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Cross-Dating Cores as a Nondestructive Method for Dating Living, Scarred Trees

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ABSTRACT. The objective of this study was to validate the use of increment cores for dating scarred trees as part of fire-history studies. Thirty-seven scarred conifers from four sites in the western United States were sampled both by coring and wedging (removing a partial cross section from the scar). For each tree the cores and wedge were analyzed using dendrochronological techniques to determine absolute fire dates, and the core and wedge dates were compared. Twenty-one of the 37 sampled trees were successfully dated and had identical core and wedge dates. Given certain constraints, researchers can effectively cross-date prescar growth from cores in fire- or other disturbance-history studies, and can accurately date scars with cores when wedge sampling is inappropriate or prohibited. FOR. SCI. 34(3):781–789.

ADDITIONAL KEY WORDS. Fire history, dendrochronology.

THE USE OF INCREMENT CORES from living, fire-scarred trees to date fires for fire-history studies has been criticized as inaccurate (Cwynar 1977). Stokes (1980) implied that cores are inadequate because analysis should be done along a radius away from the scar to avoid rings distorted by the scar. As an alternative to coring, extracting a partial cross section or wedge from the scar face, or even cross-sectioning the tree, was suggested so that a larger area of ring growth could be analyzed (McBride and Laven 1976, Arno and Sneck 1977). Although wedging removes more wood than coring, it might be considered nondestructive in particular cases (Madany et al. 1982). McBride and Laven (1976) reported removing only 5% of the circumference by wedging, and Arno (1976) removed an estimated 10% of basal area. Wedging, however, may be prohibited by management policies or may otherwise be deemed inappropriate for some study sites (e.g., within designated state and federal wildernesses or other natural areas). Because coring is less damaging than wedging, it would be preferable for these sites if proven accurate.

The objective of this study was to validate the use of increment cores for dating scars in fire-history studies. Scarred trees were sampled both by coring and by wedging. The cores and wedge were analyzed with dendrochronological techniques (Stokes and Smiley 1968), particularly cross-dating, to independently establish core and wedge dates for each scar, which were then directly compared.

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STUDY SITES AND METHODS

Thirty-seven scarred trees from three high-elevation (above 2700 m) sites and one low-elevation (600 m) site in three states were studied. Ten Sierra variety lodgepole pines (*Pinus contorta* Dougl. ex Loud. var. *murrayana*) from the Mt. San Jacinto State Park Wilderness (33°49′N;116°41′W) and 4 from the Sugarloaf Mountain Roadless Area (34°15′N;116°52′W) were sampled in California; 5 Rocky Mountain variety lodgepole pines (*P. contorta* var. *latifolia*) from the Medicine Bow Mountains (41°18′N;106°09′W) in Wyoming; and 16 Douglas-firs (*Pseudotsuga menziesii* [Mirb.] Franco) and 2 western hemlocks (*Tsuga heterophylla* [Raf.] Sarg.) from the H.J. Andrews Experimental Forest (44°15′N;122°15′W) in Oregon.

Sampled trees were cored on both sides of their scars. Coring was positioned away from the open scar face, through the pitch deposit/structural break, and toward the pith to include as much prescar growth as possible (Figure 1). After coring, a wedge was extracted using the techniques of Arno and Sneck (1977), with the intent of minimizing impact to the tree. All cores and wedges were carefully sanded and polished to expose cross-sectional rings (Swetnam et al. 1985), which were viewed with a 10–70× zoom stereo microscope using reflected light.

ANALYSIS OF CORES

For each sample tree, prescar ring growth of the cores was first cross-dated (matching relative ring-width patterns) using skeleton plots (Stokes and Smiley 1968). In skeleton plotting, the ring-width patterns were reduced to series of vertical lines on strips of graph paper; such graphs are easier to compare to one another than are cores. By comparing skeleton plots to each other and to skeleton-plotted master tree-ring chronologies (Table 1), locally absent or false rings were identified, and the cores were absolutely dated. Skeleton plotting requires practice to be effective, but it is otherwise simple to perform. As a further check, postscar rings of each core were counted to ensure that the scar date was not more recent than permitted by the number of postscar rings.

