

ANALYSIS OF TREE RINGS AND FIRE SCARS TO ESTABLISH FIRE HISTORY

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ABSTRACT

Traditional counting of tree rings between fire scars to establish a fire history is examined for a better understanding of factors influencing fire scar formation and wound healing. The problem of dating fires which burn prior to or after the period of cambial activity is emphasized. A methodology for fire history studies based on fire scar and tree-ring analysis developed by Arno and Sneek (1977) is reviewed and elaborated upon. The importance of crossdating, height of sample cross sections, and problems associated with the extrapolation of data are discussed. Ongoing research involving the examination of the mineral concentration of tree rings and the presence of traumatic resin canals as markers of past fires is reviewed.

Um eine Waldbrandgeschichte zu erarbeiten, werden üblicherweise die Jahrringe zwischen den Feuernarben gezählt. Es wird geprüft, ob dieses Verfahren auch zum besseren Verständnis der Faktoren eingesetzt werden kann, die die Feuernarbenbildung und Wundheilung beeinflussen. Hierzu muß festgestellt werden, ob ein Feuer vor oder nach der Kambialaktivität brannte. Die von Arno und Sneek (1977) entwickelte Methode zur Analyse von Waldbrandereignissen auf der Grundlage von Feuernarben und Jahrringuntersuchungen wird geprüft und weiter ausgearbeitet. Es werden die Bedeutung des "cross-dating", die Höhe der Probenentnahme und Fragen zur Extrapolation von Daten diskutiert. Weiterführende Untersuchungen über die Mineralienkonzentration in Jahrringen und das Vorkommen von traumatischen Harzkanälen als Hinweis auf vergangene Feuerereignisse werden besprochen.

Le traditionnel comptage des cerne entre les cicatrices causées par le feu pour établir l'histoire de ces feux, est examinée en vue d'obtenir une meilleure compréhension des facteurs influençant la formation de la blessure et sa cicatrisation. L'attention est attirée sur la période d'incendie, soit qu'elle se présente avant ou après l'activité cambiale. Une méthodologie pour retracer l'histoire des feux et basée sur les cicatrices et l'analyse des feux développée par Arno et Sneek (1977) est revue et améliorée. L'importance des datations croisées, de la hauteur des sections transversales et les problèmes associés avec l'extrapolation des données sont discutées. Des recherches en cours concernant la concentration de minéraux dans les cerne et la présence de canaux résinifères traumatiques comme marqueurs de feux anciens sont passées en revue.

INTRODUCTION

A renewed interest in fire history emerged in the 1970's as various state and federal land management agencies began to re-assess the traditional approach to fire management in the western United States. Encouraged by the findings of the Leopold Report on management of wildlife in Yellowstone National Park (Leopold et al. 1963) and research on prescribed burning in Arizona by Weaver (1951) and in California by Biswell et al. (1952), land managers began exploring the possibility of re-introducing fire through "let burn" programs and controlled burning. By the mid-1970's fire management policies for most federal forest lands required that fire be used to maintain and enhance resources (Kilgore 1976; Parsons 1981). Knowledge of the fire history of an area is fundamental to understanding how the mosaic of vegetation types has developed and to planning the re-introduction of fire. The need for this knowledge has stimulated the use of traditional as well as new methods for developing fire

histories. The most common of these methods has been the dating of fire scars using procedures common to dendrochronology. The purpose of this paper is to review and evaluate the methodology of this emerging field which has been named by Dieterich (1975) "pyrodendrochronology."

HISTORICAL DEVELOPMENT OF THE FIELD

The recorded history of tree-ring analysis dates back to Theophrastus who in the 3rd century BC described rings in wood. Whether Theophrastus or his contemporaries understood the annual nature of ring formation is unknown. It was not until about A.D. 1500 that the annual formation of tree rings was first suggested by Leonardo da Vinci (Studhalter et al. 1963). Malpighi made the first anatomical investigations of annual rings and described the characteristics which distinguish springwood from summerwood in 1675. Proof of the annual production of growth rings was not developed until 1753 when Schober showed that the number of rings agreed with the number of branch whorls in a pine tree.

The first attempts at crossdating were those of Duhamel du Monceau in 1737. He used frost rings as markers to crossdate sections of several newly felled trees. The use of relative ring width for crossdating was independently reported by Twining (1833) in the United States and Babbage (1838) in England. The modern application of crossdating, which is basic to the science of dendrochronology, must be credited to Douglass (1919). His work led to the establishment of the Laboratory of Tree-Ring Research at the University of Arizona in 1937.

The presence and origin of basal fire scars must have been recognized by early man. However, the first report of dating of fire scars did not come until the 20th century. In 1909, Mills interpreted the life history of a large yellow pine by using tree rings to date several events during the life of the tree. These events included fires in 1840 and 1859 which caused basal scars. In 1910, Frederick Clements published the first account of the reconstruction of the history of a burned area by means of fire scar analysis. Working in the lodgepole pine (*Pinus contorta*) forests near Estes Park, Colorado, he dated 13 fires occurring from 1707 to 1905. He emphasized the simplicity of fire scar analysis but also pointed out the problem of distinguishing between fire scars and scars due to other causes and the possible error in dating due to the season of the fire. Clements' pioneering work was followed by important early studies in Canada (Howe 1915) and California (Boyce 1920; Lackmund 1921; Show and Kotok 1924). Howe was the first to calculate fire free intervals from data produced by fire scar analysis. Boyce first applied the technique to a wide geographic area, the Sierra Nevada Mountains, and was also the first to discuss limitations caused by partial decay of heartwood. Lackmund reported the first observations on the relative susceptibility of different conifer species to fire scarring. Show and Kotok were the first to use prescribed burning to study the formation of new fire scars and the extension of old fire scars.

