A cross-dated fire history from coast redwood near Redwood National Park, California

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Cross sections from coast redwood trees (*Sequoia sempervirens* (D.Don.)Endl.) in and near Redwood National Park were dendrochronologically cross-dated and used to develop a fire history from 1714 to 1985. A master chronology for the study area was first developed from old-growth trees and provided dating control for fire-scarred samples. Redwood offers a challenge for dendrochronology owing to partially absent rings (ring wedging) and uniform ring widths (complacency). Cross dating was successful in portions of 12 of 24 fire-scarred trees. Fire events were dated by noting the position of fire scars and other fire-associated ring structures (resin ducts, double latewood, growth releases, and ring separations) in the cross-dated ring series. Using only dates of fire scars, the mean fire interval (MFI) was 9.9 years from the first recorded fire in 1714 to the last in 1962. The MFI was 8.0 years for the best represented (greatest sample depth) presettlement period from 1714 to 1881. Using dates for all fire-associated ring features, the MFI from 1714 to 1962 was 7.0 years and from 1714 to 1881 was 6.0 years. Use of all fire-associated ring characteristics is argued to be a more complete representation of past fire frequency due to possible under-representation of fire-scar records from stump-top samples. Based upon scar positions within annual rings, fires occurred predominately late in the growing season or after growth ceased for the year. The mean fire intervals determined are shorter than those reported in all except one other fire history study from coast redwood and suggest that fire frequency in redwood may have been underestimated in many past studies.

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Des sections radiales de séquoia côtier (*Sequoia sempervirens* (D. Don) Endl.) provenant d'arbres situés dans et à proximité du "Redwood National Park" ont été datées par recoupement dendrochronologique et utilisées pour reconstituter l'historique des feux de 1714 à 1985. La chronologie de base dans l'aire d'étude avait d'abord été établie à partir de vieux arbres et a servi de référence pour la datation des échantillons portant des cicatrices laissées par les feux. Le séquoia présente un défis pour la dendrochronologie à cause de l'absence partielle de certains cernes, qualifiés de cernes incomplets, et de l'uniformité dans la largeur des cernes typique d'un environnement favorable. La datation par recoupement a donné des résultats concluants dans des sections de 12 des 24 arbres portant des cicatrices laissées par les feux. Cinq événements furent datés en notant la position des cicatrices laissées par les feux ainsi que d'autres particularités des cernes associées aux feux; comme les canaux de résine, le dédoublement du bois d'été, les poussées de croissance et le décollement des cernes dans les séries de cernes utilisées pour la datation par recoupement. En utilisant seulement l'âge des cicatrices laissées par les feux, l'intervalle moyen entre les feux était de 9,9 ans depuis le premier feu survenu en 1714 jusqu'au dernier, en 1962. Au cours de la période la mieux représentée, c'est-à-dire la période où l'intensité d'échantillonnage était la plus élevée, qui est la période précédant la colonisation, de 1740 à 1881, l'intervalle moyen entre les feux était de 8,0 ans. En utilisant les dates obtenues en tenant compte de toutes les particularités des cernes associées aux feux, l'intervalle moyen entre les feux était de 7,0 ans entre 1714 et 1962 et de 6,0 ans entre 1714 et 1881. On considère que l'utilisation de toutes les particularités des cernes associées aux feux fournit une représentation plus complète de la fréquence passée des feux étant donné la sous-représentation des données sur les cicatrices laissées par les feux obtenues à partir d'échantillons prélevés à la surface des souches. En se basant sur la position des cicatrices laissées par les feux dans les cernes, les feux seraient survenus surtout à la fin de la saison de croissance ou après que la croissance ait cessée pour l'année. Les intervalles moyens que nous avons calculés entre les feux sont plus courts que ceux qui ont été rapportés dans toutes les autres études portant sur l'historique des feux chez le séquoia côtier, à l'exception d'une, et suggèrent que la fréquence des feux chez le séquoia pourrait avoir été sous-estimée dans plusieurs études antérieures.

[Traduit par la rédaction]

Introduction

Fire has long been recognized as an important disturbance process influencing coast redwood (*Sequoia sempervirens* (D.Don) Endl.) (Fisher 1903; Fritz 1931). Redwood trees with charred bark are present throughout redwood forests. Many trees also have large basal fire-scar cavities (known locally as "goosepens"). However, the degree to which redwood is dependent upon fire for establishment and maintenance within the community is debated (Veirs 1985; Finney and Martin 1989). Redwood has thick bark and the ability to sprout prolifically, both of which can offer competitive advantage in a fire environment (Wright and Bailey 1982). In contrast, redwoods grow in relatively mesic, often fog-shrouded, coastal locations not usually associated with widespread or frequent fires. Some researchers have suggested that redwood should be considered a climax species and fire independent (Fritz 1931; Roy 1966; Wright and Bailey 1982). Others contend that without fire, redwood is replaced by more shade-tolerant but less fire-adapted species such as Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco) (Cooper 1965; Stone et al. 1972*a*, 1972*b*). This debate has important implications for management of redwood communities,

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particularly concerning the reintroduction of fire through prescribed burning programs (Veirs 1985; Jacobs et al. 1985).

Central to this debate is the historical nature of fire regimes in coast redwood forests. Fire regimes are combinations of temporal and spatial components that govern community and species response to fire. Fire frequency is an especially important fire regime variable to consider. The structure and composition of many forest types are inherently dependent upon how often fire occurred in the past (Wright and Bailey 1982). Reconstructions of past fire frequency in redwood are difficult to compare between studies owing to differing methodologies and study areas (Finney and Martin 1989). However, fire frequencies found by individual studies have tended to significantly influence conclusions concerning the "role" of fire in redwood forest dynamics.

Here we report a dendrochronologically cross-dated fire history for a stand of coast redwood near Redwood National Park in northern California. This study is different from other fire-scar analyses in redwood in that this was the first to use cross-dating methods. Previous studies of fire scars in coast redwood used ring counts to determine the number of years between scars. Ring counting does not always allow absolute temporal comparison of fire scars within and between trees because of the presence of ring anomalies (i.e., missing or false rings) in tree-ring series of some species (Madany et al. 1982). Cross dating of ring series (Stokes and Smiley 1968; Swetnam et al. 1985) offers a means for identifying such anomalies and provides absolute calendrical dates for fire scars or other fire-associated ring features. Cross dating also permits dating of stumps and other remnant (dead) material for which there is no a priori information about cutting or death dates (Baisan and Swetnam 1990).