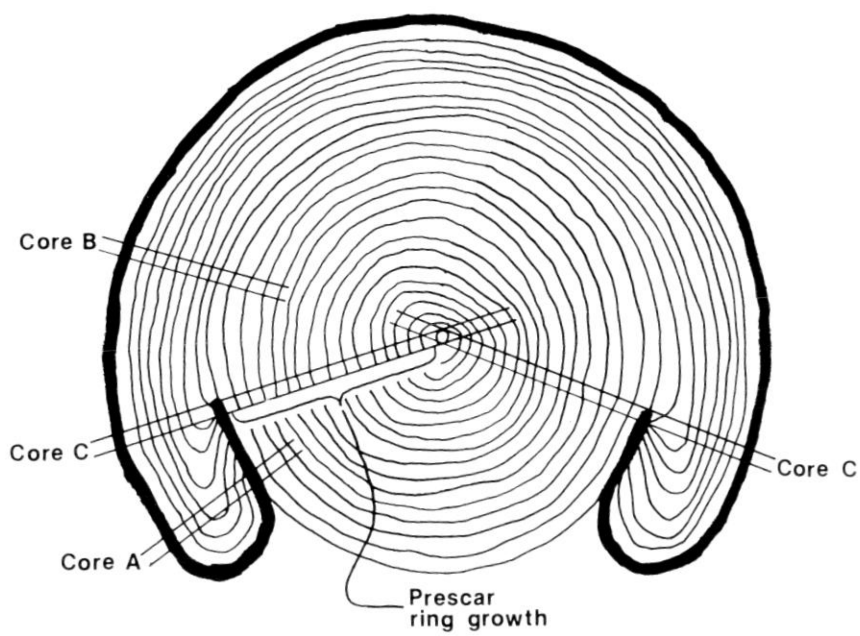

FIGURE 1. Cross-sectional view of a scarred tree. Core A is positioned too close to the open scar face; core B is too far from the open scar face. Core C positions are correct and are as deep as possible in order to maximize the number of prescar rings. One core was extracted from each side of the scar.

TABLE 1. Master tree-ring chronologies used to cross-date cores and wedges.[a]

Sample location	Master chronology	Species
Mt. San Jacinto, CA	Mt. San Jacinto	*Pinus contorta* var. *murrayana*
Sugarloaf Mountain, CA	Baldwin Lake South	*Pinus jeffreyi* Grev. & Balf.
Medicine Bow Mountains, WY	Laramie A	*Pseudotsuga menziesii*
	Medicine Bow	*Pinus contorta* var. *latifolia*
H. J. Andrews Forest, OR	Andrews Forest	*Pseudotsuga menziesii*

[a] The Mt. San Jacinto, Medicine Bow, and Andrews Forest chronologies were constructed specifically for this study; Baldwin Lake South (Drew 1972) and Laramie A (Drew 1975) were obtained from the Laboratory of Tree-Ring Research, Tuscon, AZ. All chronologies were constructed by merging standardized ring growth from undistrubed, climate-sensitive trees that were independent of the scarred trees (Fritts 1976).

Since some researchers might consider cross-dating to be subjective in nature, computer-aided cross correlation was done to confirm the fire dates. Objective cross-dating approaches can be useful when studying a tree species that is difficult to skeleton plot, possibly because of complacency to climatic variation (Holmes 1983). Prescar ring growth was first measured to the nearest of ± 0.01 mm (Jacoby 1982), which yielded ring-width series (Figure 2a) that may be considered as aggregations of several sources of variation, such as growth/size trends, climate, endogenous and exogenous disturbances, and random variation (Cook 1987). A ring-width series commonly has a mean that varies across time and a variance that varies with the mean, two traits that disqualify it from cross-correlation analysis. These ring-width series were therefore detrended to stabilize the overall mean and variance using log transformation followed by first-differencing, done by subtracting the value of each datum from its successor (Fritts 1976):

$$FD = \ln RW_{t+1} - \ln RW_t$$

where FD = first-difference value (ln mm), RW = ring width (mm), and t = year number. Each detrended time series had a stable mean and homogeneous variance (Figure 2b). They were merged within each tree yielding 37 averaged series, and each series was dated by cross-correlating it to its first-differenced master (Figure 2d). All possible overlapping positions (to a minimum overlap of 15 years) were tested for cross-correlation (Baillie and Pilcher 1973), and the correct position resulted in a high correlation coefficient (e.g., $r = +0.80$, Figure 2b). This position was then visually rechecked to the master chronology (Yamaguchi 1986). First-differencing and cross-correlation testing were done quickly and easily with BASIC programs on a standard personal computer.

