaged into an index chronology for the site (Fritts 1976, Graybill 1979). Cubic splines of 50% frequency response and 100 year length were used for standardization (Cook and Peters 1981) and an autoregressive model was fit to the chronology to produce a set of "prewhitened" indices for use in later analyses. The program ARSTAN (Cook and Holmes 1984) was used to perform the autoregressive modeling. The standard chronology (arithmetic mean) and prewhitened chronology were both used in subsequent analysis.

Climatic Analysis

An investigation of the effect of climate on variation of redwood ring-width growth was conducted. Monthly precipitation (totals) and temperature (means) were obtained for Crescent City and Eureka, California. The Crescent City data was later excluded from the analysis following examination of double mass and cumulative difference plots (paired comparisons with other California stations), which indicated inhomogeneity in this time series due to a move of the recording location in 1945. Climatic data from Eureka for the 1912 to 1980 period was used in subsequent analysis. Product moment correlation coefficients were computed for combinations of the standard and prewhitened chronologies with 28 climatic variables. The variables included 14 months each of mean temperatures and total precipitation from October of the current year back to September of the previous year. These months were chosen based on MacDougal's (1936) observations that the months April to October usually included the entire period of active cambial growth in redwood, as well as knowledge that climatic conditions in months prior to the growing season can affect subsequent growth (Fritts 1976).

A response function was also computed from stepwise multiple regression using principal components extracted from the original 28 climatic variables (Fritts 1976). Only the principal components for which the multiple of the eigenvalues exceeded 1.0 were entered in the regression (Guiot et al. 1982).

RESULTS

Crossdating

The skeleton plots of the increment core ring series failed to reveal consistent crossdating within or between trees. Skeleton plots from radii of some of the cross sections showed matching of ring-width patterns within trees, but there was no conclusive crossdating visible between trees. After counting rings along various radii of the cross sections and noting the high frequency of wedging, i.e., the disappearance of rings at unpredictable locations, it became clear that the primary reason for a failure to observe crossdating in the increment cores was due to undetected ring absence caused by the wedging phenomenon. Some of the redwood ring series were also fairly complacent, i.e., there was relatively little ring-width variation from one year to the next. Thus, ring complacency in redwood decreased the overall effectiveness of skeleton plots for observing crossdating.

Ring-width plots from the measured, undated series, however, were much more useful in identifying crossdating between series. When these plots were overlaid on a light table it was possible to observe matching of obviously small rings between series, as well as similarities in the subtle changes in ring growth that were not recorded in the skeleton plots. Matching of long term growth fluctuations were also visible between some of the series. In comparison of all of the measured increment core and cross section ring-width series it was possible to confidently crossdate portions of seven radii of five different redwood trees from the Prairie Creek corner area. All of these measured radii were from cross section samples. Table 1 is a summary of ring count data and observations on all of the analyzed specimens.

Examples of crossdating within and between redwood trees are shown in Figure 1. Based on the visual comparison of the ring-width plots of these series and the other crossdatable series, the probable location of several locally absent rings were identified. Subsequent search along the ring boundary where the suspected missing rings should be located resulted in discovery of the partial rings.

Spiral Compression Wood

One unusual redwood cross section is worthy of special note. Specimen RCX101 displayed a very striking pattern of spiral compression wood. According to Timell (1986) this phenomenon has been described in only ten trees, nine of which were spruces (Picea sp.), and only one other redwood (Fritz 1940). RCX101 has 248 rings, and is an oblong shaped cross section - about 70 cm wide at the narrowest diameter and

Table 1. Tree-ring samples collected and analyzed.

Location & ID	Species	(C)ores (X)sect.	No. of Rings	Approx. Inside Date	Fire Scars, Resin Ducts, etc.
Prairie Creek					
RCX021 RCX023	SESE	X	501p*	1485	traumatic resin ducts visible in years 1716-1719, strong growth release after 1719
RCX032	SESE	X	634p	1351	growth release after about 1740
RCX043 RCX044	SESE	X	294p	1691	traumatic resin ducts visible in years 1716-1719, strong growth release after 1719
RCX050	SESE	X	250p	1735	fire scar about 1931 and 1745
RCX060	SESE	X	1,148	837	fires scars at about 1778-1779 and 1715
RCX071 RCX072	SESE	X	618	1367	fire scars at about 1721, 1784, 1411, 1399, 1339
RCX083	SESE	X	1,150	835	1715-16 fire scar, release after 1719 and stronger release after 1770
RCX101	SESE	X	248	1737	spiral compression wood
RCX183	SESE	X	1,050	935	very slow growth in last several centuries
RCX160	TSHE	X	164p	1821	fires scar at about 1827, slight release 1828-1835, fire scar about 1945, growth release after about 1957

