known and then applying a model once to determine "the optimal management schedule" should not be the intended use of the model.

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Dendrochronology of a Fire-Scarred Ponderosa Pine

John H. Dieterich and Thomas W. Swetnam

ABSTRACT. Historical fire frequency in a stand of southwestern ponderosa pine has been documented in a master fire chronology developed for a prescribed burning study area in Arizona. One of the 12 specimens used to assemble this chronology was a small, suppressed tree that contained 42 fire scars. Standard crossdating techniques were used to date the fire scars accurately, locate missing and locally absent rings, and identify special problems relating to analysis and dating of this unusual specimen. Mean fire interval for the study area was about 2 years; mean fire interval for the individual specimen was 4 years for the 178-year period, 1722–1900. FOREST SCI. 30:238–247.

ADDITIONAL KEY WORDS. Fire history, fire interval, fire frequency.

THE STUDY OF FIRE HISTORY provides important information for evaluating change in plant communities where fire is, or was, a significant ecological factor. By analyzing and dating fire scars on trees, researchers may determine the dates and frequency of historical fires. Data from several trees are combined into a master fire chronology for a particular area. This information is useful in identifying fire regimes for specific areas and periods of time, and for interpreting ecosystem changes that may have occurred as a result of excluding fire from the area (Arno and Sneck 1977, Stokes 1980, Heinselman 1981).

Analyses of fire-scarred material involve both dating of annual growth rings and dating of fire scars. Specimens obtained from some forest types contain multiple fire scars and have tree-ring characteristics which require careful inspection and crossdating to arrive at accurate dates. A recent fire history study (Dieterich 1980b) in a mature stand of ponderosa

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pine (*Pinus ponderosa* Laws.) on the Long Valley Experimental Forest near Clints Well, Ariz., yielded a specimen which illustrates an unusual example of multiple fire scarring.

The specimen of interest (LMF 3) was a ponderosa pine tree that was scarred by fire 42 times during its 327-year life span. These 42 fire years represent the largest number of fires reported to date for an individual tree. This paper describes the detailed analyses of this specimen, including tree-ring and fire-scar characteristics. These characteristics are typical of problems encountered when dating fire-scarred material and illustrate the wealth of information that can be extracted from such an analysis.

THE STUDY AREA

LMF 3 is one of 12 specimens collected from the Limestone Flats prescribed burning study plots (Sackett 1980). The prescribed burning study is designed to evaluate the effects of using fire at various intervals on fuel accumulation and consumption, and to document response of various resources to this planned program of burning. Fire history studies provide important supplemental information for this research by providing historic and scientific bases for using fire at selected intervals.

The specimen was a small tree—only 8 inches (20 cm) dbh and 28 feet (8.5 m) tall growing near the southeast corner of the prescribed burning study area (Dieterich 1980b). It was severely overtopped, had a badly deformed crown, and apparently had suffered intense competition from surrounding dominant trees as evidenced by the number of large stumps in the immediate vicinity. The tree was within a 240-acre (97-ha) area of ponderosa pine that was treated with an experimental commercial clearcut in 1965.[1]

The Limestone Flats study area can be characterized as a ponderosa pine-Arizona fescue (*Festuca arizonica* Vasey) habitat type.[2] Soil type is classified as McVickers very fine, sandy loam and is derived primarily from sandstone. Outcroppings of limestone are present throughout the area and contribute to the parent material (Wheeler and Williams 1974).

METHODS

In July 1978, the tree was felled with a chain saw and a 2-foot section of the fire-scarred bole was removed and taken to the laboratory. This section was further divided into smaller cross sections for subsequent analysis (Fig. 1). Cross section LMF 3A (Fig. 2) was cut from the lowest portion of the bole, approximately 3 inches (7.5 cm) above ground surface. It was one of the cross sections used in developing the master fire chronology for Limestone Flats area described by Dieterich (1980b). Sections LMF 3B, LMF 3C, and LMF 3D were cut from successively higher positions. The wider section between 3C and 3D was not used in the analysis.