Although first-differencing results in stable series with homogeneous variances, it also results in serial autocorrelation, whereby the value of a datum is dependent on its predecessors to some degree (Fritts 1976). A first-order negative autocorrelation is illustrated by the 1782 and 1783 values of the example series (Figure 2). The first-differenced 1782 value is quite small, properly reflecting the narrow 1782 ring width. The first-differenced 1783 value, however, is inordinantly high, due more so because of the narrow 1782 ring width than because of the 1783 ring width.

Violating the statistical assumption of serial independence can lead to errors when cross-correlating two time series (Monserud 1986). To mitigate this problem, autoregressive moving average (ARMA) modelling (Box and Jenkins 1979) was performed on the first-differenced series. Correlograms (plots of autocorrelation and partial autocorrelation values) for 10 lags were inspected to determine exactly which ARMA model was best for each series. First-order moving average, MA(1), was best for most cases. The series were ARMA modelled using SYSTAT (Wilkinson 1987); resultant series were free of significant autocorrelation (Figure 2c) and were dated by cross-correlating to the appropriate ARMA modelled master (Figure 2e). A detailed description of ARMA modelling tree-ring series is found in Monserud (1986). If skel-

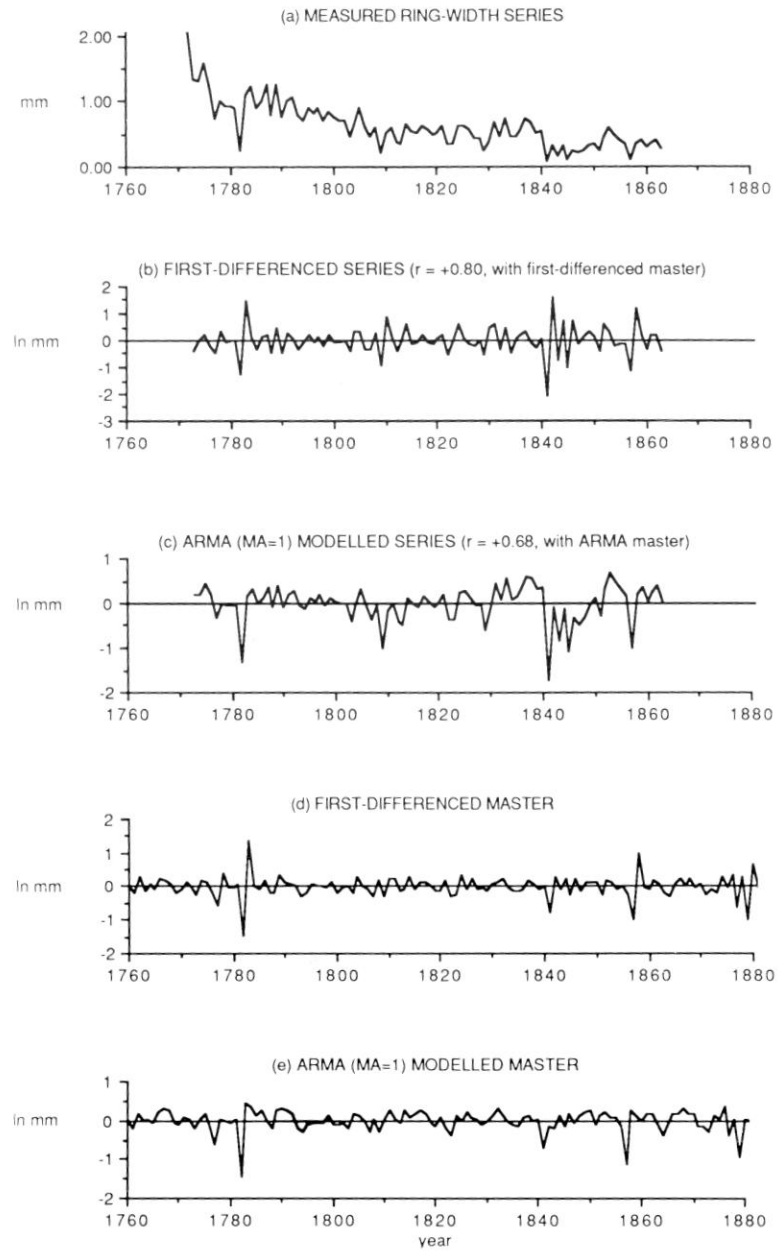

FIGURE 2. (a) A representative measured ring-width series (from Mt. San Jacinto), (b) the transformed, detrended version of that series, (c) the ARMA modelled version of that series, (d) the first-differenced San Jacinto master series, and (e) the ARMA modelled San Jacinto master. Respective coefficients are shown for the first-differenced and ARMA cross-correlation testing.

eton plotting followed by cross-correlation testing of a core series did not yield an unequivocally dated position, then that scar was deemed "undateable by coring."

With the outermost prescar ring absolutely dated, the scar for each tree was dated in one of two ways. First, if a core's outermost prescar ring was only partially formed (lacking a full latewood band), then the scar date was defined as the year of that ring. Second, if the outermost prescar ring was complete, then we defined the fire date based on the likely historical season of fire within each study site. Douglas-fir forests on the west-side Cascades, for example, predominantly experience fires late in the growing season in the summer and fall (Pyne 1982), so the fire date was defined as the year of the outermost prescar ring. In San Jacinto, however, lodgepole pine fires commonly occur throughout the growing season—only rarely in the fall (Sheppard and Lassoie 1987)—so we assumed the tree was scarred the year following that of the outermost prescar ring.