This early work pioneered the basic methodology still in wide use today. However, since an understanding of the formation of fire scars is essential to this topic, I would like to review this prior to discussing the methodology. In addition, since scars do not form uniformly on trees or across the landscape, an understanding of the factors influencing the occurrence of scars is necessary. This brief discussion will illustrate some of the problems inherent in the methods used to establish fire histories.

FORMATION, HEALING, AND OCCURRENCE OF FIRE SCARS

A fire scar is formed on a tree when a fire burning adjacent to the tree (1) raises the temperature of the cambium to a lethal level or (2) consumes the bark, cambium, and a portion of the adjacent xylem. Temperatures above 60° C are reported to be lethal to the cambium (Hare 1965). Bark is commonly sloughed off of those portions of tree trunks reaching this lethal temperature within one to seven years after burning in hardwood species (Toole 1961). This leaves exposed the surface of the sapwood which is vulnerable to subsequent fires and wood rotting fungi (Boyce 1921). Madany and West (1980) found that ponderosa pine was most susceptible to initial scarring between the ages of 10 and 80. They concluded that trees less than 10 years of age would not generally survive fire and this accounted for the lack of fire scars at ages less than 10 years. Beyond the age of 80 years, trees had sufficient bark to insulate the cambium.

In cases where the bark is burned away the fire scar is immediately apparent. Subsequent fires may burn into the exposed wood to deepen the scar and they may also increase the circumference of the old scar by killing or burning away the adjacent cambium. Show and Kotok (1924) reported that 71% of the original fire scars in a mixed conifer forest in the Sierra Nevada were enlarged following two successive "light" burns. The average increase in the area of scars amounted to 48%. Resin exuded around fire wounds and onto the surface of fire scars by conifers often contributes to the reburning of the wounds (Verrall 1938).

A rejuvenation process is set in motion at the margins of the wounded area once a portion of the cambium is killed by lethal temperatures or consumed by fire. A callus is formed and within this callus tissue a new vascular cambium and a phellogen are produced. In most vascular plants the vascular rays make the major contribution to callus formation (Kozlowski 1971).

The amount of callus formed during healing may vary with the extent of the fire scarred area. In very shallow scars or cases where the cambium is killed by heat, callus formation is sometimes restricted or absent. Initiation of new cambium is often associated with the original cambium at the margins of a wound (Sharples and Gunnery 1933; Soe 1959). In some species a new vascular cambium is differentiated in the middle of the callus and grows into contact with the existing unwounded cambium (Noel 1968). The newly formed cambium may not initially produce normal vascular tissue. In *Populus*, new xylem and phloem elements are cut off about nine days after the vascular cambium forms but these first formed derivatives are abnormal. Normal production of xylem and phloem is first observed about 20 days after wounding (Soe 1959). A partial healing of the fire wounded area can occur following a fire burning in the spring or early summer. Trees that are scarred by fire occurring after the growing season do not produce new xylem to heal over the wounded area until the following growing season. This potential delay in the healing process can lead to uncertainty in dating fire scars which are formed before the initiation of growth in the spring or after the cessation of growth in the summer. Tiren (1937) has suggested that the season of the fire can be determined in some instances from a study of the extent of cambial damage.

Annual production of new xylem covers the fire scarred surface by ingrowth from each side. Unless interrupted by subsequent fires, the scarred area will eventually be completely covered by new wood. Boyce (1920) reported that 29.1% of 1075 incense cedar trees surveyed on six National Forests in California had internal fire scars. These

scars had been completely healed over by the growth of new wood.

Variations in the occurrence of fire scars have been related to tree species, bark thickness, tree diameter, fuel conditions, and wind velocity. Observations by Toole (1961) in Mississippi indicate that 80% of the oaks (*Quercus* spp) and 66% of the hickories (*Carya* spp) were scarred in a single fire. Lackmund (1921) reported the following percentages of merchantable trees as fire scarred on six National Forest timber sale areas in California: incense cedar (*Calocedrus decurrens*), 61.5%; ponderosa pine (*Pinus ponderosa*), 42.7%; white fir (*Abies concolor*), 25.0%; Douglas-fir (*Pseudotsuga menziesii*), 17.2%. Somewhat similar percentages were reported by Show and Kotok (1924). The greater susceptibility of incense cedar and ponderosa pine is due to the higher resin content of their bark and the fibrous nature of the bark of incense cedar. Both white fir and Douglas-fir have a corky bark with relatively low resin content.