Previous dendrochronological study of coast redwood has been limited owing to difficulties encountered in cross-dating ring-width series. The most vexing problem is a lack of uniform ring widths around the circumference of a stem (circuit uniformity). Ring discontinuities, where one or more rings "wedge out" along the circumference, are a fairly common feature in redwood (Fritz and Averill 1924; Fritz 1940). Fritz (1940) noted differences in counts of up to 100 rings from different radii of a single tree. To add further complication, redwood ring series are generally very "complacent," with little year to year variability in ring widths. Crossdating depends upon an ability to visually or statistically match common, climatically influenced patterns of ring-width variation from tree to tree. With less variability in ring widths, in-common patterns are more difficult to discern.

Methods

Master chronology

A master tree-ring chronology was first developed for the study area from ring-width measurements of full and partial circumference cross section samples removed from old-growth redwood trees. The trees sampled were felled in 1985 in an area of old-growth redwood known as Prairie Creek Corner (Fig. 1) on the eastern side of Prairie Creek State Park in the northern end of redwood distribution. This master chronology served as dating control for the fire-scarred samples that were used to develop the fire history. Fifteen trees were sampled for the development of the master chronology.

Cross sections were essential for cross-dating efforts owing to the problem of incomplete rings. Ring wedging is an internal tree phenomenon and apparently unrelated to climate. This generally precludes the use of increment cores for dating purposes since it is necessary to search the tree circumference to detect areas of discontinuous rings. Cross sections used for the master chronology were removed from at least 6 m above ground level on sampled trees. Schulman (1940) analyzed redwood samples taken from various heights and concluded that ring series from higher up the main stem had fewer ring discontinuities than those from lower on the stem.

The transverse surfaces of the cross sections were prepared and polished using a belt sander and successively finer grits of sandpaper down to 400 grit. Ring circumferences were carefully searched to find any missing or discontinuous rings. Skeleton plots (Stokes and Smiley 1968; Swetnam et al. 1985) were used to compare tree radii with each other.

After plotting and assigning preliminary dates based upon the skeleton plots, two or three radii on selected cross sections were measured (Robinson and Evans 1980). The measured ring widths were then compared with each other in two ways. First, ring sequences were statistically compared using program COFECHA (Holmes 1983). COFECHA computes correlation coefficients between overlapping segments of ring-width series. COFECHA also checks cross dating by computing lagged correlations between ring series 10 years forward and 10 years backward from the dated position 1 year at a time. Missing rings in a series can be detected by higher correlations at other than the dated position. Second, ring series were graphically compared by overlaying plots of the ring-width measurements on a light table. Digital filters designed to emphasize longer period fluctuations also were applied to the ring widths and the resulting plots overlaid to assess low-frequency similarities between radii.

After absolute cross dating between radii was confirmed using a combination of the above methods, individual ring-width series were combined into the master chronology. Age- and stand-related growth trends in the ring widths were first removed by detrending using cubic smoothing splines with 50% frequency response at 100 years (Cook and Peters 1981). Detrending involved dividing each yearly ring width by the corresponding spline value to form a dimensionless index series with stable mean and variance. After detrending, a time-series (autoregressive) model (Box and Jenkins 1970) was fit to each ring index series (Meko 1981; Cook 1985). Detrending and autoregressive modeling were designed to emphasize high-frequency, year to year fluctuations in the ring widths which would aid in cross dating of fire-scarred samples. Yearly residuals from the autoregressive modeling were combined into a mean value function (a chronology) using an arithmetic mean. Program ARSTAN (Cook 1985; Cook and Holmes 1986) was used to detrend the series, perform the autoregressive modeling, and calculate the mean value function.

Fire history

Partial and full circumference cross sections were cut from the tops or sides of old-growth redwood stumps with a chainsaw. Stumps were sampled at two sites, Prairie Creek (PRC) and Prairie Creek North (PRN), both on the eastern boundary of Prairie Creek State Park (Fig. 1). Stumps sampled for this study were in second-growth forest that was felled as part of a highway realignment around the State Park. PRN and PRC are, respectively, 4.6 and 5.5 km east of the Pacific Ocean. Elevation at both of the sites is approximately 175 m.

PRC is located in Redwood National Park on a 20–30 m wide strip of highway right-of-way approximately 1 km long immediately south of Prairie Creek Corner (Fig. 1). Most of the PRC samples, with the exception of PRC 1 and 2, were cut by National Park Service personnel and the exact locations of the stumps within the site are unknown. Heights of the samples above ground level are also unknown. Cross sections from PRC 1 and PRC 2 were cut from the tops of stumps 1.0 to 1.2 m above the present ground surface. A total of 25 cross sections from 20 stumps were examined from this site.