The surface of each cross section was smoothed with a belt sander using nine progressively finer belt grits from 40 to 400. The very fine surface resulting from this sequence of sanding made it possible to view individual cell walls and, in several instances, to identify annual rings of only one cell width. The fine surface also helped in identifying fire scars and determining their location within a given annual ring.

Annual rings were dated using the skeleton plot technique (Stokes and Smiley 1968). This technique is one way in which annual ring-width data can be visually inspected on paper. With this technique, relative ring widths are used as an aid for chronologically relating (or crossdating) a group of specimens to each other and for assigning exact dates to the formation of each individual annual ring. Skeleton plots were constructed from the ring pattern along radii beginning at the pith and working out toward the bark. These plots were then crossdated with a master tree-ring chronology developed for the Flagstaff area (Drew 1972).

Fire scars were identified on the basis of the following criteria (Stokes 1980):

1. The presence of a break or gap within a ring or along a ring boundary.

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[1] Presale Report and Appraisal, Commercial Timber Sale—On File, Fuels Management Project RM-2108, Tempe, Ariz.

[2] Hanks, J. P., E. Lee Fitzhugh, and Sharon R. Hanks. 1977. Preliminary habitat types and community types in the ponderosa pine forests of northern Arizona. Final Report for Contracts 16-427 and 16-2158, USDA Forest Service, Southwestern Region, Albuquerque, N. Mex., 143 p.

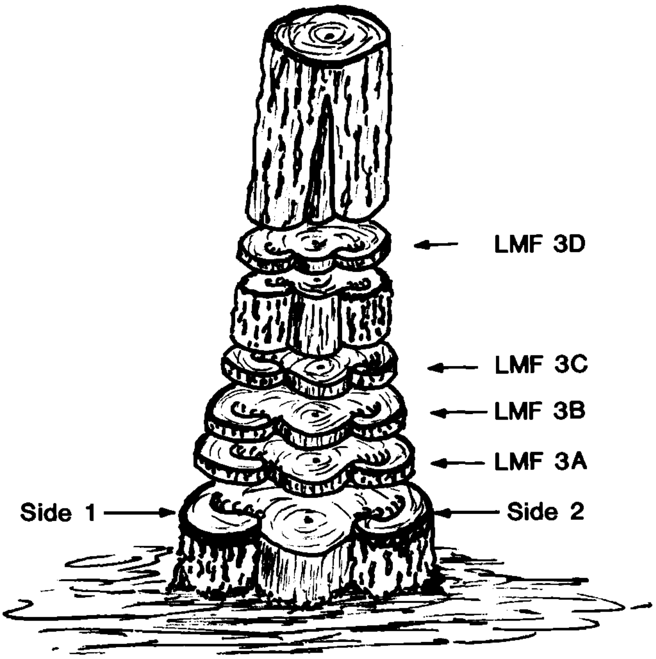

FIGURE 1. Schematic drawing of LMF 3 catface showing relative positions of the four cross sections (3A, B, C, and D).

2. The presence of charred wood within the break or gap.
3. Subsequent overlapping curvilinear growth over the break.

Most fire scars reflected all of these characteristics and were easily identifiable. However, some were difficult to identify because of the extremely compressed ring patterns (reduced growth), and because repeated burning on the face of the scar (catface) had charred into the wood removing portions of the curvilinear healing and the original wound. There were also areas along the fire-scarred surface where portions of the charred healing had broken off leaving only a line of charred wood leading into a ring. All scars identified as fire scars displayed at least criterion number 1.

Dating of the fire scars was essentially a matter of determining which ring contained each scar. This task was generally quite easy, although some scars were more difficult to date because of cell disruption, charring of the wood in the area, or damage to the specimen.

Often the break and charred area of the fire scars were within the earlywood portion of the ring (Fig. 3). In these instances it can be said with certainty that fire scarred the tree during the growing season. Other fire scars were found between the latewood cells of one season's growth and the earlywood cells of the next season's growth (Fig. 3). In these cases the fire could have burned at any time from the end of the dormant season to the onset of growth in the spring.