Analysis of Wedges

Because each wedge had a large area of ring growth to inspect, the measuring, detrending, and cross-correlation procedures were not necessary. Instead, prescar growth of the wedge from each tree was cross-dated with skeleton plots to the master chronologies. As with the cores, the postscar rings of the wedges were counted to ensure that the scar date was not more recent than allowed by the number of postscar rings. If skeleton plot cross-dating of a wedge series did not yield an unequivocally dated position, then the scar was deemed "undateable by wedging."

In addition, as an independent confirmation of the accuracy of coring for scar dating, cores were collected from three scarred lodgepole pines (from the Mt. San Jacinto State Park Wilderness) that were "cat-faced" by survey blazing for the corner marker SBM, T4S R3E, S20 S21 S28 S29. Scar dates from these cores were compared to the actual survey records instead of removing wedges from the trees.

RESULTS

Twenty-one of the 37 sampled trees were successfully dated; for each of these, the core and wedge scar dates were identical (Table 2). One tree (from the H.J. Andrews Forest) had two scars, both of which were dated by cores and the wedge. All three dating techniques (skeleton plotting and cross-correlation testing of first-differenced and ARMA modelled series) confirmed each other within each tree. The ARMA model testing resulted in correlation coefficients that were only slightly different from those by first-difference testing. Of the 16 sampled trees that could not be dated, one had prescar growth that was too suppressed to cross-date and the others contained too few prescar rings to confidently cross-date or cross-correlate.

The three cat-faced survey trees had the same scar date—1904 (Table 2). Since their outermost prescar rings were incomplete (that is, partial earlywood and no latewood), these scars were dated as 1904. Historical survey records from the Bureau of Land Management, Sacramento, CA, confirm that the team of John F. Abbott and Charles W. Garside surveyed the San Jacinto Mountains in 1904 and cat-faced those particular witness trees on August 25.

DISCUSSION

These results, obtained from two tree species sampled from three different forest ecosystems, validate the use of dendrochronological analysis of increment cores on fire-history studies. This analysis is also useful for dating other tree disturbances that produce callus-growth scars. Swetnam (1984) successfully used dendrochronological analysis of cores to date scars on ponderosa pines (*Pinus ponderosa* Dougl. ex Laws.) that were peeled for food by native Americans.