PRN is located approximately 0.5 km northwest from Prairie

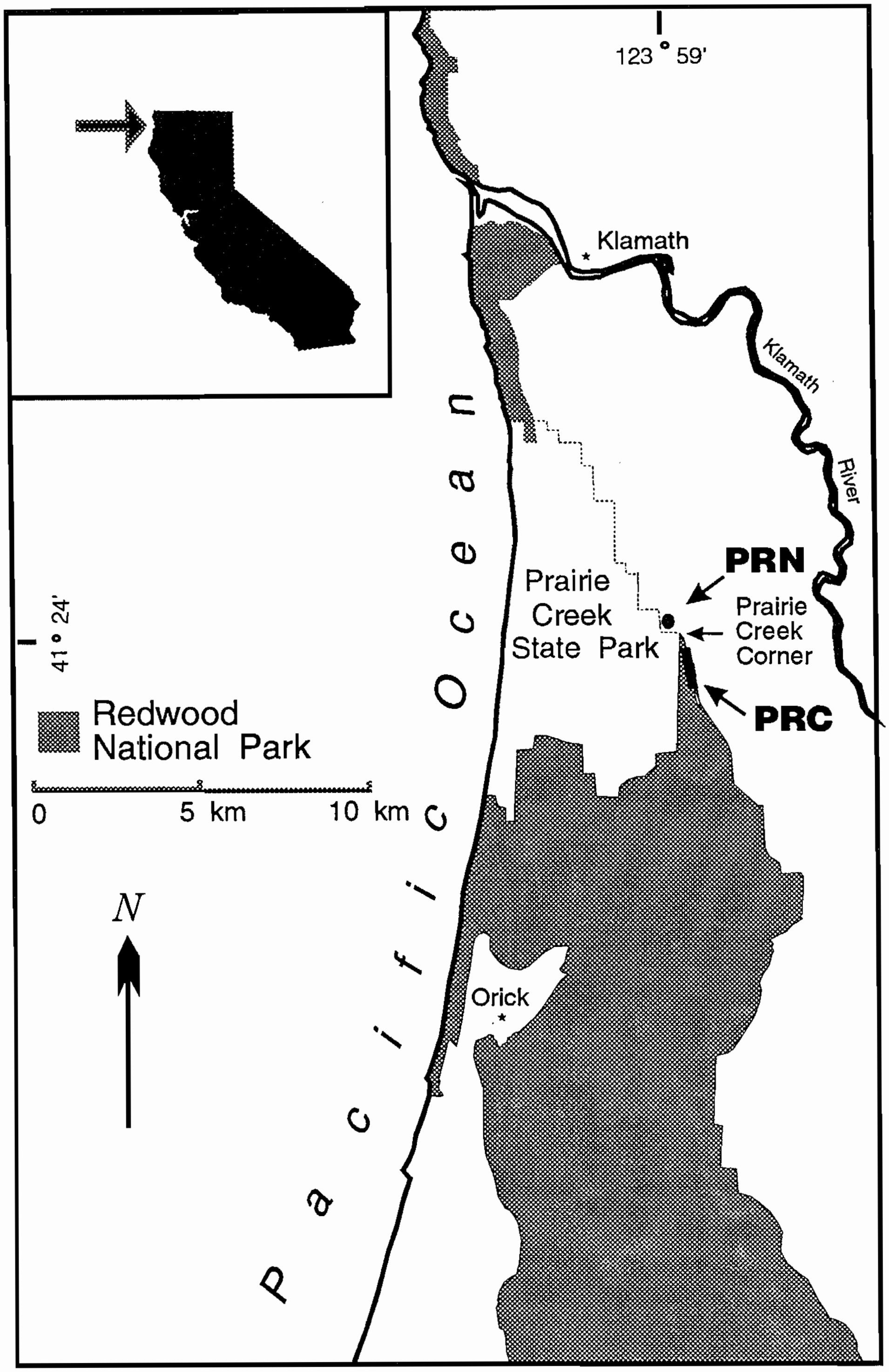

FIG. 1. Locations of study sites Prairie Creek (PRC) and Prairie Creek North (PRN).

Creek Corner on a south-facing slope near the head of a small tributary of the Klamath River. The slope at this site is approximately 20°. Nine cross sections from four stumps were collected in an area of approximately 0.25 h.

Cross sections from PRN were excised from the sides of stumps 0.2–0.5 m above the present ground surface. Fire history studies in giant sequoia (*Sequoiadendron giganteum* (Lindl.) Buchh.) (Swetnam 1993), the closest extant relative of coast redwood, show that for this species the best fire-scar records occur at the base of the main stem directly above the root crown. Most fire scars in giant sequoia do not extend more than a meter up the bole. Redwood appears similar to giant sequoia in fire-scar morphology and, in general, the tops of stumps are found well above the butt flare of the trees, a meter or more above ground level. It is, therefore, probable that the sequences of fire-scars recorded on stump-top samples underestimate fire frequency. Fritz (1931) also commented on a possible under-representation of stump-top scar records in samples he examined.

The fire-scarred sections were surfaced and dated following similar methods used to develop the master chronology. Dates of logging activity for this area were unknown but the master chronology provided absolute dating control for the fire-scarred

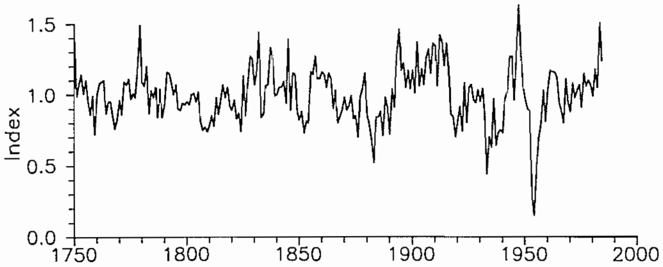

FIG. 2. Master ring-width chronology for Prairie Creek Corner.

samples. Only after cross dating was confidently identified and corrected on the fire-scarred samples were calendrical dates assigned for fire scars and other fire-associated ring features. All dates for fire scars and other fire-associated features (discussed in the next section) were compiled into a master fire chronology and mean fire intervals determined for different periods of the record.

Results and discussion

Dendrochronology

For the master chronology, ring width measurements from six radii of four trees were complied into a mean series from 1750 to 1985 (Fig. 2). Ring wedging was noted on all of the cross sections examined. Most of the crossdated samples had relatively open ring series where locally absent or wedging rings were easily located. Complacency (uniform ring widths) complicated cross-dating by reducing the effectiveness of skeleton plots. However, "signature years" (narrow rings consistently found from tree to tree; Douglass 1919) were occasionally present and aided in crossdating efforts.

For the fire-scarred samples, cross-dating was confidently identified in portions of 12 of 24 trees from both sites. Ring discontinuities appeared to be more numerous on the fire-scarred sections, possibly owing to their lower position on the stem (Schulman 1940). Although the master chronology only extended back to 1750, cross dating of ring widths was observed among the fire-scarred trees back to 1714. Before this date, correlations were lower among the trees examined and there were missing rings in the series that could not be confidently assigned to specific years. A major problem encountered before 1714 was a general increase in ring suppressions and corresponding missing or wedging rings on all of the samples analyzed. It appears that widespread fire in 1714 may have resulted in a growth increase in many of the sampled trees (Fig. 3). Increases in ring width after fire, referred to as "growth releases," were often associated with other fire years (see following fire-associated ring features section). Since there was not as much confidence in dates before 1714, earlier fire years were not included in the fire history.

Fire history

Fire scars and other fire-associated ring characteristics (see following section) recorded in the 12 confidently dated fire-scarred trees are summarized in Fig. 4. Samples from sites PRC and PRN were grouped together to extend the sample depth (numbers of samples per year) for analysis of the fire history. These sites are approximately 0.75 km apart and in similar environmental settings.

Horizontal lines in Fig. 4 represent dated time spans for individual trees with fire scars and other ring characteristics represented by symbols at the dates they were recorded. The bottom portion of Fig. 4 is a composite of the fire index for individual years computed in two ways. A fire index is the percentage of trees recording a scar or other fire-associated ring feature relative to the total sample depth for a given year. A fire index of 100% would mean that all sampled trees recorded a fire in that year. The middle graph is a summary of fire indices using only those years during which actual fire scars were recorded on any sample. The bottom graph is a summary using all fire evidence (fire scars plus other fire-associated features) for calculation of yearly indices. Dates marked at the bottom of the top graph are those when 25% or more of the sampled trees recorded a fire scar or other fire evidence.