Tree bark can insulate the cambium from lethal temperatures if it is of sufficient thickness. The thickness of the bark and its capacity to diffuse heat varies within a species with the age of the tree as well as between species (Vines 1968). Variation in bark thickness was shown by Reifsnnyder et al. (1967) to be a more important variable affecting fire resistance in trees than the ability to diffuse heat. This accounts for the greater frequency of initial fire scars on younger trees. Fire scars seldom form on undisturbed portions of the tree once the bark is of sufficient thickness to insulate the cambium. In both longleaf (*Pinus palustris*) and slash pine (*P. elliotii*) this threshold thickness is around 2.5 cm (Hare 1965). Bark thickness varies on eccentric stems being thinner along the smaller radius (Chang 1954) which may partially account for differential scarring on some trees.

Gill (1974) and Tunstall et al. (1976) have suggested that increased tree diameter leads to increased fire scarring. Their conclusions are based on observations of flame and heat distribution around physical models studied in simulated and grass fires. The extrapolation of these results to living trees requires careful consideration because of the increasing bark thickness one observes with increasing tree diameter.

Fuel conditions also influence the formation of fire scars. The distribution, amount and moisture content of fuels around the base of the tree have all been correlated with fire scarring. Show and Kotok (1924) reported most of the new fire scars caused by a light prescribed burn were associated with debris adjacent to trees. On sloping ground greater quantities of fuel accumulate on the uphill side of the tree and provide additional heat which favors fire scar formation (Vines 1968). Gill (1974) and Tunstall et al. (1976) demonstrated the relationship between the amount of fuel and the potential for fire scarring through the use of physical models. In their experiments scarring potential increased with increasing amount of fuel. Noble et al. (1980) have shown that the intensity of a fire around the base of a tree increases as fuel moisture content decreases.

The influence of wind velocity as a factor in the fire scarring of trees has been studied under field conditions as well as through the use of laboratory simulation models. Davis and Martin (1961) measured bark surface and cambium temperatures on the leeward and the windward sides of longleaf pines (*Pinus palustris*) trees during ground fires. In their experiments, mean maximum bark temperature was 638° C at 1 ft. above the ground on the leeward side of trees and only 376° C on the windward side. Corresponding temperatures in the cambium were 82° C and 29° C. This temperature pattern would result in death of the cambium and subsequent fire scar

formation on the leeward side but not on the windward side. These results were similar to those found by Hare (1965) who used a kerosene-oil soaked wick to study temperature distribution around the bark surface and in the cambium of several species common to the southeastern forests of the United States. Hare also indicated lethal temperatures would occur completely around the entire base of the tree under conditions of no wind, assuming sufficient fuel was available.

An experiment which linked the pattern of temperatures around the base of a tree to the distribution of flames was conducted by Gill (1974). He used a metal rod, a Meker gas burner, and a fan to simulate field fire behavior around the base of a tree. Sequential photography was used to document a greater height and persistence of flames on the leeward side of the rod. These observations on the influence of wind on temperature and flame patterns around the base of trees may explain in part, along with the previously mentioned fuel accumulation, the more common occurrence of fire scars on the uphill side of trees reported by several investigators (Fawcett 1955; McBride and Laven 1976; Arno and Sneck 1977).

METHODS IN FIRE HISTORY STUDIES

Arno and Sneck (1977) presented a methodology for fire history studies which has become the standard for researchers in this field. Their method was comprised of the following steps:

- (1) Selection of sample fire scarred stumps and/or trees
- (2) Removal of cross-sections or other types of samples from fire scarred stumps and trees
- (3) Preparation of samples for ring counts
- (4) Dating fire scars
- (5) Summarization of fire dates
- (6) Calculation of fire free intervals.

My purpose is not to simply review their report but to elaborate upon it by indicating additional approaches to the steps.

Selection of Samples

The selection of sample fire scarred stumps and/or trees may be made along a reconnaissance transect as suggested by Arno and Sneck or adjacent to grid points (McBride and Laven 1976) or randomly located points (Weaver 1951). Where relatively small areas are to be studied, a 100% sample of fire scarred trees and stumps can be used (McBride and Jacobs 1978). The area to be investigated should be stratified with regard to physiographic features (Houston 1973), forest habitat type (Arno and Sneck 1977), and hydrological conditions of the forest (Zackrisson 1977). The purpose of stratification is to subdivide the forest landscape into those units which can be expected to have similar fire occurrence and behavior. Kilgore and Taylor (1979) have provided a thorough discussion of the necessity of stratification of sampling in fire history studies.

Sample fire scarred stumps or trees should be selected on the basis of external evidence of several fire scars when less than a 100% sample is used. Multiple fire scars are evidenced by more or less parallel grooves along the margins of the cut face. Care should be taken to avoid selecting trees with rot, carpenter ant, or termite damage that may prevent accurate counting of tree rings.