Some researchers feel that dendrochronological techniques should be employed even when wedges are used for scar dating (Madany et al. 1982). Others may feel that the accuracy obtained from counting tree rings is sufficient for their study purposes (Duever and McCollom 1987). Ring counting generally fails to account for anomalies such as missing rings, which are especially pervasive in high-elevation, low-productivity sites (Fritts et al. 1965). A simplified example illustrates how a negligible error in dating can result in an important misinterpretation. Assume that four single-scarred trees from a particular stand are tentatively fire dated to 1810, 1860, 1863, and 1910. Without absolute confidence in the 1863 scar, that date might

TABLE 2. *Fire dates from all successfully dated scars.*

Sample location and no.	Core date	Wedge date	First-difference correlation coefficient[a]	ARMA correlation coefficient[a]	Number of prescar rings[b]
		Pseudotsuga menziesii			
H. J. Andrews Forest					
1	1975	1975	+.62	+.60	74
2	1947	1947	+.54	+.50	116
3	1839	1839	+.61	+.65	108
4	1839	1839	+.71	+.71	108
5	1849	1849	+.77	+.71	118
6 #1[c]	1828	1828	+.68	+.62	97
6 #2	1849	1849	+.57	+.55	118
7	1950	1950	+.50	+.50	37
8	1846	1846	+.47	+.48	115
9	1889	1889	+.33	+.28	157
10	1738	1738	+.58	+.37	38
11	1889	1889	+.43	+.39	98
		Pinus contorta			
Sugarloaf Mountain					
12	1963	1963	+.80	+.66	24
13	1887	1887	+.69	+.62	73
14	1887	1887	+.68	+.60	27
15	1878	1878	+.66	+.55	21
Medicine Bow Mountains					
16	1868	1868	+.39	+.39	54
Mt. San Jacinto					
17	1773	1773	+.53	+.35	25
18	1798	1798	+.85	+.56	52
19	1798	1798	+.89	+.91	18
20	1798	1798	+.87	+.67	26
21	1810	1810	+.70	+.57	22
CAT1[d]	1904	1904[e]	+.36	+.36	112
CAT2[d]	1904	1904[e]	+.49	+.50	104
CAT3[d]	1904	1904[e]	+.66	+.54	75

[a] Correlation coefficients are from analyses of core series to master series. Because of the multiplicity of testing all possible overlaps, *a posteriori* significance levels are difficult to determine (Wigley et al. 1987); consequently no statistical significance is inferred.
[b] These represent "actual" n-sizes for correlation tests; because of possible autocorrelation of time-series data, "effective" n-sizes are theoretically reduced (Wigley et al. 1987).
[c] This tree had two fire scars, both of which were dated.
[d] This tree was cat-faced for a section corner by surveyors.
[e] This is the actual date from survey records, not from a wedge.

be adjusted back to 1860, and the resultant mean fire return interval (Romme 1980) would be as follows:

$$\frac{((1860 - 1810) + (1910 - 1860))}{2} = 50 \text{ years}$$

If, however, the 1863 date is real—not a misdate of 1860—then the mean fire return interval should be as follows:

$$\frac{((1860 - 1810) + (1863 - 1860) + (1910 - 1863))}{3} = 33 \text{ years}$$

Compensating for this error by sampling more trees will not necessarily work; there is no guarantee without cross-dating that a specific fire date chosen for a majority of trees is indeed the correct one (Madany et al. 1982).

Additionally, fire dates are useful for more than just fire return intervals. Researchers may wish to determine the relationship of fire danger to drought severity by correlating fire years to climate (Tande 1980); such dendroclimatic analysis requires accurate dating of ring growth (Fritts 1976). Correct fire dates are also important in other applications of dendrochronicity. Wallace and LaMarche (1979), for example, used tree rings to study paleoseismicity of the San Andreas fault in northern California. They sampled trees that were either fire scarred and/or seismically disturbed, and they relied on correctly dating ring growth in order to not confound these two disturbance agents and misinterpret the paleoseismic history. Furthermore, although it may seem intuitive that cross-dating requires more effort than ring counting, in reality there may be relatively little difference between them in total effort required when both are done properly (Duever and McCollom 1987).