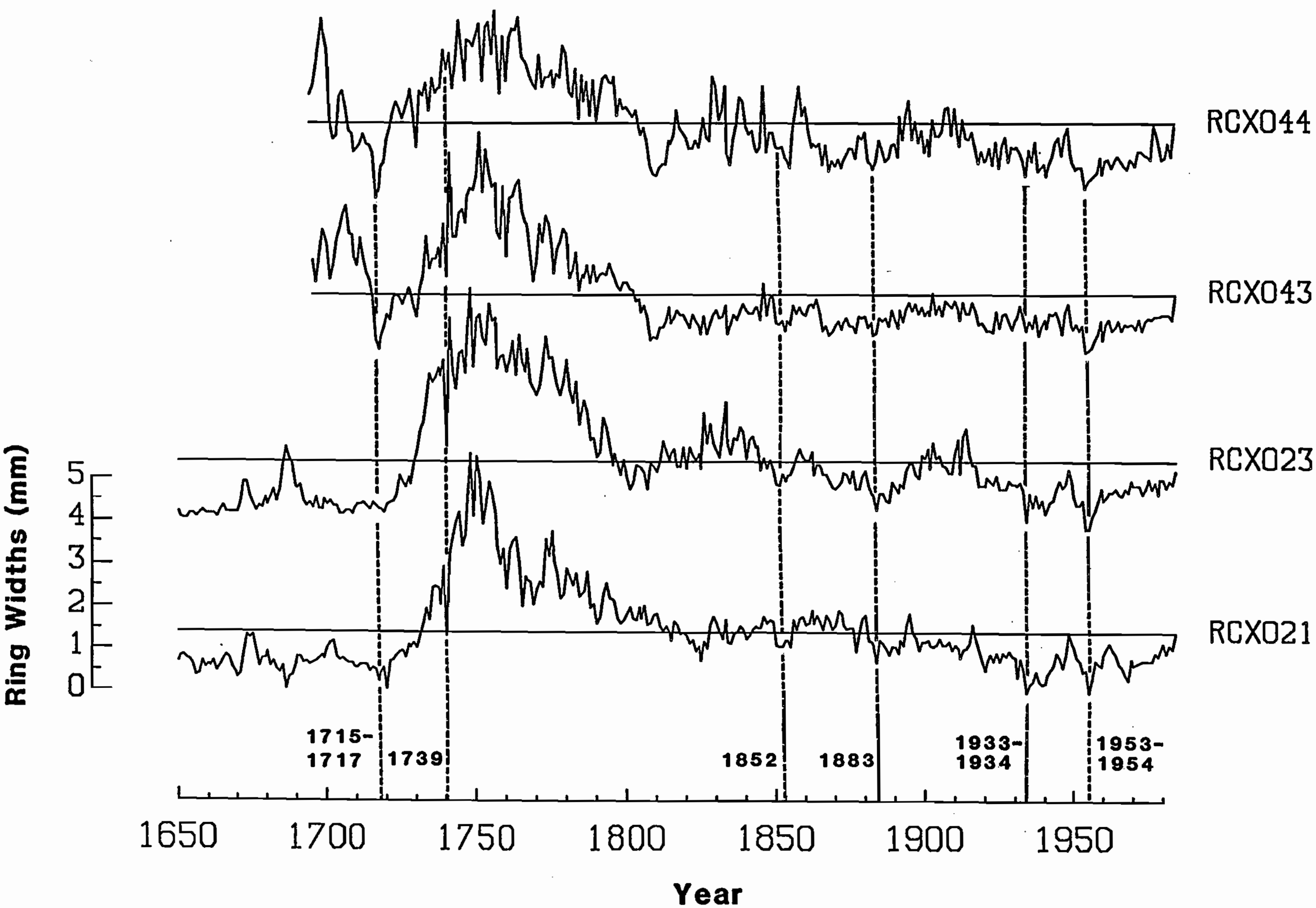
Table 1. Continued.

Location & ID	Species	(C)ores (X)sect.	No. of Rings	Approx. Inside Date	Fire Scars, Resin Ducts, etc.
RCX140	TSHE	X	193p	1792	growth release after about 1953
RCX150	TSHE	X	182p	1803	growth release after about 1952
RCX130	PSME	X	244p	1741	
RCX120	PSME	X	262p	1723	
RCX170	PSME	X	264p	1721	
PCC021	SESE	C	422		
PCC022	SESE	C	379		
PCC032	SESE	C	279		
PCC042	SESE	C	261		
PCC051	SESE	C	276		
PCC052	SESE	C	403		
PCC061	SESE	C	511		
PCC062	SESE	C	527		
PCC081	SESE	C	448		
PCC082	SESE	C	399		
PCC091	SESE	C	547		
PCC092	SESE	C	296		
Jedediah Smith					
JDS011	SESE	C	296		
JDS021	SESE	C	521		
JDS031	SESE	C	269		
JDS032	SESE	C	201		
JDS041	SESE	C	289		
JDS042	SESE	C	320		

* Number of rings with the letter "p" indicates pith was present.

SESE = *Sequoia sempervirens*, TSHE = *Tsuga heterophylla*, PSME = *Pseudotsugae menziesii*.

Figure 1. Examples of paired ring-width series from two coast redwood cross sections. Years with notable corresponding small rings are indicated with dashed vertical lines.



112 cm on the longest diameter. About 3 1/4 counter-clockwise spirals can be observed on the upper transverse surface. It is interesting to note that nine of the other described spiral compression wood specimens had clockwise spirals, while one, a spruce, had a counter-clockwise spiral (Timell 1986). Compared with the published photographs of other specimens, RCX101 has a relatively irregular spiral that varies considerably in the width of the compression wood and spacing between the bands of the spiral.

Although a number of theories have been put forward, Timell (1986) states that the causes and mechanism(s) resulting in spiral compression wood are poorly understood. It is generally accepted that this feature is a record of the circular movement of a leaning stem around the axis of the tree base, through a span of time encompassed by the rings in the spiral.

A combination of mechanical and physiological causes are probably involved. Timell suggests that snow may be one of the mechanical forces involved by adding weight in the crown every season to an already leaning stem, thus maintaining a lean that is counteracted during the growing season by growth of compression wood on the side of the lean. This could not be the case for redwood, where snowfall is infrequent and usually only on higher ridge tops. I would suggest that an important mechanical factor may be the tendency for both spruce and redwood stems to develop (and perhaps maintain) leans by shifting of the roots and stem in the ground substrate. This may be due to shallow rootedness in the case of spruces, and loose alluvial soils in the case of redwoods. A more thorough discussion of this curious phenomenon is beyond the scope of this report.