Removal of Samples from Trees

Wood sections may be removed from fire scarred stumps and trees in a variety of ways. Early investigators cut entire cross-sections from stumps or from living trees (Clements 1910; Boyce 1920). This destructive method of sampling is frequently not suitable in parks, nature reserves, or certain experimental forests. Alternative sampling procedures involve the removal of partial cross-sections (Arno and Sneck 1977), wedges (Heinselman 1973; Dieterich 1980a), thin wood wafers (McBride and Laven 1976), or increment cores (Heinselman 1973). Wherever possible a complete cross-section should be obtained. Such complete cross-sections provide an opportunity to compare ring counts on both sides of a fire scar and to crossdate the tree rings. Laven et al. (1980) have suggested taking increment cores on the side of the tree opposite the fire scar when partial cross sections are obtained. These cores can be used for crossdating. Increment cores taken through the fire scarred portion of the tree have been shown to be the least reliable samples for establishing fire histories. Siren (1961) reports that errors, in the use of increment cores to determine fire dates, may be as high as ± 10 years. Errors ranging from +1 to -21 years have been reported by Zackrisson (1980).

The height at which the wood adjacent to a fire scar is sampled can influence the accuracy of dating fire scars. Trees may not produce complete annual rings throughout the entire length of their trunk during years of stress brought about by drought or defoliation (Keen 1937). Zackrisson (1980) cut cross sections at the root neck and at 1.3 m on the same fire scars on a Scots pine (*Pinus sylvestris*) in order to compare fire dates based on ring counts. The cross-section taken at the base of the tree showed an accurate number of rings (based on well-documented fires) while the cross-section cut at 1.3 m was off by 3 to 19 years. A similar comparison on a Norway spruce (*Picea abies*) tree by Zackrisson indicated a greater accuracy in dating fires could be obtained by analyzing sections taken at the root neck. When partial sections or wedges are cut from living trees it is advisable to paint the cut surfaces with an asphalt-base tree paint to prevent entrance of insects or pathogens (McBride and Laven 1976).

Preparation of Samples

Cross-sections and other wood samples containing fire scars must be prepared by sanding or slicing before accurate ring counts can be made. A disc sander attached to an electric drill (Arno and Sneck 1977) or a belt sander (Stokes and Smiley 1968) can be used. Sanding should begin with coarse sandpaper (40 grit) and proceed to very fine sand or emery paper (400 or 600 grit). Slicing the surface of increment cores with a single edge razor blade, spoke shave, or knife will produce surfaces of unusual clarity for ring counting and analysis (Stokes and Smiley 1968). Some investigators have counted rings on stumps in the field after preparing the surfaces with various hand tools such as knives, chisels, gouges, wire brushes, and sandpaper (Wagener 1961; Jacobs et al. 1980). Paper rubbings have been made along radii of a weathered stump surface in lieu of preparing the surface (Zinke 1976). Counts are then made on the image of the rings.

Dating Fire Scars

Dating of fire scars is done by counting the annual bands of summerwood from the outer edge of the cross-section or tree core. Ring counts can sometimes be made

without the aid of magnifying instruments; however, magnification of 7X to 25X is usually essential for accurate counting (Arno and Sneck 1977). Wetting the area to be counted with water or applying various stains such as phloroglucinol, safranin, or chlorine can heighten the contrast between the spring and summer wood bands.

Two major problems confront ring counting as a means of determining the age of fire scars: (1) correct identification of fire scars and (2) abnormalities in the production of annual rings. Fire scars must be distinguished from other types of wounds and scars caused by frost crack and root rots which can superficially resemble them. Rowe et al. (1974) has suggested the following characteristics for recognizing fire scars:

- “1. Elongated or triangular in shape. The broadest part of the scar is usually at the base of the trunk.
2. Black charcoal flecks occur on the adjacent bark (first burns) and in the exposed scar wood (second and subsequent burns).
3. When viewed in cross-section, ring width usually increases or decreases dramatically immediately after a fire has occurred.
4. In cross-sections a black crust can be seen on scar margins, marking the outer margin of the annual ring which was formed in the year in which the fire took place.”

Abnormalities in the production of annual rings may involve missing, discontinuous, and false rings. Missing or discontinuous rings can be caused by drought (Fritts 1976), defoliation by insects (Keen 1937), defoliation by fire (Craighead 1927; Jordan 1966), or loss of one side of the tree crown (Larson 1965). False rings can be produced by various climatic patterns (Panshin and de Zeeuw 1980), the growth pattern in multinodal species (Matton 1915), defoliation by insects (Panshin and de Zeeuw 1980), and lightning (Boyce 1923).

Crossdating of tree rings on fire scarred sections can provide a solution to problems presented by abnormalities in ring production (Stokes 1980). Crossdating was first applied to fire history studies by Weaver (1951) using techniques developed at the Laboratory of Tree-Ring Research, University of Arizona, by Douglass (1919). Zackrisson (1976) used crossdating techniques similar to those used in archaeology (Bannister and Robinson 1975) to establish a fire chronology covering some 600 years in Sweden. The methods used to crossdate increment cores and cross-sections have been summarized by Stokes and Smiley (1968) and Fritts (1976) and will not be reviewed here. Recent applications of computer technology to crossdating should be considered by investigators concerned with crossdating fire scarred samples (Cropper 1979; Graybill 1979).