Several other points should be considered when using cores to date living, scarred trees:

1. Cores must be extracted properly. Cores must contain a definite structural break delineating prescar from postscar growth (Sheppard and Lassoie 1986). They must also contain as much prescar growth as possible; if a tree was young when scarred, has a decayed center, or was cored incorrectly, then its scar may not be accurately cross-dated because of insufficient prescar growth. A minimum number of rings necessary for cross-dating varies depending on mean ring-width sensitivity—the relative differences in widths from one ring to the next (Fritts 1976). In all cases, however, the functional practicality of dendrochronological analysis decreases as tree-ring series length decreases (Wigley et al. 1987).
2. Scarred trees with little year-to-year ring growth variation may not be cross-dateable, by either cores or wedges. For example, lodgepole pine ring growth from the Medicine Bow Mountains was relatively complacent to climatic variation, and only one of those five sampled trees was confidently cross-dated. Conversely, Douglas-fir ring growth from dry sites on the H.J. Andrews Experimental Forest was relatively sensitive, and 11 of those 16 samples were dated. Researchers must judge whether or not particularly difficult cores are cross-dated with sufficient confidence to include in a study (Wigley et al. 1987).
3. Although skeleton plotting would suffice in many fire regime studies, confirmation by cross-correlation testing can increase researcher confidence in fire dates. For valid cross-correlation testing, measured ring widths must first be normalized and detrended. Several detrending techniques exist, and it would be prudent to investigate all options before data reduction. The smoothing spline (Cook and Peters 1981), for example, would be helpful in a study of trees growing in mesic, closed-canopy forests of eastern North America.
4. Serial autocorrelation of time series data should not be ignored. The results of this study were not changed because of the ARMA modelling, and indeed, little may be gained by ARMA modelling series that are highly correlated at one dating position (Monserud 1986). Nonetheless, such modelling can further improve researcher confidence in results from correlation testing (Yamaguchi 1986).
5. Cores are not practical for dating multiple scars within a tree. No single core can easily sample more than one scar. In our sole case of dating two scars from one tree, we had additional cores containing the earlier scar. Nonetheless, many subalpine and alpine forest ecosystems have fire regimes of light intensity, small area ground fires (Kilgore 1981), which may result in predominantly single-scarred trees. Such ecosystems are also likely to be designated wildernesses or natural areas (Hendee et al. 1978), where wedge sampling may be prohibited.
6. Master tree-ring chronologies exist for various species in many forest ecosystems of both the western and eastern United States. These may suffice for disturbance-history studies, but a specific master chronology, constructed from undisturbed trees within the study site (Fritts 1976), is preferable.

LITERATURE CITED

ARNO, S. F. 1976. The historical role of fire on the Bitterroot National Forest. USDA For. Serv. Res. Pap. INT-18. 29 p.

ARNO, S. F., and K. M. SNECK. 1977. A method for determining fire history in coniferous forests of the mountain west. USDA For. Serv. Gen. Tech. Rep. INT-42. 28 p.

BAILLIE, M. G. L., and J. R. PILCHER. 1973. A simple crossdating program for tree-ring research. Tree-Ring Bull. 33:7–14.

BOX, G. E. P., and G. M. JENKINS. 1970. Time series analysis: Forecasting and control. Holden-Day, San Francisco. 553 p.

COOK, E. R. 1987. The decomposition of tree-ring series for environmental studies. Tree-Ring Bull. 47:37–60.

COOK, E. R., and K. PETERS. 1981. The smoothing spline: A new approach to standardizing forest interior tree-ring width series for dendroclimatic studies. Tree-Ring Bull. 41:45–53.

CWYNAR, L. C. 1977. The recent fire history of Barron Township, Algonquin Park. Can. J. Bot. 55:1524–38.

DREW, L. G. 1972. Tree-ring chronologies of western America. III. California and Nevada. Laboratory of Tree-Ring Res., Univ. of Arizona, Tucson. 38 p.

DREW, L. G. 1975. Tree-ring chronologies of western America. V. Washington, Oregon, Idaho, Montana, and Wyoming. Laboratory of Tree-Ring Res., Univ. of Arizona, Tucson. 45 p.