Fire Scars, Traumatic Resin Ducts, and Growth Releases

Fires scars were identified on the samples by physical characteristics visible in the cross sectional view (transverse view) - they formed a break in an annual ring, charcoal was usually present on the surfaces of the break, and subsequent rings grew laterally around the edges of the wound forming an overlapping callous growth (Stokes 1980). In some cases the wound apparently was never fully exposed, i.e., the bark did not slough off following the fire and cambium continued to grow all along the top of the break. In the latter case, abnormally shaped tracheid cells that were probably killed or injured by heat were visible on the borders of the break. It is possible that these injuries were not caused by fire, but another source such as impact of a falling tree, logging machinery, or possibly by freezing temperatures during the growing season. However, the author has observed this type of scar in other conifers, including giant sequoia (Sequoiadendron gigantea [Lindl.] Decne.), and through matching of the dates of these injuries with obvious fire scars on another part of the same tree, or nearby trees, these injuries are almost always determined to have been caused by fire.

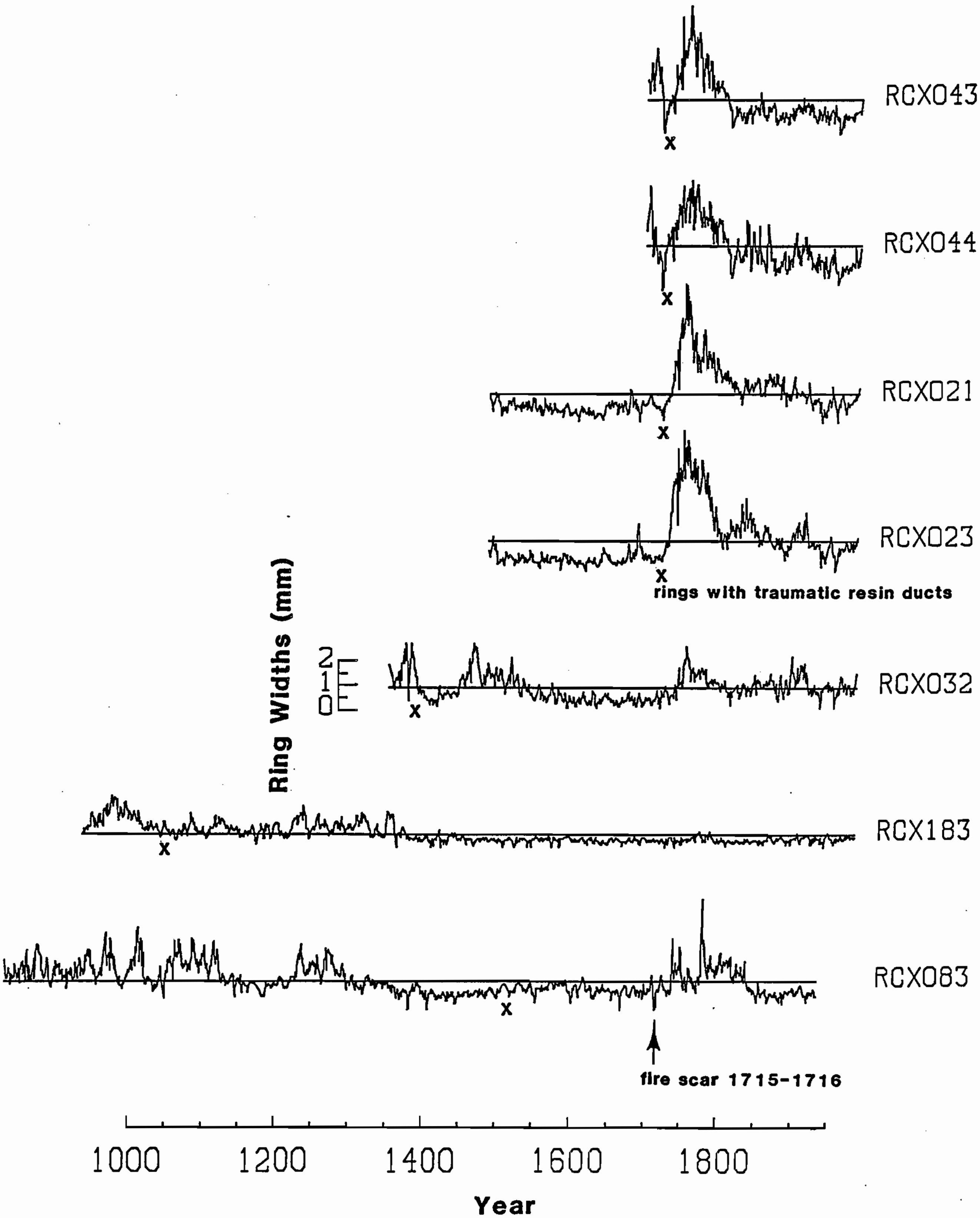
Unfortunately, most of the fire scars were not successfully dated. This was because many of the scars were in earlier periods (prior to 1750) on older trees with slower growth rates and too many partial rings, so crossdating was not possible with the existing chronology. Other specimens with fire scars had too much distortion and growth fluctuations following the scars that were unique to the individual trees and this prevented matching their ring patterns with other crossdatable trees. Approximate dates of the fire scars in the uncrossdated trees were estimated from the number of rings between the bark ring (1985) and the scar. Thus, fire scar dates listed in Table 1 must be considered estimates only. It is likely that they are off by as many as ten years and possibly more.