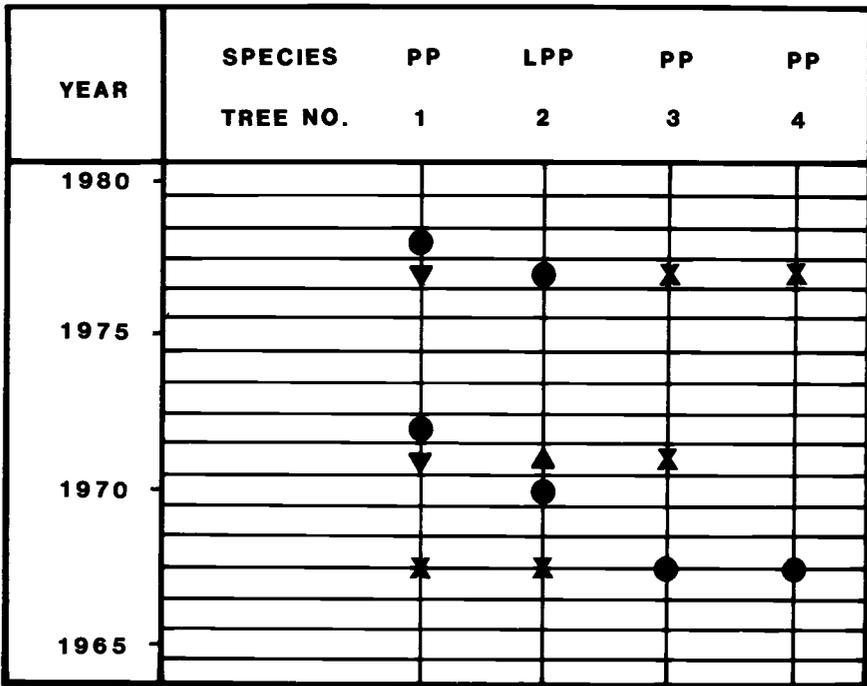
Although crossdating can resolve problems of abnormal ring production it cannot resolve the problem of dating fires occurring prior to or after the period of annual cambial activity. Zackrisson (1977) points out that an error of ± 1 year will often be associated with the date of any fire scar since it may be impossible to establish whether the fire damage occurred during the autumn of one year or the early spring of the following year. Climatic conditions may eliminate the probability of early spring fires in some forest regions and solve this problem in dating fire scars.

Summarization of Fire Data

Fire dates have been summarized for samples collected over an area by combining dates from individual trees to produce frequency diagrams, master fire chronologies,

or composite fire intervals. Frequency diagrams are prepared by plotting the frequency of fire scars in each year of the period under study (Wagner 1961). Those years showing a high frequency of fire scars are considered to be years of severe fires. Attempts to correlate the severe fire years with climatic conditions, such as low precipitation, thought to favor burning, have not been particularly successful. Failure to crossdate specimens and the previously mentioned problem of dating fire scars produced by early spring or late summer fires are in part responsible for the poor correlation. Other factors such as fire ignitions, fuel loading, and wind velocity should also be considered.

Arno and Sneek (1977) suggested a procedure of synchronizing the fire chronologies of individual trees by shifting scar dates that are within a few years of each other to produce a master fire chronology. Their procedures involve the preparation of fire chronology graphs showing the calendar year on the vertical axis and the individual trees on the horizontal axis (Figure 1). For each fire scar a symbol is placed on the chart at the year of the fire. Dates of fire scars are then adjusted to provide the



SCAR DATES:

X - CLEAR RINGS (DATE ACCURATE)

● - RINGS SLIGHTLY OBSCURED (DATE APPROXIMATE)

● or ● - DATE ADJUSTED TO CORRELATE CHRONOLOGY

Figure 1. Graph for synchronizing fire chronologies of individual trees (after Arno and Sneek 1977).

best synchronization. Arno and Sneck have justified the shifting of fire data on the basis of missing or false rings having occurred in the cross sections. They suggest that it is best not to hypothesize that separate fires occurred on the same area at short intervals unless a tree has definite scars for two fires within three years of each other. This assumption may be valid for western Montana where Arno and Sneck worked but should be cautiously applied in regions where climatic conditions, ignitions, and the production of ground fuels can support annual fires. Crossdating of ring sequences between cross-sections could provide a basis for identifying missing and false rings. Synchronizing fire dates, after crossdating, may be justified where shifts of only one year are made in view of the above mentioned problem of assigning accurate dates to early spring or late summer fires.

Dieterich (1980a; 1980b) suggested the tabulation of a Composite Fire Interval as a means of more accurately expressing historical fire frequency for a particular area. The composite fire interval is prepared by plotting dates of fire scars on a chart that spans the total number of years represented by the specimens collected. Time is represented on the horizontal axis while the specimen number is represented on the vertical axis (Figure 2). The date of the first annual ring is listed next to the specimen number and the date of each fire scar is indicated by placing an X under the proper year. These marks represent a composite of all fires having burned in the area under study. Dieterich considers crossdating prerequisite to establishing the dates of fire scars and does not attempt to shift dates like Arno and Sneck (1977). The problem of assign-