DUEVER, M. J., and J. M. MCCOLLOM. 1987. Trade-offs between the use of tree-ring counting and dendrochronology in ecological studies. P. 611–621 *in* G. C. Jacoby and J. W. Hornbeck (compilers), Proc. Int. Symp. on Ecological aspects of tree-ring analysis. Tree-Ring Laboratory, Lamont-Doherty Geological Observatory, Palisades, NY.

FRITTS, H. C. 1976. Tree rings and climate. Academic Press, New York. 567 p.

FRITTS, H. C., ET AL. 1965. Tree-ring characteristics along a vegetation gradient in northern Arizona. Ecology 46(4):393–401.

HENDEE, J. C., G. H. STANKEY, and R. C. LUCAS. 1978. Wilderness management. USDA For. Serv. Misc. Publ. No. 1365. Wash., DC. 381 p.

HOLMES, R. L. 1983. Computer-assisted quality control in tree-ring dating and measurement. Tree-Ring Bull. 43:69–78.

JACOBY, G. C. 1982. Notes on microcomputer measuring meachines. Tree Ring Soc. Newsl. 21:4–6.

KILGORE, B. M. 1981. Fire in ecosystem distribution and structure: Western forests and scrublands. P. 58–59 *in* Proc. Fire Regimes and Ecosystems Properties Conf. USDA For. Serv. Gen. Tech. Rep. WO-26.

MADANY, M. H., T. W. SWETNAM, and N. E. WEST. 1982. Comparison of two approaches for determining fire dates from tree scars. For. Sci. 28(4):856–61.

MCBRIDE, J. R., and R. D. LAVEN. 1976. Scars as an indicator of fire frequency in the San Bernardino Mountains, California. J. For. 74(4):439–42.

MONSERUD, R. A. 1986. Time series analyses of tree-ring chronologies. For. Sci. 32(2):349–372.

ROMME, W. H. 1980. Fire history terminology: report of the ad hoc committee. P. 135–137 *in* Proc. Fire History Workshop. USDA For. Serv. Gen. Tech. Rep. RM-81.

PYNE, S. J. 1982. Fire in America. Princeton University Press, New Jersey. 654 p.

SHEPPARD, P. R., and J. P. LASSOIE. 1986. A non-destructive method for dating living, fire-scarred trees in wilderness areas. P. 35–38 *in* Proc. Nat. Wilderness Res. Conf.: Current Res. USDA For. Serv. Gen. Tech. Rep. INT-212.

SHEPPARD, P. R., and J. P. LASSOIE. 1987. Natural fire history of lodgepole pine of Mt. San Jacinto, California. P. 106–107 *in* Proc. Ninth Conf. on Fire and For. Meteor. Am. Meteor. Soc., Boston, MA.

STOKES, M. A. 1980. The dendrochronology of fire history. P. 1–3 *in* Proc. Fire History Workshop. USDA For. Serv. Gen. Tech. Rep. Rm-81.

STOKES, M. A., and T. L. SMILEY. 1968. Tree-ring dating. Univ. of Chicago Press, Chicago. 73 p.

SWETNAM, T. W. 1984. Peeled ponderosa pine trees: A record of inner bark utilization by native Americans. J. Ethnobiol. 4(2):177–90.

SWETNAM, T. W., M. A. THOMPSON, and E. K. SUTHERLAND. 1985. Using dendrochronology to measure radial growth of defoliated trees. USDA For. Serv. Agric. Handb. No. 639. 39 p.

TANDE, G. F. 1980. Interpreting fire history in Jasper National Park, Alberta. P. 31–34 *in* Proc. Fire History Workshop. USDA For. Ser. Gen. Tech. Rep. RM-81.

WALLACE, R. E.,and V. C. LAMARCHE. 1979. Trees as indicators of past movements on the San Andreas fault. Earthquake Info. Bull. 2(4):127–131.

WIGLEY, T. M. L., P. D. JONES, and K. R. BRIFFA. 1987. Cross-dating methods in dendrochronology. J. Archaeol. Sci. 14:51–64.

WILKINSON, L. 1987. SYSTAT: The system for statistics. SYSTAT, Inc., Evanston, IL.

YAMAGUCHI, D. K. 1986. Interpretation of cross correlation between tree-ring series. Tree-Ring Bull. 46:47–54.