The only accurately dated fire scar was on specimen RCX083 from Prairie Creek corner. Crossdating of the rings in this 1,050 ring sample was confirmed only for the outer 280 years (from about 1700 to 1985). The fire scar appeared on the ring boundary of the 1715 and 1716 rings. Therefore this fire occurred during the dormant season of the tree and may have been either in the fall of 1715 or the spring of 1716.

Several other lines of evidence support the observation of an intense fire at Prairie Creek corner in 1715-16. The first is multiple observations of traumatic resin ducts in the 1716-1720 rings of different redwood samples from Prairie Creek that did not have visible fire scars (Table 1). Traumatic resin ducts appearing in conifer rings are known to be a physiological response to stress or injuries (Shigo and Marx 1977). Traumatic resin ducts were also frequently observed in the growth rings containing fire scars, or in the rings immediately following fire scars on the redwood cross sections. Figure 2 shows the timing of the dated fire scar and traumatic resin duct rings among the crossdated redwood specimens from Prairie Creek.

Growth "releases" characterized by large increases in ring widths following the 1715-1716 fire were noted in several of the specimens from Prairie Creek (Figure 2). This phenomenon has been observed by many researchers in studies of forest disturbance history and is strong evidence for the occurrence of mortality of competing vegetation due to a disturbance agent (Lorimer 1985).

Figure 2. Ring-width series from five trees sampled at Prairie Creek corner area. RCX043, RCX044, RCX021, and RCX023 are paired radii measured on two different trees. A strong growth release and traumatic resin ducts were observed in rings following the fire recorded by a scar on the boundary of the 1715 and 1716 rings in specimen RCX083.



Additional evidence of a severe fire event in 1715-16 involves the estimated ages of the three Douglas-fir trees that were sampled at Prairie Creek corner. Full cross sections were cut from the stumps of these understory trees, and pith dates were determined to be approximately 1741, 1723 and 1721 (samples were not crossdated). The height above ground at which these specimens were taken is not known exactly, but it was within 1 m of ground level. Therefore, germination dates were at least 5 to 10 years earlier than the pith dates. Thus, it is likely that the Douglas-fir understory observed in this part of the Prairie Creek stand germinated and established following the intense 1715-16 fire. The evidence suggests that this fire opened up the stand through mortality of competing trees or other herbaceous vegetation, and provided a mineral soil bed that facilitated germination and survival of seedlings. This observation of the probable establishment of an understory cohort of Douglas-fir following fire in coast redwood is similar to the findings of Viers (1980) and Stuart (1987).

The estimated pith dates of the three hemlock cross section samples were 1821, 1792, and 1803. There was no accompanying fire scar evidence, traumatic resin duct rings, or consistent and obvious growth fluctuations prior to this period (1790-1820s) that might also suggest a fire origin for this cohort of hemlocks. Also, it is acknowledged that three samples of each of these understory species (Douglas-fir and hemlock) is too small to make any firm observations on the age structure of the stand.

Evidence of past fire was also recorded by one of the hemlock samples (RCX160, see Table 1). This tree had fire scars recorded in approximately 1827 and 1945 (not crossdated). Other redwood partial sections from the May Creek site (Prairie Creek area), that were not crossdated also had fire scars with estimated dates of about 1339, 1399, 1411, 1721, 1715, 1739, 1779, 1784 and 1931. Since these dates are estimated from simple ring counts from the known bark ring date (1985) to the fire scar the correct dates could easily be ten to twenty years earlier because of undetected partial rings. It is quite possible, for example, that the 1715 and 1721 scar dates, and the 1779 and 1784 scar dates that were found on different trees, actually record the same fire event in the 1710s, and in the 1770s respectively.

Index Chronology

Although crossdating was visible in seven radii from five trees the COFECHA program showed that correlations among the series were lowest in combinations with the series RCX183 (see Figure 2). This tree was one of the oldest sampled and had a very low growth rate during the period of comparison (1650-1984). Correlations among the series were also lower for the periods preceding about 1750 than after 1750. The best overall synchrony of growth patterns was observed for the 1750-1984 period, so all crossdated series excluding RCX183 were standardized and averaged into the final chronology for this period. Thus, the index chronology includes only six growth series from four trees. Table 2 lists the correlation matrix for the series included in the final chronology and other descriptive statistics for the standardized chronology and the prewhitened chronology.

A second order autoregressive model (AR2) was fit to the original index series. The residuals of this model (differences of values predicted by the model and the original series) were called the "prewhitened" indices. The standard and prewhitened index chronologies are listed in Appendix A.

Table 2. Chronology statistics for Prairie Creek coast redwood.