Barrett (1978) investigated the seasonality of fire scars and encountered similar difficulties in interpreting both the position of scars within annual rings and the relationship between scar position and specific seasons. No attempt was made to relate position of the fire scars to seasons when analyzing the specimen. For the purpose of consistency, scars between the latewood of one year's growth and the earlywood of the next year's growth were dated to the year of the earlywood growth.

RESULTS

Tree-Ring Characteristics.—Crossdating revealed numerous absent or partial rings. (Rings that are missing around portions of the circumference but are present at other locations are often referred to as partial, or locally absent, rings.) When the plotted tree-ring sequence was compared with the Flagstaff master tree-ring chronology (Drew 1972), the absence of growth rings for specific years resulted in the displacement of the plot backward in time

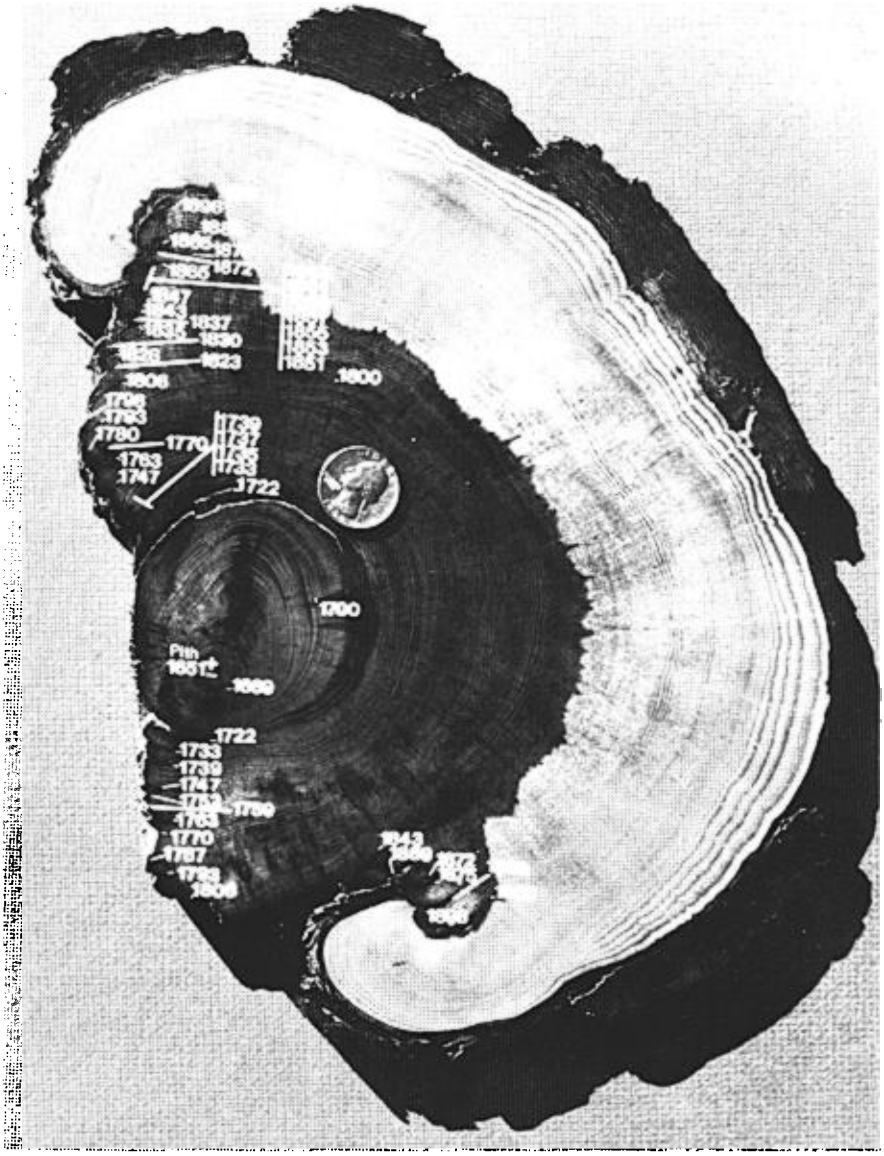

FIGURE 2. Cross section of LMF 3A showing evidence of 36 individual fire scars. This small, suppressed ponderosa pine cut in 1978 contained an unusual record of fires for a 231 year period 1669–1900. Dated surface was approximately 4 inches (10 cm) above the ground; scarred surface faces to the ENE.