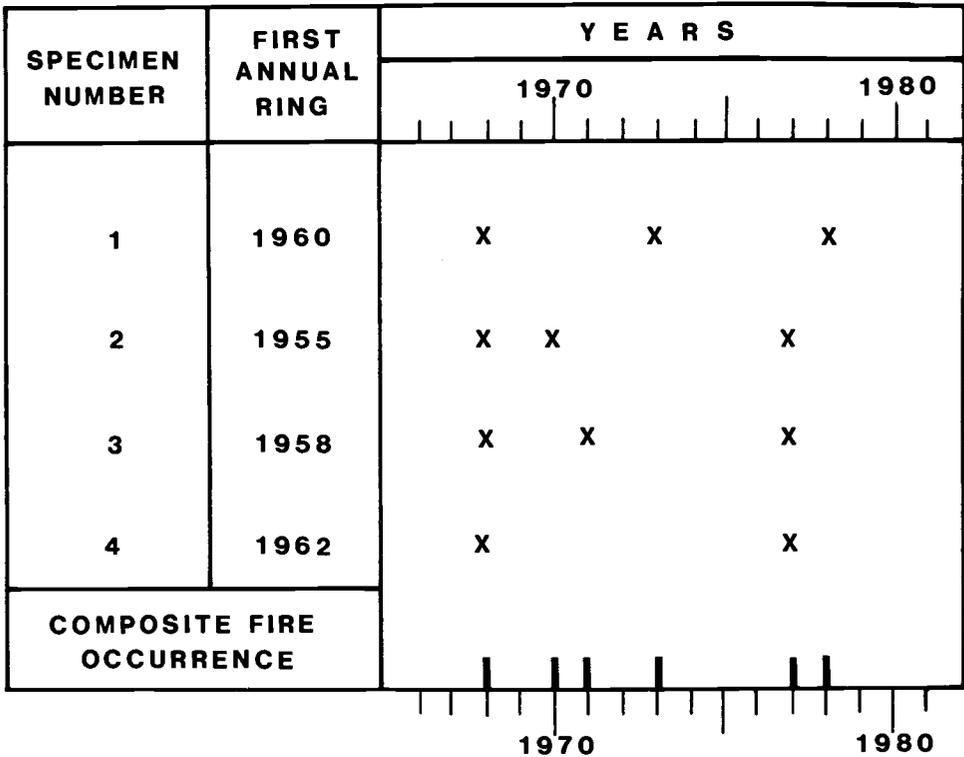


Figure 2. Composite fire interval (based on Dieterich 1980b).

ing dates to fires occurring before or after the initiation of cambial growth is, however, not addressed in Dieterich's determination of composite fire intervals.

Calculation of Fire Free Intervals

Knowledge of the time intervals between fires is of considerable value in understanding the ecology of forest types and planning prescribed burning programs. Several terms such as fire interval, fire free interval, fire return interval, and fire periodicity have been used by various authors to indicate this time interval. A standardization of these and other terms used in fire history studies was proposed by an *ad hoc* committee at the Fire History Workshop conducted in Tucson, Arizona in 1980 (Romme 1980). They recommended the use of the following terms and definitions:

Fire interval = the number of years between two successive fires documented in a designated area.

Mean fire interval = arithmetic average of all fire intervals determined in a designated area during a designated time period.

Mean fire intervals have been calculated for a single tree, small group of trees, forest stands, and entire forest regions. Kilgore and Taylor (1979) have recommended caution in extrapolating the fire chronologies of individual trees over areas of increasing size. The period of time over which the mean fire interval is calculated should also be given consideration. McBride and Jacobs (1980) suggested that periods based on the history of land use be considered in fire history studies. For the mountains of southern California they proposed the following periods: Native American, American Pioneer, and Modern American. Similar periods based on land use history have been suggested by various authors for other regions (Tande 1980; Barrett 1980; Madany and West 1980). Mean fire intervals calculated for such land use periods can often be useful in understanding the human impacts on both fire history and forest ecology.

Contrasting mean fire intervals for different physiographic conditions can provide another dimension to understanding the fire history of a region. Habitat type (Arno 1976), aspect (Kilgore and Taylor 1979), elevation (Hawkes 1980), and landscape relief (Zackrisson 1977) have been used alone or in various combinations to represent different physiographic conditions. Significant differences in the mean fire intervals for these physiographic conditions attest to their control of fire behavior. An example of the confusion caused by not acknowledging the differences in intervals between the physiographic conditions has been pointed out by Kilgore and Taylor (1979). They reference various studies in the Sierra Nevada where different investigators have suggested intervals of two to 25 years for the entire region. Moir (1980) has seriously questioned the extrapolation of fire history information beyond the particular location where it is collected. He is not convinced that one can generalize on the basis of physiographic conditions in some regions.

Frequency distributions of fire intervals should also be considered as a further aid to the understanding of fire history. The median fire interval may be more significant than the mean when the frequency distribution of fire intervals is highly skewed (Kilgore and Taylor 1979; Jacobs et al. 1980).

Fire history can also be presented by preparing maps of past fires based on fire chronologies. Maps for each fire year are prepared by mapping the location of each tree with a dated fire scar for the particular fire year. Again, extrapolation of the fire boundaries beyond locations of the fire scarred trees should be done with considerable care. Use of stand age data, topographic maps, and fire suppression records are

helpful in extrapolating fire boundaries (Arno and Sneek 1977).