CORRELATION MATRIX: (common period is 1750-1934)

Series:	RCX021	RCX023	RCX043	RCX044	RCX083	RCX032 (core series)
RCX023	0.41					
RCX043	0.42	0.41				
RCX044	0.36	0.46	0.73			
RCX083	0.22	0.39	0.25	0.32		
RCX032	0.51	0.37	0.51	0.48	0.10	
RCXBG0 (mean series)	0.67	0.72	0.78	0.79	0.56	0.71

Mean corr. among all radii: 0.408

Mean corr. between trees: 0.375

Mean corr. within trees: 0.592

Signal-to-noise ratio: 2.403, based on sample size of 4 trees

CHRONOLOGY STATISTICS:

1750-1984 (235 years), 4 trees, 6 radii

	Chronology Type	
	Standard	Prewhitened
Mean index	0.999	1.000
Median	0.999	0.993
Mean Sensitivity	0.152	0.187
Standard Dev.	0.200	0.161
Skewness	-0.260	-0.029
Kurtosis	4.936	4.414
Autocorrelation order 1	0.563	-0.053
Partial Autocorr. order 2	0.191	0.048
Partial Autocorr. order 3	0.007	0.087

The mean redwood index chronology from Prairie Creek was also compared with the two redwood chronologies developed by Schulman from the Willits-Fort Bragg and the Weott areas. Specific location of trees sampled in these areas has not been determined, but distances south from Prairie Creek are approximately 230 km and 130 km respectively. Schulman's index chronologies were obtained from archived files at the Laboratory of Tree-Ring Research. The common periods of the three chronologies (1750-1930) were compared by overlaying plots and computing correlations. Crossdating was obvious between the plots, with the years 1759, 1768, 1783, 1824, 1834, 1844, 1846, 1850, 1865, 1867, 1918, 1919, 1922, and 1924 occurring as smaller than average rings in all three chronologies. Larger than average rings common to all three chronologies included 1761, 1832, 1838, 1841, 1842, 1894, 1895, 1906. Some differences between the chronologies in low frequency trends were also visible, especially during the 1790s-1800s and 1840s-1850s. Plots of the three chronologies and correlation coefficients are shown in Figure 3.

Dendroclimatic Analyses

The response functions derived from the principal components regression and the simple correlation analysis for Eureka precipitation and temperature records and the standard and prewhitened tree-ring chronologies are illustrated in Figure 4. Significant positive values ($p < 0.05$) include growing season temperatures and precipitation, especially during the month of July. With 11 principal components retained in the regression on prewhitened indices, the climatic variables explained 43.7% of the chronology variation ($F = 3.96$, $p = 0.0003$, R^2adj. = 0.327). With 10 principal components retained in the

Figure 3. The redwood chronology from Prairie Creek (RCX) is compared with chronologies developed by Schulman from the Weott area (WTR) and the Willits-Fort Bragg area (WFB). Correlation coefficients are listed for the full common period of the three chronologies (1750-1930) and arbitrary subperiods. The index scale is oriented with respect to the middle plot.

CORRELATION COEFFICIENTS (r)

Period:	1750-1930 n = 181		1750-1800 n = 51		1800-1850 n = 51		1850-1900 n = 51		1900-1930 n = 31	
ID:	WTR	WFB	WTR	WFB	WTR	WFB	WTR	WFB	WTR	WFB
RCX	.387	.189	.274	.285	.637	-.013	.466	.323	.658	.553
WTR		.208		-.065		.236		.217		.634