relative to this master chronology. This displacement alerted the dendrochronologist to the area within the tree-ring sequence where a growth ring had failed to form. Further examination around the circumference of the cross section, along the outer ring boundary of the previous year's growth, often resulted in discovery of the locally absent ring in other areas of the cross section.

One example of a locally absent ring was the 1748 ring, which was visible at only one location on each cross section (Fig. 4). This ring occurred within the curved portion of growth overlapping the 1747 fire scar. There were 11 years in which locally absent rings were identified on one or more of the four LMF 3 cross sections: 1710, 1711, 1717, 1748,

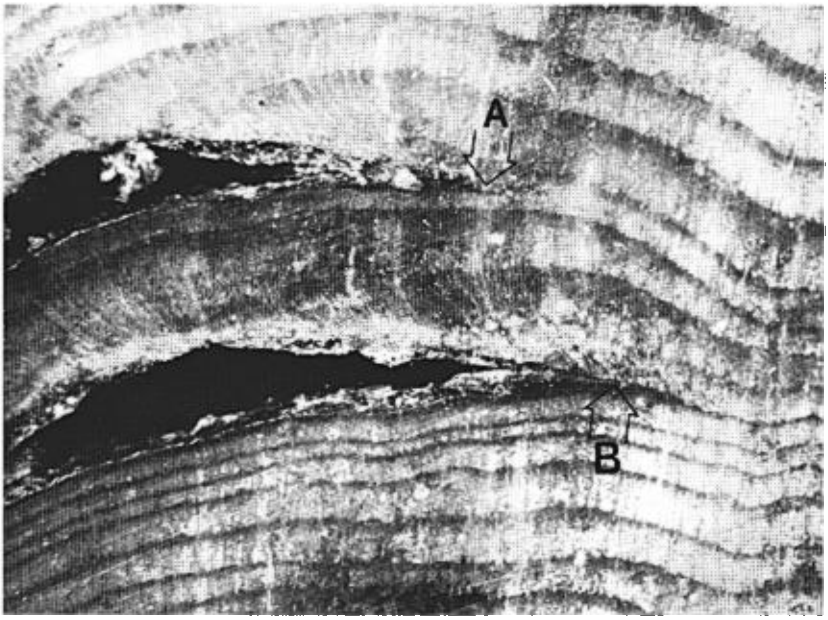

FIGURE 3. Careful inspection may occasionally reveal the season in which the fire occurred. The upper scar (A) was produced in the earlywood while the tree was actively growing. The lower scar (B) was produced between the latewood cells of the previous year's growth and the earlywood cells of the next year's growth, indicating that the tree was dormant at the time of the fire.

1820, 1842, 1847, 1884, 1940, and 1956. There were three years in which growth rings were entirely absent: 1943, 1950, and 1951. This portion of the ring series was very narrow, indicating a period of very slow growth. Surprisingly, there were no totally absent rings prior to 1940. The number of missing or locally absent rings varied among the cross sections dated. This reflects a difference in growth characteristics vertically along the stem and emphasizes the need to apply standard dendrochronological techniques to achieve accurate dating.

Intra-annular (false) rings can add to the difficulty of crossdating a ring series, especially when increment cores or small, partial sections are the only material available. Full cross sections enable the dendrochronologist to examine and follow suspicious rings around the circumference and verify whether they are true rings or false rings. All annual rings along the plotted radii for this specimen had distinct boundaries, and no false rings were identified by the crossdating procedure.