Various modifications of the methods described in the preceding pages have been used by numerous investigators to determine local as well as regional fire histories. Alexander (1979) in his bibliography of fire history has documented studies in nine Canadian provinces, 26 states in the United States, as well as in Australia, Finland, Mexico, Sweden, and South America. Arno (1976) provided an overview of fire history investigations for the Northern Rocky Mountains which not only summarized previous work but identified those habitat types in which work needs to be done. The papers of Arno and Sneek (1977) and Kilgore and Taylor (1979) should be studied by all students of fire history for their treatments of methods and interpretations of results of fire scar dating. Heinselman's (1973) study of the fire history of the Boundary Water Canoe area should be consulted for the method of preparation of detailed maps of past fires. The Proceedings of the Fire History Workshop (Stokes and Dieterich 1980) contain reports on fire history research as well as important discussions on methodologies, terminology, and the future significance of the field.

ONGOING RESEARCH

Current research projects underway in Australia, Sweden, and the United States are exploring alternative techniques for dating fires through the analysis of tree rings. These techniques are seeking evidence other than fire scars which could be used to date fires. Fire scars are not always present on trees and any alternative evidence of past fires that could be detected in tree rings would be useful in preparing fire histories. Two tree-ring characteristics which are being examined in ongoing research are the chemical composition of annual rings and traumatic resin canals.

John Banks, working at the Australian National University at Canberra, initiated studies in 1978 to examine the mineral content of the annual rings of snow gum (*Eucalyptus pauciflora*). A report on this research was presented at the 13th International Botanical Conference in Sydney, Australia (Banks 1981). Banks did not observe any definitive change in nutrient content in the heartwood which could be correlated with fire scars. Banks (1982) concluded that evidence of fires could not be detected in the heartwood of snow gum because the high concentration of minerals absorbed by the tree following a fire remains in a sapwood pool from which it is redistributed to various meristems. He suggests that the mineral content drops in the oldest annual ring of sapwood as it matures into heartwood. This drop occurs as minerals are mobilized out of this ring and shifted to the remaining rings in the sapwood.

I have applied Bank's method of tree-ring nutrient analysis to fire-scarred sections of sapwood from a white fir (*Abies concolor*) growing in the Sierra Nevada in California. This tree was scarred by a prescribed fire in the autumn of 1978. Wood samples were taken from the two annual rings produced before and the two rings produced after the fire. These were analyzed for phosphorus and for nitrogen content. Phosphorus was determined using an atomic absorption spectrophotometer, while the nitrogen content was determined by the micro-kjeldahl method. Both the amounts of phosphorus and nitrogen increased significantly in the years following the fire (Figure 3). The change in the year after the fire appears to be abrupt enough to possibly serve as an indicator to date a fire. My observations have been made on rings in the sapwood and a question can be raised as to the persistence of these elevated mineral concentrations in view of Bank's work with snow gum. I am continuing my nutrient analysis of

tree rings to see if, in fact, the contrasting mineral concentration levels persist as the rings of the sapwood mature into heartwood. If they do persist, it might be possible to determine the fire history of an area, with species like white fir, by an analysis of the nutrient concentration of tree rings.

Olle Zackrisson is currently examining the occurrence of traumatic resin canals in Scots pine (*Pinus sylvestris*) as a means of dating fires in Sweden. He described this research at the Fire History workshop at Tucson, Arizona in October, 1980. Traumatic resin canals are tubular, intercellular spaces which are filled by resin secreted from surrounding epithelial cells. Traumatic resin canals are formed in response to tree stress which may be caused by insect attack, disease, mechanical damage, or fire. They are generally distinguished from normal resin canals on the basis of number per unit area. One often observes rows of traumatic resin canals adjacent to a fire scar in the first ring to grow over the surface of a fire scar. These are not unusual in many species of pine. Zackrisson reported on the occurrence of very long rows of traumatic resin canals in trees which had no fire scars. Ring counts indicated these traumatic resin canals were produced in years of known fires. Zackrisson is continuing his observations on this phenomenon and expects to be able to construct fire histories using traumatic resin canals alone.

I have initiated exploratory studies of traumatic resin canals in the five conifer species of the mixed conifer type of the Sierra Nevada in California (ponderosa pine, *Pinus ponderosa*; sugar pine, *P. lambertiana*; incense cedar, *Calocedrus decurrens*; white fir, *Abies concolor*; Douglas-fir, *Pseudotsuga menziesii*). The first step in these studies has been to establish the frequency and extent of traumatic resin canals. Each annual ring on 10 cross-sections from trees of each species was examined under a 30X magnification dissecting microscope. None of these cross-sections were taken from trees with fire scars, but all trees were cut from sites where the fire history since 1900