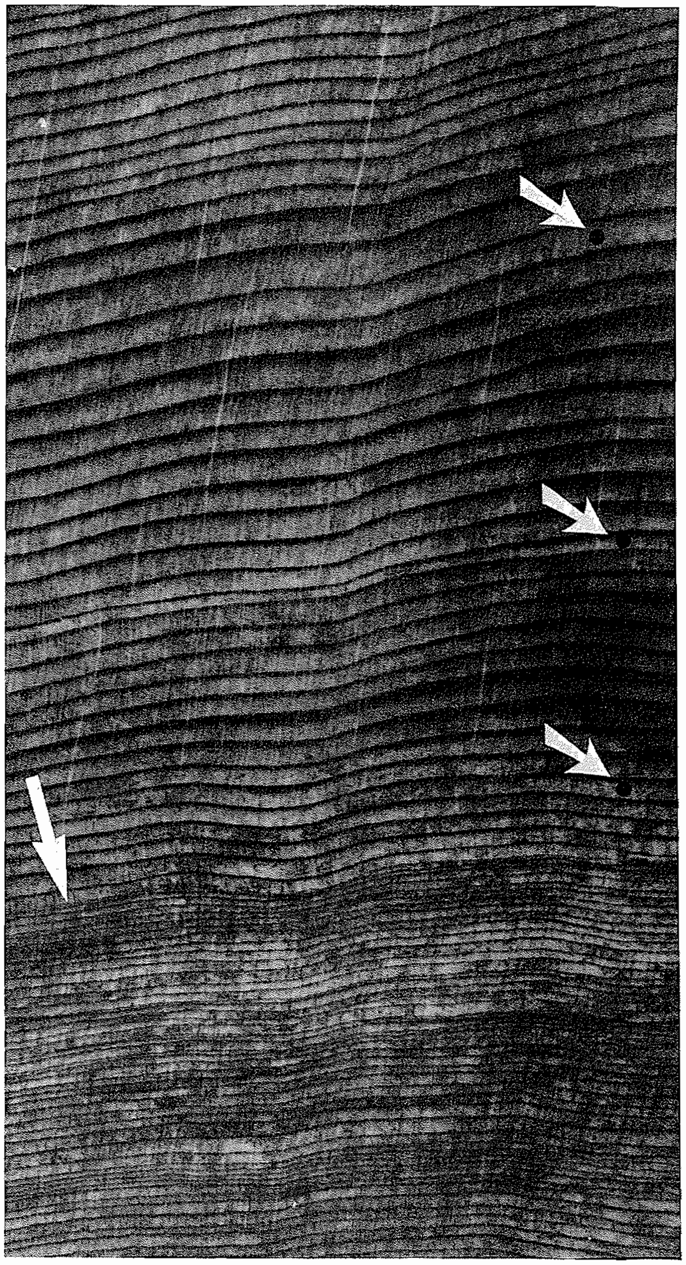

FIG. 3. Photograph of growth release (left arrow) from fire in latewood of 1714 on sample PRC 14. Release begins in 1716, 1715 is a fire ring (see text). Arrows on right point to 1720, 1730, and 1740.

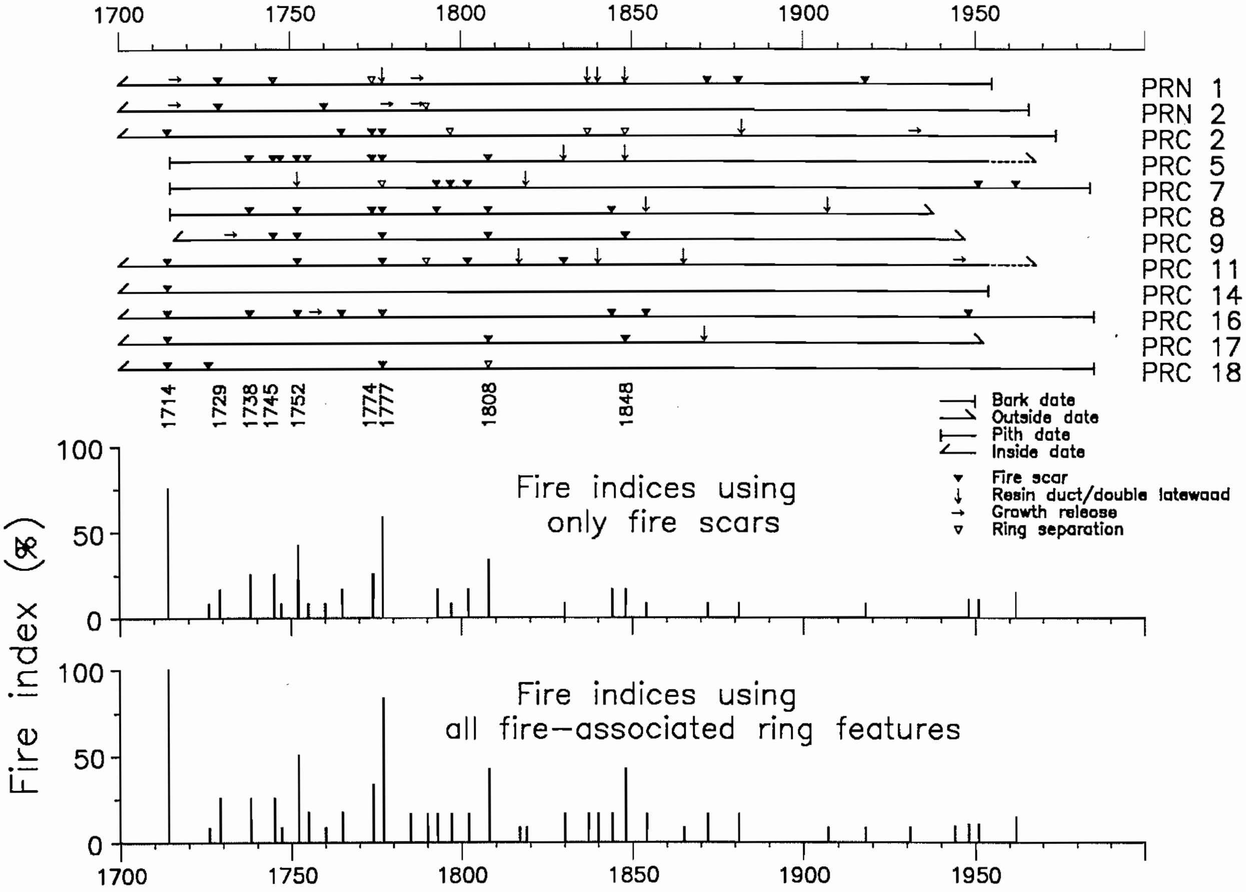

FIG. 4. Fire chronology for sites PRC and PRN.