Trees respond to various external stimuli and this specimen exhibited such a change. A striking increase in annual ring development was evident following the cutting operation in 1966 (Fig. 5). Growth rate increased and remained at an accelerated rate until the tree was cut in 1978. The most unusual aspect of this response is the fact that a tree of more than 300 years in age can still respond, and respond aggressively, to the stimuli resulting from removal of competing associates.

Fire Scar Dates.—Table 1 lists all of the fire scar dates recorded for the four cross sections and for sides 1 and 2 of the cross sections. Collectively the four cross sections yielded 187 fire scars representing 42 fire years for the 309-year period, 1669 to 1978. None of the individual cross sections recorded all 42 of the fire years.

The 1669 and 1722 dates (Table 1) are the oldest fire years recorded on any of the sample trees at Limestone Flats. While it is possible that there were no fires around the base of this tree for this 53-year period (1669–1722), it appears more likely that the tree just wasn't a consistent recorder of fire until after the 1722 fire. The 1669 fire scar apparently healed over completely within a few years and developed a new layer of fire resistant bark. After the 1722 fire, the resulting scar area never quite healed over, and pitch exuding from the wound probably increased the chances for each passing fire igniting the catface and re-

TABLE 1. Summary of LMF 3 fire scar dates for both sides (1 and 2) of four cross sections. Total number of fire years recorded by all cross sections is 42.

	Cross section							
	LMF 3A		LMF 3B		LMF 3C		LMF 3D	
	Side 1	Side 2	Side 1	Side 2	Side 1	Side 2	Side 1	Side 2
		1968[a]		1968[a]				
	1900	1900	1900	1900	1900	1900	1900	1900
	1898	1898	1898	1898	1898	1898	1898	1898
	1889	1889	1889	1889	1889	1889	1889	1889
			1885		1885			
	1875	1875	1875	1875	1875	1875	1875	1875
	1872	1872	1872	1872	1872	1872	1872	
	1865		1865		1865		1865	
	1863		1863		1863		1863	
	1861		1861		1861			
	1859	1859	1859	1859	1859	1859	1859	1859
	1857		1857	1857	1857		1857	
	1855				1855		1855	
	1853		1853	1853	1853	1853	1853	
	1851		1851		1851		1851	
	1847		1847		1847		1847	
	1843		1843		1843	1843		
	1837		1837		1837		1837	
	1835		1835		1835		1835	
	1830		1830		1830			
	1827		1828	1828	1828		1828	
	1823		1823	1823	1823		1823	
	1816							
	1808	1808	1808		1808	1808	1808	1808
	1802		1802					
	1798		1798		1798	1798	1798	
	1793		1793	1793	1793	1793	1793	
						1787		
					1780			
		1770	1770		1770	1770		1770
	1766							
	1765						1765	1765
		1763	1763	1763	1763	1763	1763	1763
		1761						
		1752		1752				
	1747	1747	1747	1747	1747	1747	1747	1747
		1739	1739	1739	1739	1739		
			1737	1737	1737			
			1735		1735			
	1733	1733	1733	1733	1733	1733	1733	1733
	1722	1722	1722	1722	1722	1722	1722	
	1669		1669		1669			
Total number fire scars recorded	31	16	33	19	34	18	25	11
Total number fire years	37		35		35		26	

[a] Scar probably caused by slash disposal burning or mechanical damage following logging in 1966.

scarring the cambial tissue along the wound boundaries. During the 178-year period 1722–1900, the mean fire interval for this specimen was 4.3 years.