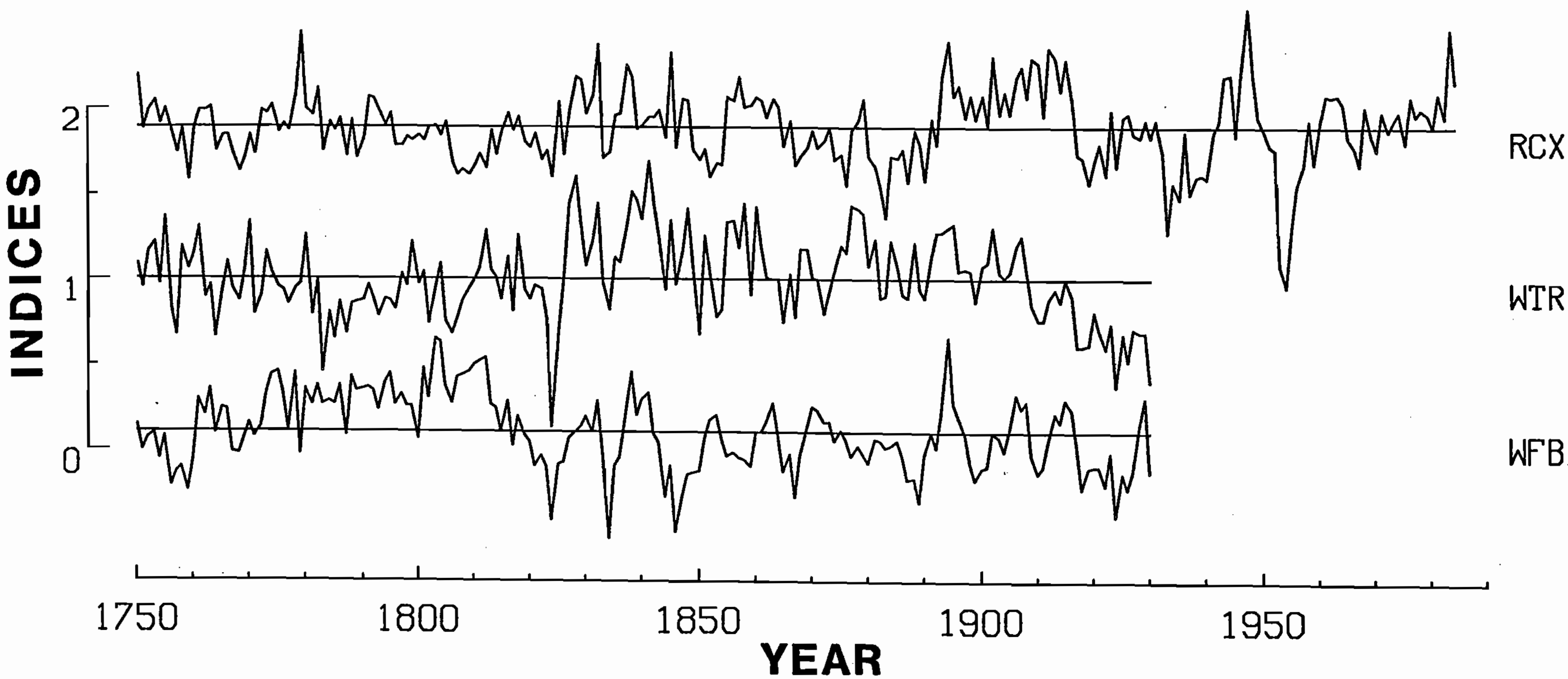
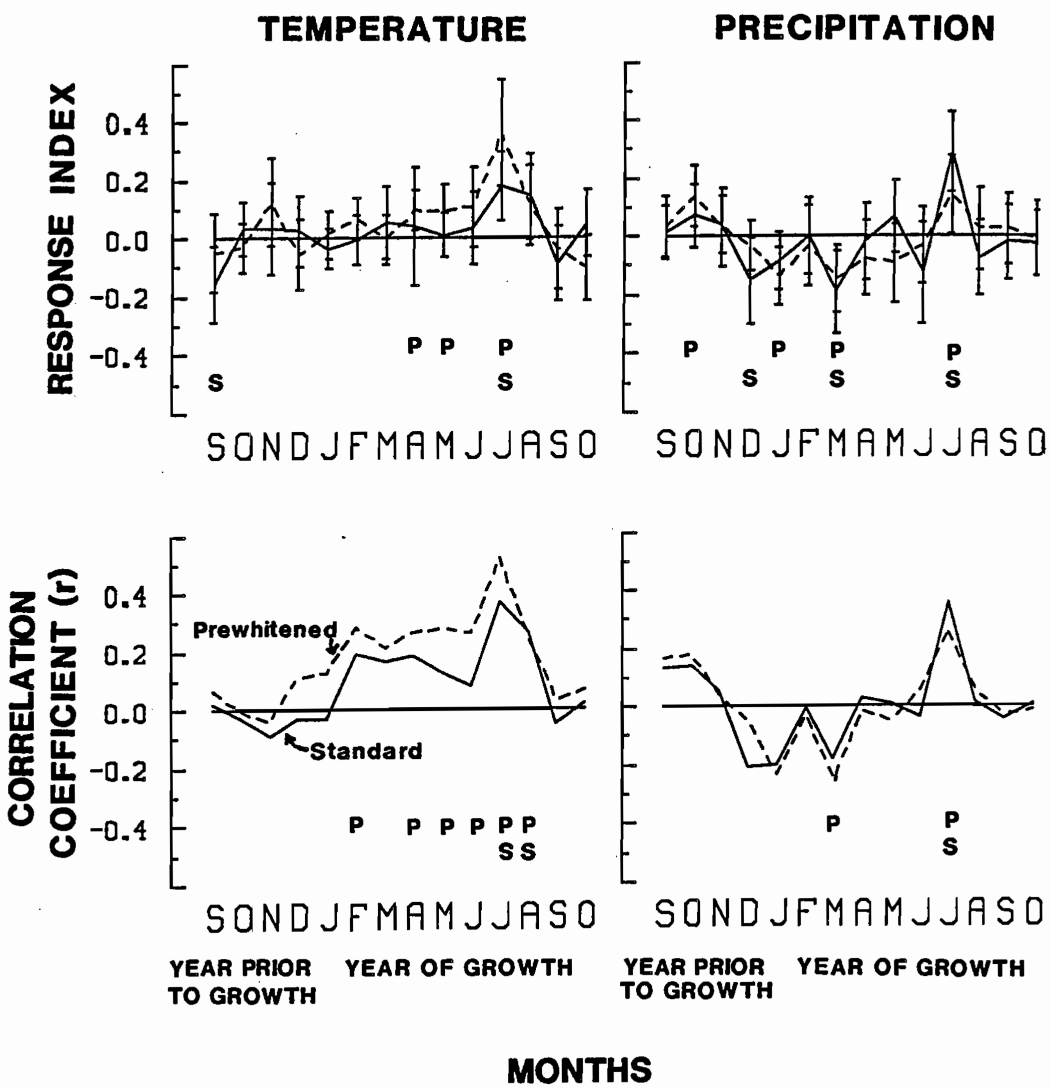


Figure 4. Response functions from principal components regression (top) and simple correlations (bottom). Ninety-five percent confidence limits are shown for the standardized response indices. Significant monthly climatic values ($p < 0.05$) are indicted by the letters "P" and "S" when the dependent variable was prewhitened tree-ring indices and standard tree-ring indices respectively.



regression on the standard indices the climatic variables explained 32.6% of the chronology variation (F = 2.76, P = 0.0076, R^2adj. = 0.208). Lower correlations with the standard chronology may be due to the "biological persistence" in the redwood series which may confound the climatic signal (Fritts 1976, Monserud 1986, Biondi and Swetnam 1988).

July is typically the driest and warmest month at Eureka and inspection of plotted precipitation values for this month and other summer months with the growth index values showed that drought years were often associated with lower than usual growth. Warmer temperatures during the growing season, however, were often associated with increased growth in redwood, especially when it was not particularly dry during these months.