Based solely on the number of trees scarred, there appears to have been at least 2 years of widespread fire. The first was 1714, during which fire scarred or otherwise influenced all the trees that were alive during that year (PRN 1, PRN 2, PRC 2, PRC 11, PRC 14, PRC 16, PRC 17, and PRC 18). The other four trees appear to have established immediately after this fire year. Three of these trees, PRC 5, PRC 7, and PRC 8, have pith dates of 1715. PRC 9 has an inside date of 1716, which is estimated to be 1 year later than pith. These trees may have been either basal sprouts from trees killed by fire in 1714 or new seedlings that established immediately after 1714. Basal sprouting after fire is a well-known characteristic of redwood (Fritz 1931; Daubenmire 1984; Stuart 1987; Abbott 1987). Stuart (1987) noted similar establishment patterns for basal sprouts after fire in his study areas. Nine of 10 sprouts in an area that burned in 1974 had inner dates of 1975. In another area that burned in 1936, eight of 10 sprouts had inner dates of 1937 (Stuart 1987).

Fire in 1777 is also recorded as either a scar or other fire-associated ring characteristic on 10 out of 12 trees. On three trees (PRC 2, PRC 5, and PRC 8) the fire year of 1777 follows fire recorded in 1774. Short interval fires (3–5 years) were also recorded on other trees (PRN 1 and PRC 7). Both Jacobs et al. (1985) and Finney and Martin (1992) also found short interval fire scars (2–5 years) on redwood trees they examined.

Fire-associated ring structures

Stump-top fire-scar records could underrepresent the total number of fires that have affected a tree since scars often do not extend more than a meter above ground level. However, based upon evidence from both coast redwood and the closely related giant sequoia, it appears that other fire-associated ring characteristics extend farther up the stems of trees than do fire scars and can serve as additional proxy evidence of fire occurrences. Most of these ring structures have not been previously reported in the literature as associated with fire events.

Growth releases

Often observed were abrupt increases in ring width lasting from 2 or 3 years up to several decades after a fire scar was recorded. These growth releases extend much farther around the ring circumference and up the stem than healing surges found at scar boundaries. Growth releases can be quite dramatic as evidenced by the release associated with the fire year of 1714 (Fig. 3).

Fire-associated growth releases are common in giant sequoia (Stephenson et al. 1991; Mutch and Swetnam 1993; Hughes and Brown 1992). Hartesveldt (1964) noted growth releases following fires in the Mariposa Grove. An example of an extreme growth release in giant sequoia occurred at the Mountain Home Grove after fire recorded in the middle part of the growing season of A.D. 1297 (Stephenson et al. 1991; Hughes and Brown 1992). An increase in ring width of greater than 100% is evident for up to a century after this fire year before returning to widths comparable to before 1297. Growth releases probably represent a positive tree response to environmental modifications caused by fire. These modifications may include a reduction in competi-

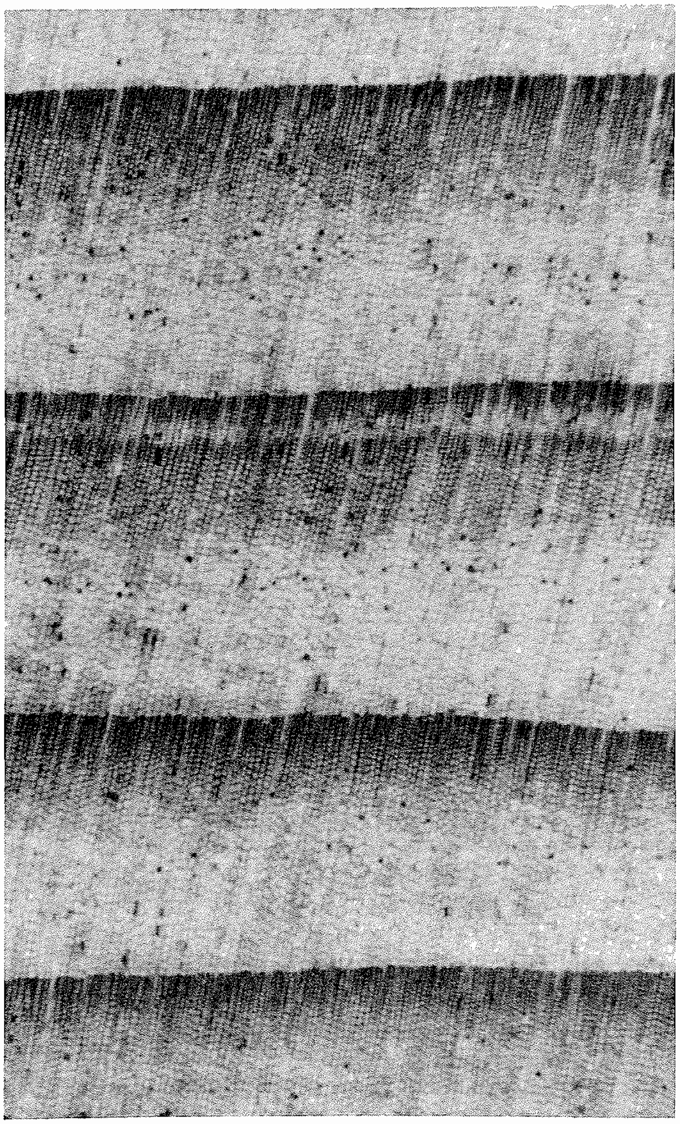

FIG. 5. Double latewood in 1848 on sample PRC 9. A latewood fire scar was present elsewhere on this sample in this year.

tion from surrounding individuals killed by fire (Hartesveldt 1964) and surges in available nutrients or changes in soil pH owing to rapid oxidation of fuels.

Double latewood

Late season fire scars were occasionally associated with a double latewood, in which a narrow zone of 2–10 thinner walled earlywood-type cells was present within the latewood band (Fig. 5). Double latewood is similar to false rings in other species, although in coast redwood and giant sequoia it appears to be only associated with fire scars. In giant sequoia, double latewood bands have been seen in radial sections removed from over 30 m above ground level.