There was considerable variation in the pattern of scarring (Table 1). A few fires scarred all cross sections on both sides of the catface, while a few of the fires are represented by

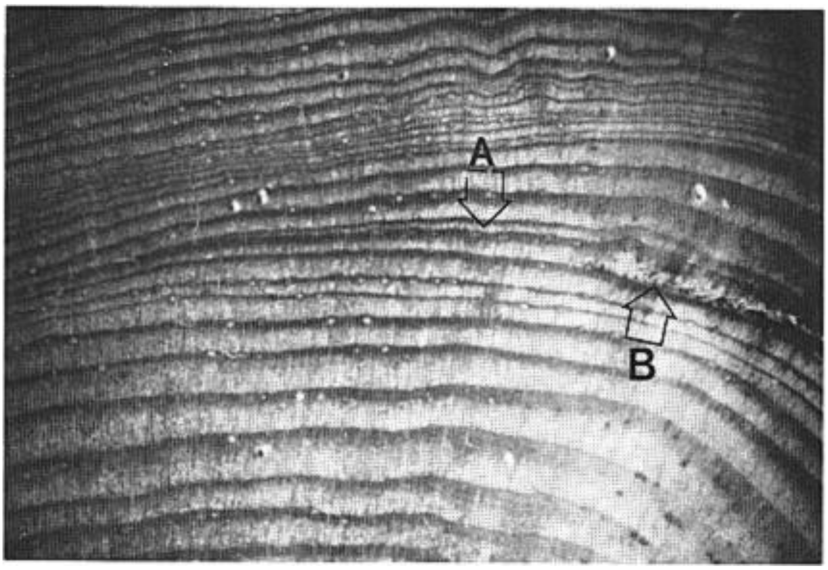

FIGURE 4. The 1748 annual ring (arrow, A) was locally absent on most of the circumference of the cross section but was evident in a short area of overlapping growth following the fire scar (arrow, B) in 1747.

only one or two scars. There was an obvious difference between the number of fires recorded on the two sides (1 & 2) of the catface. Side 1 scarred an average of 31 times while side 2 scarred an average of only 16 times (averaging the four cross sections). This finding emphasizes the importance of using full cross sections, or at least both sides of the fire scar, when collecting material to use in preparing a fire history.

A difference in scarring between the cross sections was also evident. Section 3A, which was lowest on the bole, recorded 37 fire years. Three of these fire years (1761, 1766, 1816) were not recorded on any of the other cross sections. Sections 3B and 3C each recorded 35 fire years. Section 3B recorded three additional fire years (1735, 1737, 1885) not recorded by Section 3A, and section 3C recorded two more fire years not recorded by either section 3A or 3B. Section 3D, which was highest on the bole, recorded only 26 fire years. All of the fire years recorded by section 3D were recorded by at least one of the cross sections at a lower position on the bole. This type of analysis illustrates the variability of fire scarring up and down the bole of the tree and the fact that more fires are recorded at the lower positions.

Comparing the fire scar dates for the specimen with the master fire chronology developed for the Limestone Flats study area (Dieterich 1980b), which includes 11 other fire-scarred trees, shows that 26 of the fire years recorded by LMF 3 are registered on the other trees. LMF 3 recorded 16 fire years that none of the other sample trees recorded. The additional fire years recorded by LMF 3 are partly explained by the fact that it was the oldest tree sampled and was scarred early in its life; thus it has a longer fire scar record than the other sample trees.

There are three periods in the LMF 3 fire chronology when fires burned on alternate years. These periods were 1733 to 1739 (four fires), 1761 to 1765 (three fires), and the 14-year period 1851 to 1865 when eight fires burned on alternate years. Similar intervals were found in other trees in the study area, resulting in a mean fire interval of 1.8 years derived from the master fire chronology of all fire-scarred trees sampled from the Limestone Flats study area (Dieterich 1980b).

Another interesting observation was the recording of fire scars on consecutive years—1765 and 1766. The 1766 scar was present only on section 3A of LMF 3, but the position of the two scars in adjacent rings on this cross section was unmistakable. Thus occurrence of historical fires on consecutive years, even for a limited area, must be considered a relatively rare event in southwestern ponderosa pine (Dieterich 1980a, 1980b). Grass was