It is interesting to note that fog conditions in the coastal area occur typically in the summer months when low pressure systems and associated warm surface air settle over the region. The biogeographic relationship of redwood and this fog phenomena has long been a topic of speculation. Although Schulman (1940) did not find any apparent relation between fog records and the ring variation in his chronologies, the findings presented here suggest that further dendroclimatic studies using longer fog records that may now be available, perhaps in combination with temperature and precipitation records, could provide new insights.

DISCUSSION

Detection of large growth releases in redwood seems to be a useful way of documenting severe disturbances that resulted in death of competitors. For example, LaMarche (1966) observed growth releases in redwood on the Blue Creek drainage (approximately 20 km north of Prairie

Creek) that were due to a flood event in the 1860s. He also noted a consistent large growth release among his samples in the 1530s that he inferred to be due to a past fire event (LaMarche, pers. comm.). Evidence presented in this paper also shows that redwood rings with traumatic resin ducts can be an additional source of evidence that is useful in dating past fires. However, due to observed variability in the timing of growth release in survivor trees following disturbances, and variability in timing of traumatic resin duct formation, there is often a need for additional evidence, such as dated scars, for establishing accurate dates of past disturbances.

It is concluded that a comprehensive redwood fire history study, based on crossdated fire scar specimens, is feasible. Such a study should exploit existing redwood stumps while they are still available. A concentrated effort will be required to improve and extend the existing redwood tree-ring chronology from the Prairie Creek area, which would be needed for a control in the dating of fire scars on stumps. The most successful approach for developing fire history for redwood stands would also include sampling the age structure of understory species and redwood sprouts as demonstrated by Viers (1980), Abbott (1987) and Stuart (1987).

Although useful age structure data can be obtained using simple ring counting, there are several advantages of using crossdating techniques in reconstruction of forest disturbance history. These include (1) the ability to date rings and fire scars on old stumps or logs of unknown cutting dates, or stumps without sapwood, (2) reliable comparison of fire dates between trees and study areas (locally and regionally) for analysis of spatial distribution of past fires, (3) reliable comparison of fire dates with independent environmental records, such as climate, and (4) the additional uses of tree-ring index chronologies, such as paleoclimatic investigation.

Successful crossdating of redwood samples has demonstrated that it is feasible to develop accurately dated tree-ring chronologies from coast redwood. However, the common occurrence of partial rings will probably continue to preclude the use of increment cores for developing coast redwood chronologies. The use of full or partial cross section samples where possible seems to be the most reliable way of obtaining ring-width measurement series that can be used for graphical and statistical comparison and crossdating. Several strategies are recommended for developing useful, long time span redwood chronologies. These include:

1. Samples should be obtained from carefully selected redwood stumps, and where possible from logs of harvested trees so that radii from positions high on the stem can be analyzed. As observed by Schulman (1940), samples from higher positions on the stem seem to be relatively free of the partial ring problems and extreme growth fluctuations (e.g., compression wood) that obscures common ring patterns.

2. There is a need for careful selection of specimens that have open growth series, where rings can be traced around the circumference. Specimens should have sufficient variability in ring widths for crossdating. Time periods represented by relatively wide rings may be necessary for initially establishing portions of the chronology for dating control. The inner portion of trees generally has wide rings (in sites where early establishment was in open forest conditions), so

sampling of trees with a range of ages may be useful for working out dating problems in different periods.

3. Crossdating is most efficiently accomplished by comparing ring-width plots of measured series where the original series is carefully counted on a cross section. Radii that are most free of distortion caused by compression wood can be selected on cross sections.

The dendroclimatic qualities of the Prairie Creek redwood chronology is relatively good. The mean sensitivity of this chronology compares favorably with other chronologies recently developed from other species in the northern California region (Holmes et. al. 1986). The crossdating of the Prairie Creek chronology with the redwood chronologies developed by Schulman is remarkably good considering the distances separating these collection areas. The synchrony of the three redwood chronologies, and the significant climatic correlations, indicates that there is substantial climatic signal present in redwood tree-ring series that may be profitably analyzed for past climatic information.

The tree-ring chronology developed in this study should be considered a preliminary attempt at developing a redwood chronology. Additional samples should be collected and processed into new chronologies or averaged with the chronology presented here. It is most probable that a higher signal-to-noise ratio, higher mean sensitivity, and increased length could be obtained. Indeed, with a concerted effort it should be possible to develop a chronology of at least 1,000 years length. Such a chronology would be useful for dating control in the development of very long fire chronologies and for the study of past climatic variation.

APPENDIX A

Prairie Creek, California

Tree-Ring Index Chronologies

Table A-1. Prairie Creek, California chronology - standard indices.

RCXBG0 PRAIRIE CREEK, CALIFORNIA ***STANDARD INDICES***
COAST REDWOOD
LATITUDE 41° 15' LONGITUDE 124° 0' ELEVATION 250 METERS
COLLECTED BY: R. MASTROGIUSEPPE, T. W. SWETNAM