Double latewood may also represent ecophysiological changes brought about by fire similar to those processes that resulted in growth releases. Growth response to environmental modifications during latewood formation may lead to a brief return to the production of earlywood-type cells before final latewood formation for the year.

Ring separations

On several samples, tracheid cells were separated at the boundary between two rings. These distinctive ring separations extended approximately 2–5 cm along the circumference (Fig. 6). On two samples from PRC, ring separations were noted to have occurred between two rings that had a dormant season fire scar present elsewhere on the same sample (see Baisan and Swetnam (1990) for an explanation of fire-scar position within the annual ring). Similar ring separations were associated with dormant season fire scars in giant sequoia (T.W. Swetnam, unpublished data).

Ring separations may be areas where partial cambial death from heating occurred even though a scar with a characteristic healing surge did not form. Ring separations have been found in sequoia and other species along the top margins of a fire-killed cambial surface. Fire scars are three dimensional around the tree stem with commonly an inverted wishbone shape. Often there is very little of the characteristic healing surge seen at the highest point of dead cambium on the stem. It is possible that ring separations noted on stump-top samples are the uppermost extent of a more well-developed scar present lower on the stem.

Resin ducts

Bands of traumatic resin ducts formed parallel to ring boundaries were associated with fire scars in several samples (Fig. 7). In redwood and giant sequoia, as in other members of the Taxodiaceae, resin ducts are generally formed only in response to wounding or other stress (Harvey et al. 1980; Fahn et al. 1979). In giant sequoia, resin duct bands occurred in different parts of the ring depending upon the season of formation of an associated scar (T.W. Swetnam, unpublished data). Resin ducts following a fire scar recorded in the middle to late earlywood of a ring most often occurred in the latewood of the same ring. Resin ducts following a latewood or dormant season fire generally occurred early in the earlywood of the following ring (as in Fig. 7). Redwood appears to follow a similar pattern of resin duct formation. Resin ducts associated with the 1714 fire were seen in cross sections removed from over six meters above ground level.

Fire rings

Occasionally observed within redwood ring series were narrow (micro) rings that represented the next year's growth after a fire year. These rings were termed "fire rings." Often a fire ring could be seen as a micro ring occurring sporadically around the circumference (Fig. 8) although in at least two instances a fire ring was present in only one small portion of the tree circumference right at a fire-scar boundary. At first it was thought fire rings were false rings (interannual latewood bands). However, cross dating showed that these were true annual rings. (No false rings were observed in any of the dated samples except those that were obviously double latewood.) The presence of a micro ring after a fire year was unusual. More often a release in growth was seen immediately after fire rather than an extreme suppression in radial growth represented by a fire ring.

A possible explanation for the formation of a fire ring in redwood is that fire does appear to stimulate basal sprouting, even from trees not killed by the fire (Finney and Martin 1993). It is conceivable that photosynthate production the year after fire is directed to basal sprouts to the detriment of vascular cambium, at least near the base of a tree. Subsequent years' photosynthetic production is then redirected back to radial growth. In addition, redwood can respond to foliar damage by sprouting from branches following partial or complete crown scorch (Finney and Martin 1993). Foliar

FIG. 6. Ring separation between 1808 and 1809 on PRC 17. A dormant-season fire scar between 1808 and 1809 was recorded elsewhere on this sample.

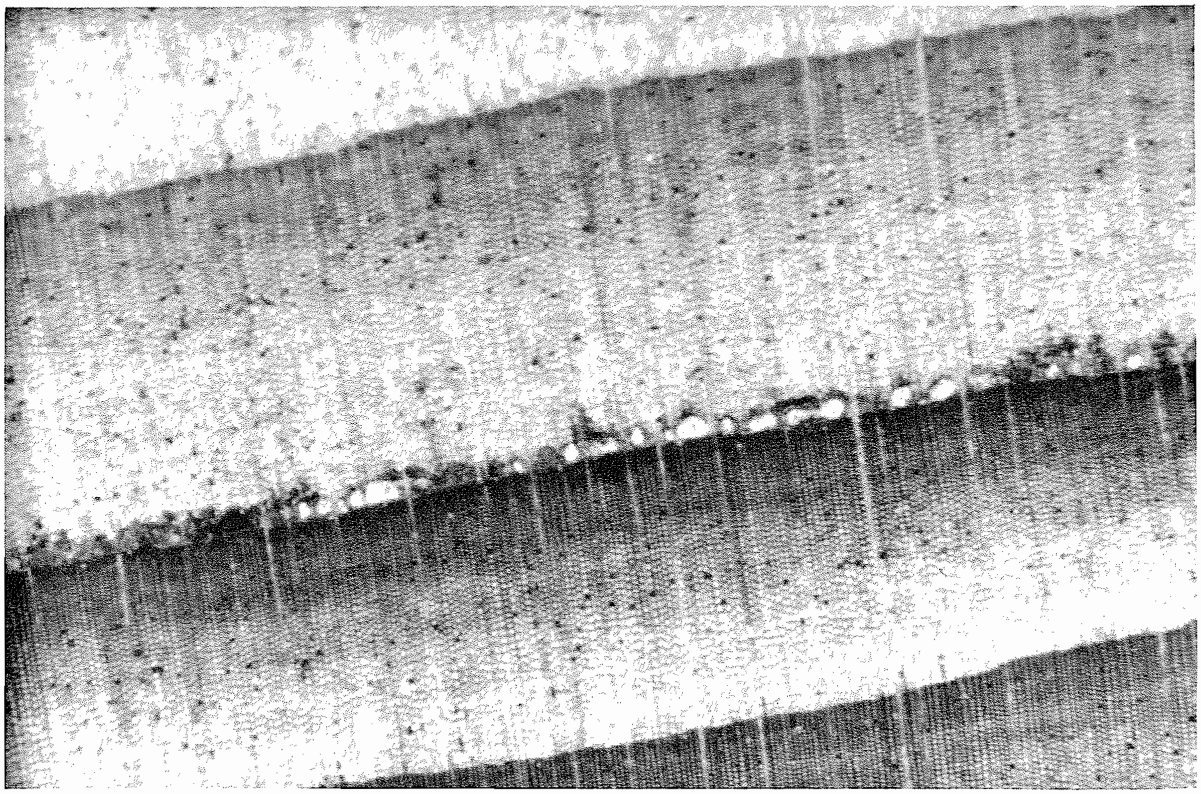

FIG. 7. Traumatic resin ducts in the earlywood of 1746 on PRC 5. A fire scar was present elsewhere on this sample in 1745, although its position within the annual ring could not be determined.