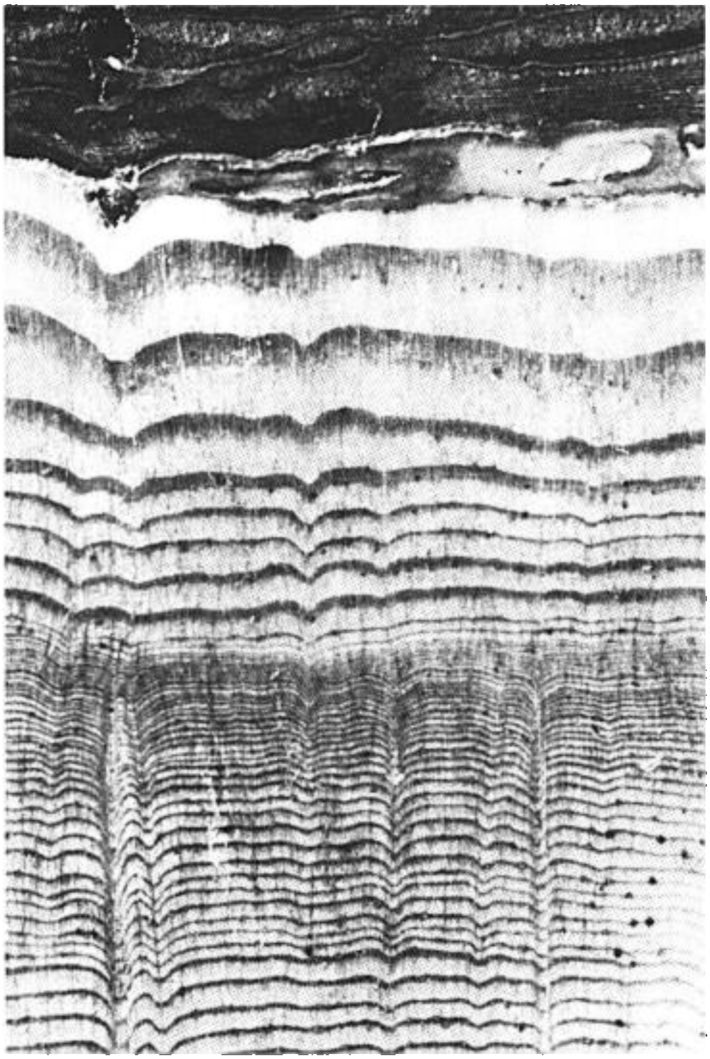

FIGURE 5. Increased growth response (release) following removal of the overstory in 1966.

probably the primary fire-carrying fuel and the annual production of this vegetative material in addition to annual needle cast would have been sufficient to insure that fires could spread if ignitions were present.

Finally, tree growth during fire-free periods can shield fire scars from exterior view. For example, evidence of the last 14 fires (1851–1900) are effectively hidden by the overlapping growth during the last 78 years of tree growth (Fig. 2).

DISCUSSION AND SUMMARY

With a record of 42 fire scars LMF 3 was an unusually good witness to the periodic burning of fuel around its base. However, as shown by the fire scar record from other trees sampled nearby (Dieterich 1980b), it still did not scar with every passing fire. The most complete record of fire occurrence in the ponderosa pine type is best obtained by sampling numerous trees in close proximity to each other.

In addition to the apparent difference in scarring from tree to tree, the analysis of this specimen shows that there is variability in the scarring pattern within the bole of individual trees. Vertical variability in scarring is illustrated by the fact that most scars appear low on the bole and are not recorded at higher positions. In rare instances, scars appear at high positions but are not evident at lower positions on the bole. The higher frequency of scars is recorded on the lower cross sections because this area is closer to burning surface fuels.

Horizontal variability of fire scars is displayed by scars appearing on one side of the bole but not on the other (Fig. 2). There are a number of possible explanations for these variabilities including healing differences, lean of the bole, presence of pitch, differences in accumulation of fuels at the base of the tree, and wind direction. Although fire intensity may also influence scarring, it is not possible to say, for example, that the 1747 fire was unusually intense just because it scarred both sides, up and down the bole of the tree. It may, in fact, have been a low intensity fire that happened to uniformly ignite pitch on the face and edge of the catface, producing temperatures that were sufficient to scar all healing edges of the wound.