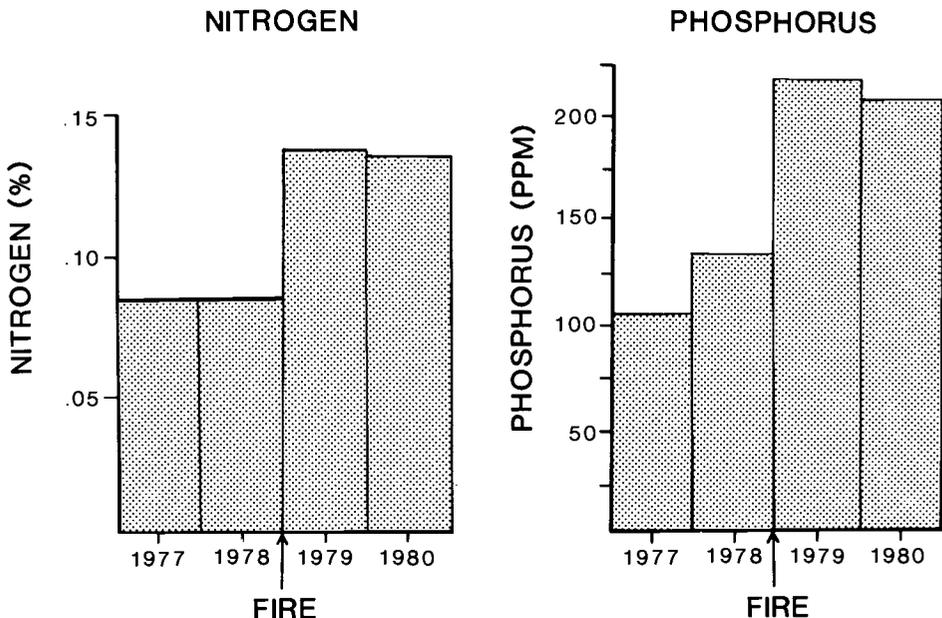


Figure 3. Concentrations of phosphorus and nitrogen in tree rings formed prior to and after a ground fire in white fir (*Abies concolor*).

was known. The cross-sections of incense cedar did not exhibit any resin canals. Pierce (1937) has reported that no members of the *Cupressaceae*, which includes incense cedar, produce normal resin canals. My results indicate that at least one member of the group does not produce traumatic resin canals as a result of fire. The cross-sections from the two pine species exhibited innumerable resin canals. After an extensive examination of the anatomy and number of canals per unit area, I was not confident that I could distinguish a normal canal from a traumatic one. A similar conclusion had been reached earlier by Bannan (1941). He concluded that all resin canals in pines were produced in response to external stress. If this is the case, then the extremely high frequency of resin canals I observed in ponderosa and sugar pine would suggest they are of no practical value in establishing fire history. Both normal and traumatic resin canals have been reported in Douglas-fir (Panshin and de Zeeuw 1980) and the two types can easily be distinguished on the basis of number per unit area. The Douglas-fir wood specimens which I examined had far fewer traumatic resin canals than the pines; however, the frequency was too great to be of value in dating past fires. An even larger frequency was observed in white fir which produces only traumatic resin canals (Bannan 1936). The high frequency suggests a variety of stress factors are acting to produce traumatic resin canals. The resulting frequency of resin canals limits the use of resin canal frequency as a distinct marker of past fires for this species also.

The extent of traumatic resin canals along the circumference of an annual ring varied considerably in the specimens of white fir and Douglas-fir. Assuming that the heat of a fire might induce resin canal formation along a fairly long arc, I measured all traumatic canal zones in the white fir and Douglas-fir samples. These zones ranged in length from less than 1% up to 39.8% of the annual ring in white fir and from less than 1% up to 75.7% in Douglas-fir. Only four white fir and three Douglas-fir had arcs of traumatic resin canals which extended over more than 20% of the circumference of the annual ring in which they were located. The years in which these longer arcs were produced did not synchronize with each other nor did they correspond with the known fire year in the study area. Based on these observations I must conclude that the frequency and extent of traumatic resin canals in the five conifer species of the mixed conifer type are not useful in determining fire history. These preliminary results should not, however, discourage further examination of the relationship between traumatic resin canals and fire.

RESEARCH NEEDS

In conclusion, three areas for further research into pyrodendrochronology should be noted. These include (1) testing of sampling procedures, (2) identification of alternative fire markers, and (3) measurement of the accuracy of fire scar histories.

A rigorous examination should be undertaken to evaluate the procedures used for locating sample trees. No one has compared the efficiency or accuracy of random versus regularly located samples. Research also needs to be conducted on the sample size needed to establish a fire history for physiographically uniform sites.

Two alternative fire markers have previously been described: mineral concentration of tree rings and traumatic resin canals. Much more work needs to be done on the use of these markers for dating fires. In addition, one might examine the correlation between wood density in annual rings and fire occurrence. Recent developments in the use of X-ray to measure wood density may be applicable here (Schweingruber et al. 1978.) Anatomical characteristics such as fiber length, cell diameter, or the

microfibrillar angle in cell walls might be worth exploring.

Research efforts should also be directed toward testing the accuracy of fire histories established through fire scar and tree-ring analysis. Recorded fire records spanning up to 100 years are available for some regions of North America and for even longer periods in Northern Europe. These records may allow investigators to address the question of the accuracy of fire histories developed through fire scar analysis. The increasing use of prescribed burning also affords an opportunity to relate fire behavior to fire scar formation and an opportunity for validity testing.

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