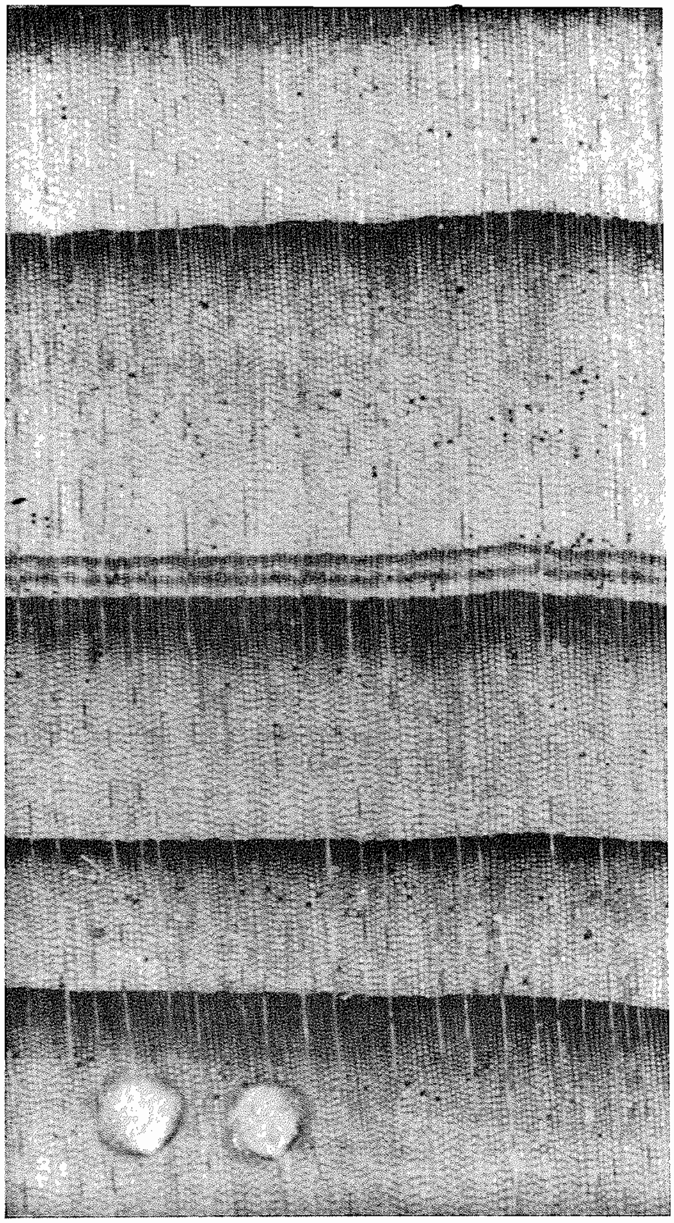

FIG. 8. "Fire rings" (micro rings) at 1753 and 1754 on sample PRC 16. Double pin pricks are at 1750. These rings follow the fire year of 1752, during which fire scars were recorded elsewhere on this sample. This location was the only place on the entire circumference where both of these rings were seen together. This was also the only sample that showed fire rings for 2 years after fire; in all other instances in which fire rings were noted, it was a single ring after a fire year.

recovery the year after a crown-damaging fire could also lead to reduction in cambial growth.

Fire scar position

Where fire scar position within annual rings could be discerned, 95% occurred within the latewood band or along the boundary between two adjacent rings (dormant season; see Baisan and Swetnam 1990). The other 5% were found in the middle to last third of the earlywood. No scars were seen in the first third of earlywood growth. Resin ducts occurred in the latewood of a fire year or early in the earlywood of the following ring. This indicates that fire in redwood most often occurred late in the cambial growing season or just after growth had ceased for the year. According to dendrograph studies on redwood conducted by MacDougal (1936) and Haasis (1934) at the southern end of the range of redwood south of Monterey, redwood growth was generally complete by late August to late September, depending upon the tree sampled and climatic factors for the particular year.

TABLE 1. Mean fire intervals (MFI) for sites PRC and PRN computed in two ways

Period	No. of intervals	MFI (years)	SD (years)	Range (years)
		Using only fire scars		
1714–1962	25	9.9	6.2	2–37
1714–1881	21	8.0	5.5	2–22
		Using all fire-associated features		
1714–1962	35	7.0	4.7	2–26
1714–1881	28	6.0	2.9	2–12

The occurrence of late season fires is consistent with what is known about historical patterns of fire and fire weather in northern California (Schroeder 1969; Gripp 1976; Lewis 1973). Summer synoptic-scale weather systems with dry, offshore winds can raise fire hazards for coastal areas (Schroeder 1969). Gripp (1976) discussed historical records of lightning fires that occurred during the late summer period. In an analysis of 64 large fires (>300 acres) in the northern redwood area for the period 1955–1974, Gripp (1976) found that most of these fires occurred in August (23%) and September (45%) vs. June (5%), July (14%), and October (13%). Lewis (1973) cites numerous examples of anthropogenic burning practices, several from tribes such as the Yurok and Hupa that lived in the Prairie Creek and Klamath River area, that point to predominately late summer or early fall burns. Whether the fires recorded in the Prairie Creek redwoods were started by natural or anthropogenic ignitions cannot be answered with currently available data.

Mean fire intervals

Mean fire intervals (MFIs) for the fire chronology were calculated in two ways (Table 1). First, MFIs were determined using only those years in which actual fire scars were recorded (middle graph of Fig. 4). Second, MFIs were calculated using years in which both fire scars and other fire-associated ring features were recorded (bottom graph of Fig. 4). Fire intervals were averaged over both the total length of the fire scar record from the first recorded fire in 1714 to the last in 1962 as well as the best represented (maximum sample depth) presettlement period from 1714 to 1881. Owing to the potential for under-representation of the scar record from stump-top samples, MFIs using all fire-associated ring features are considered to be a more accurate and complete estimation of past fire frequency in this area.

Comparisons with previous fire history studies in redwood

Fire events in redwood have been reconstructed by aging fire scars (Fritz 1931; Veirs 1980; Greenlee 1983; Jacobs et al. 1985; Stuart 1987; Finney and Martin 1989, 1992), dating of stump basal sprouts (Abbott 1987; Stuart 1987), and aging of understory associates such as Douglas-fir and grand fir (*Abies grandis* (Dougl.) Lindl.) that establish after fire (Veirs 1980; Stuart 1987). However, there has been little agreement between these various studies on how often fire burned in the past. Estimates of average fire intervals in redwood communities have ranged from over 250 years

(Veirs 1980) to under 10 years (Finney and Martin 1989). Only the mean fire intervals found by Finney and Martin (1989) in their well-replicated composite fire-scar chronology from Salt Point State Park in the middle of redwood distribution are comparable with those reported in Table 1. Finney and Martin (1989) found MFIs of 6.6–9.2 years in the 1700s and 1800s. All other reconstructions of fire frequency in redwood show longer intervals between fires.