The fire scar characteristics of this specimen suggest a number of implications for those individuals actively engaged in fire history studies:

A researcher interested in collecting information on fire history should realize that a wedge or a cross section from a single fire-scarred tree provides, at best, a conservative estimate of fire frequency.

Small overtopped or suppressed trees can provide a valuable source of fire history material if care is taken in preparation and analysis of the specimen. Their small size makes them more convenient to handle, but because the ring patterns are so compact, and fire scars are so small, extreme care must be taken in removing the cross section and in preparing the surfaces for analysis. Destruction of the fire scar through improper sanding can destroy the evidence needed to accurately date this type of specimen.

The extremely tight ring patterns associated with suppressed trees make it difficult to identify the season in which a particular fire occurred. Differentiating between a fire that occurred very late in the season in one year, and very early in the following year requires careful inspection, and in many instances, may be impossible to accomplish.

The most "productive" cross section in terms of number of fire scars usually comes from a point low on the bole of the tree where the fire scar is widest. However, an expanded dissection of the entire fire-scarred catface may reveal fire years that do not show up on the base-cut cross section. For example, the year 1885 showed up on section 3B and not on section 3A; 1780 and 1787 showed up on section 3C but were not evident on any of the other sections.

An extended fire-free period, even for slow growing trees, is sufficient to shield from view any exterior evidence of the most recent fire or fires. In fact, if growth is fairly rapid, and the callus that heals over the scar continues to expand, the tree begins to once again develop an immunity to subsequent scarring because of the increasing thickness of the bark.

DATING ACCURACY

A detailed and accurate fire chronology is a summary of fire occurrence through time, and as such, is a step toward quantifying fire as an ecological factor. In this regard, the specimen described here is of particular significance because it illustrates a number of difficulties involved in accurately dating fire-scarred material. For example, absent and locally absent rings identified in the ring series of this specimen are not uncommon phenomena in stressed trees or in trees of certain species. Zackrisson (1980) discussed asymmetrically developed rings, partial rings (locally absent), and absent rings in Norway spruce (*Picea abies*) and birch (*Betula pubescens* and *B. verrucosa*).

False rings, locally absent rings, and absent rings, in some cases, may be related to drought or other physiological stress (Fritts 1976). These irregularities are less likely to occur in material taken from mesic sites or in northern regions of the country, but even here false or missing rings may occasionally be present. Only through the use of crossdating can these uncertainties be eliminated. Wagener (1961) listed several types of environmental stress that can produce missing or absent rings, including the effects of fire and insect defoliation. Climate may also cause a temporary cessation of growth. These observations emphasize the importance of crossdating for establishing a fire chronology composed of accurate fire scar dates.

For some forest types and areas, management objectives may be met by sampling fire scar material and conducting simple ring counts or "adjusting" fire dates to account for possible false or absent rings (Arno and Sneck 1977). These techniques may be acceptable where precise dates of fires are not necessary for obtaining estimates of mean fire intervals or fire frequency. However, in forest types where fire regimes are characterized by short interval fires (1 to 15 years), the precision obtained by using the crossdating technique is strongly recommended (Madany and others 1982).

In addition to obtaining precise mean fire intervals and fire frequency calculations, accurate determination of fire dates will be necessary for comparing specific fire years with climatic data and for comparing fire years between fire chronologies within a region. Another advantage of crossdating is that it may be used to date well preserved fire-scarred snags and downed logs. This material can extend the record of fire scars and increase the sample size where the felling of live trees is undesirable.

There are disadvantages to the crossdating technique. Not all species have crossdatable tree-ring series and not all geographic areas have trees with crossdatable tree-ring series. In addition, because fire history researchers must take the time to learn the techniques of dendrochronology (crossdating), or must contract with dendrochronologists to do the tree-ring analyses, crossdating fire-scarred material will be more time consuming and more expensive than other techniques. In those areas where the crossdating of tree-ring series is possible, and the fire history data are to be used as a base-line reference for other research, benefits obtained by accurately dating the material will probably exceed the costs of doing the job.

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