	TREE RING INDICES										NUMBER OF SAMPLES									
DATE	0	1	2	3	4	5	6	7	8	9	0	1	2	3	4	5	6	7	8	9
1750	128	99	109	115	102	110	97	86	100	73	6	6	6	6	6	6	6	6	6	6
1760	101	109	109	111	87	96	96	86	77	84	6	6	6	6	6	6	6	6	6	6
1770	96	86	109	107	111	97	102	99	118	150	6	6	6	6	6	6	6	6	6	6
1780	110	107	121	88	103	98	105	85	104	84	6	6	6	6	6	6	6	6	6	6
1790	94	117	115	109	101	107	90	90	95	93	6	6	6	6	6	6	6	6	6	6
1800	96	93	100	101	96	103	82	75	78	75	6	6	6	6	6	6	6	6	6	6
1810	80	85	79	98	86	98	108	99	106	92	6	6	6	6	6	6	6	6	6	6
1820	90	97	84	87	74	114	85	109	127	125	6	6	6	6	6	6	6	6	6	6
1830	107	117	144	84	86	106	107	134	127	100	6	6	6	6	6	6	6	6	6	6
1840	101	105	105	109	95	140	89	115	115	89	6	6	6	6	6	6	6	6	6	6
1850	83	89	74	82	81	117	114	127	111	112	6	6	6	6	6	6	6	6	6	6
1860	116	115	106	115	111	90	104	81	85	90	6	6	6	6	6	6	6	6	6	6
1870	98	90	93	100	83	86	70	99	104	116	6	6	6	6	6	6	6	6	6	6
1880	85	80	68	53	85	84	89	72	99	91	6	6	6	6	6	6	6	6	6	6
1890	72	105	91	127	146	117	122	105	118	105	6	6	6	6	6	6	6	6	6	6
1900	117	101	138	107	119	107	127	133	116	137	6	6	6	6	6	6	6	6	6	6
1910	134	107	143	137	120	136	114	86	84	71	6	6	6	6	6	6	6	6	6	6
1920	82	92	75	109	80	105	108	96	95	103	6	6	6	6	6	6	6	6	6	6
1930	95	104	87	44	71	63	98	65	74	76	6	6	6	6	6	5	5	5	5	5
1940	73	97	103	127	128	96	129	163	128	106	5	5	5	5	5	5	5	5	5	5
1950	97	90	88	28	16	48	70	80	103	81	5	5	5	5	5	5	5	5	5	5
1960	104	117	116	117	113	95	90	80	111	95	5	5	5	5	5	5	5	5	5	5
1970	89	108	98	104	108	92	116	106	110	107	5	5	5	5	5	5	5	5	5	5
1980	100	118	105	152	125						5	5	5	5	4					

SERIAL CORRELATION = .567 STANDARD DEVIATION = .200 MEAN SENSITIVITY = .152 N = 235

Table A-2. Prairie Creek, California chronology - prewhitened indices.

RCXBG0 PRAIRIE CREEK, CALIFORNIA ***PREWHITENED INDICES***
COAST REDWOOD
LATITUDE 41° 15' LONGITUDE 124° 0' ELEVATION 250 METERS
COLLECTED BY: R. MASTROGIUSEPPE, T. W. SWETNAM

TREE RING INDICES

DATE	0	1	2	3	4	5	6	7	8	9
1752			106	111	93	107	92	86	107	75
1760	114	112	105	105	82	101	98	89	84	97
1770	107	91	116	103	106	89	102	99	119	141
1780	81	96	117	77	106	98	105	82	111	85
1790	101	122	107	100	96	106	87	95	102	98
1800	100	96	105	102	95	105	81	85	91	88
1810	95	99	88	111	90	105	110	96	106	90
1820	93	102	87	97	81	129	81	113	123	111
1830	92	110	135	60	87	114	106	129	109	82
1840	98	105	102	105	89	141	72	115	109	80
1850	87	99	82	96	93	128	109	119	96	102
1860	109	105	96	111	103	82	106	80	94	100
1870	106	92	98	106	84	95	79	116	108	114
1880	76	86	81	71	114	98	99	79	116	96
1890	77	120	93	131	133	90	108	93	113	96
1900	112	91	134	88	110	96	121	119	96	125
1910	114	84	135	115	94	121	92	75	90	82
1920	99	103	80	123	79	114	108	93	95	106
1930	94	108	85	50	102	91	120	71	91	95
1940	90	113	109	127	114	79	127	150	91	81
1950	91	92	94	37	53	103	105	102	118	83
1960	111	118	107	105	103	88	91	88	123	90
1970	90	114	96	103	107	87	119	100	106	101
1980	94	117	96	146	97					

NUMBER OF SAMPLES

DATE	0	1	2	3	4	5	6	7	8	9
1752			6	6	6	6	6	6	6	6
1760	6	6	6	6	6	6	6	6	6	6
1770	6	6	6	6	6	6	6	6	6	6
1780	6	6	6	6	6	6	6	6	6	6
1790	6	6	6	6	6	6	6	6	6	6
1800	6	6	6	6	6	6	6	6	6	6
1810	6	6	6	6	6	6	6	6	6	6
1820	6	6	6	6	6	6	6	6	6	6
1830	6	6	6	6	6	6	6	6	6	6
1840	6	6	6	6	6	6	6	6	6	6
1850	6	6	6	6	6	6	6	6	6	6
1860	6	6	6	6	6	6	6	6	6	6
1870	6	6	6	6	6	6	6	6	6	6
1880	6	6	6	6	6	6	6	6	6	6
1890	6	6	6	6	6	6	6	6	6	6
1900	6	6	6	6	6	6	6	6	6	6
1910	6	6	6	6	6	6	6	6	6	6
1920	6	6	6	6	6	6	6	6	6	6
1930	6	6	6	6	6	5	5	5	5	5
1940	5	5	5	5	5	5	5	5	5	5
1950	5	5	5	5	5	5	5	5	5	5
1960	5	5	5	5	5	5	5	5	5	5
1970	5	5	5	5	5	5	5	5	5	5
1980	5	5	5	5	4					

SERIAL CORRELATION = -.053 STANDARD DEVIATION = .161 MEAN SENSITIVITY = .187 N = 233

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