There are several possible explanations for differences in fire frequency estimates. First, there are differences in the methods used to determine fire dates. Dates of sprout initiation or understory establishment provide minimum ages for single fire events while aging of fire scars provides a more continuous record. Compilation of fire-scar records has been done using either single-tree (point) samples or composite fire-scar chronologies, in which fire scars and fire-free intervals are cross-matched from tree to tree at a site (sensu Dieterich 1980). Using point samples, fire intervals within individual trees are averaged before a mean fire interval for the site is determined. A point sample average for the period 1714 to 1881 was calculated from data found by this study. Using only dates of fire scars, the MFI determined by this method was 20.7 years. This value agrees with point sample mean fire intervals found by Finney and Martin (1989; 20.6–29.0 years), Jacobs et al. (1985; 21.7–27.1 years), and Fritz (1931; roughly 25 years). However, these estimates are undoubtably considerably greater than actual mean fire intervals owing to the problem of incomplete scar records on individual trees. Not all fires that burned around a tree are recorded by that tree and scars may be lost by weathering or burning by subsequent fires (Finney and Martin 1989). Under-representation of scar records from stump-top samples would also contribute to lengthening MFIs calculated from single trees.

Use of cross-dating or ring-counting methods for determining the number of years between fire scars may also lead to differences in fire frequency. Cross-dating is more accurate than ring counting for determining dates of past fires and estimating past fire frequency (Madany et al. 1982; Dieterich and Swetnam 1984). Both Wagener (1961) and Zackrisson (1980) noted that missing or false rings led to inaccurate fire intervals in ring-counted fire history data they examined. Problems encountered in redwood ring series, such as ring discontinuities, suppressed rings, and fire rings, have the potential for compounding the inherent inaccuracies of ring counts. Estimated scar dates from different trees may be adjusted such that scars "fit" with others of the same general time period (Arno and Sneck 1977). Mismatching of estimated scar dates between trees could lengthen fire intervals if assumed contemporary scars are actually different dates representing 2 or more fire years.

Comparison of fire frequency in redwood forests is undoubtedly further complicated by differences in study sites (Finney and Martin 1989). Variations in environmental conditions between redwood stands could have led to significant differences in fire frequency. For example, Veirs (1980) used stand-age structure distributions on plots in Del Norte and Humboldt Counties to suggest that there was an ocean–inland gradient in fire frequency. Veirs estimated that the most mesic coastal sites burned only once every 250–500 years, while drier, inland sites burned closer to once every 50 years. The sites analyzed for this study are somewhat intermediate in the ocean–inland distribution of redwood in this area of the California coast, and presumably intermediate in any sort of moisture gradient. It is, therefore, possible that the samples collected for this study recorded higher fire frequency due to more xeric conditions than other sites closer to the coast. However, even if this were the case, the fire frequency found by this study is still considerably greater than that estimated by Veirs in even the most xeric sites. Whether there was less frequent fire in more mesic sites closer to the coast or more frequent fire inland can only be answered with more extensive fire history data from this general area.

Differences in fire intervals may be furthermore related to the size of the study area from which samples were drawn (Finney and Martin 1989). In fire regimes where fire sizes were generally small, there is an inverse relationship between mean fire intervals and study area size (Finney and Martin 1989). Although a limitation of this study is that the locations of samples at PRC are almost entirely unknown, all fire-scarred samples at PRN and PRC were removed from an area of approximately 45 ha (1.5 km wide by 30 km long), a narrow band that corresponds to the right-of-way cleared for highway realignment around Prairie Creek State Park. This compares to Finney and Martin's (1989) plots of 125–250 ha that had similar estimates of mean fire intervals in the 1700s and 1800s.

Finally, there is the possibility that fire frequencies recorded since 1714 were not representative of longer term fire frequency in this area. Although cross dating of ring widths before 1714 was not successful, there did appear to be fewer fire scars and other fire evidence in the one to two centuries before 1714 than in the period after. Finney and Martin (1989) also noted an increase in fire frequency at Salt Point from the 1600s (MFI 16.8 years) into the 1700s (MFI 9.2 years). Possible changes in fire frequency through time may be related to changes in climate or anthropogenic burning activity (Finney and Martin 1992). Longer term changes in fire frequency through time at sites PRC and PRN may also be investigated with additional and longer term fire history data.

Conclusions

Despite the methodological and analytical problems inherent in coast redwood tree-ring series, development of crossdated ring-width chronologies and fire histories in this species is feasible. The use of fire scars and other fire-associated ring structures such as growth releases, double latewood, resin ducts, ring separations, and fire rings, provides information not only about past fire frequency but also about community and individual tree response to fire.

This study, and those by Finney and Martin (1989, 1992), suggests that the frequency of past fire in coast redwood forests may have been underestimated in previous studies. Possible differences in estimates of past fire frequency owing to intra- or inter-site moisture gradients or sampling areas, or changes through time caused by climate dynamics or human activities, cannot be answered because of dissimilar methodologies used to determine fire intervals. Only with well-replicated crossdated fire chronologies from sites of similar size would one have the temporal resolution needed for site to site comparisons to answer questions raised in the preceding section. Nevertheless, it is evident that at least some redwood forests are not burning nearly as often today as they were in the presettlement era. Meaningful reintroduction of fire into these forests may be warranted, and will require a greater commitment from land management agencies and funding sources.

It often takes a great deal of effort and time simply looking at a species' tree-ring characteristics before one is familiar with its crossdating potential. The use of dendrochronological methods may take longer than ring counting, particularly in difficult species such as coast redwood, but the increase in accurate knowledge should demand that extra effort. Absolute dating control not only provides more accurate estimates of fire intervals but permits dating of dead material and assessment of intersite and fire-climate relationships (e.g., Swetnam and Betancourt 1990; Swetnam 1993) that are not possible from ring counts. Redwood offers the possibility for development of extremely long tree-ring and fire chronologies owing to the old age of individual trees and its remarkable resistance to decay which may provide remnant material for extending chronologies beyond living trees. Coast redwood chronologies exceeding several centuries, if not millennia, in length are feasible and would be unique records of not only fire but climate and other environmental change on the central and northern coasts of California.

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