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Fire Dating from Tree Rings in Western Cascades Douglas-fir Forests: An Error Analysis

Abstract

Cross dating, the matching of tree-ring patterns to determine absolute dates or tree-ring series, is a valuable technique for dating wildfires. However, most recent fire history studies conducted in Pacific Northwest Douglas-fir forests have not employed cross dating. The error associated with non-cross-dated, field-counted, fire history data was assessed at four sites in Douglas-fir forests of the western Cascades, Oregon. Fire scar and tree origin years were dated in the field by counting tree rings on minimally prepared stump surfaces. Wood samples from these same stumps were then prepared in the laboratory, where tree rings were re-counted and cross dated. Fire histories from field-counted, laboratory-counted, and cross-dated efforts were compared.

Cross dating required 22 times the effort of the field-counted fire history reconstruction, and 87% of fire-scarred samples could be cross dated. The field-counted data generally underestimated ages of fire scar and tree origin years, and fires reconstructed from field-counted data were estimated as having occurred from 1 to 16 years more recently than they actually did. Field-counted scar years were within 10 years of their true values for about 75%, and within 20 years for about 87% of observed cases. Errors in fire frequency estimates were small unless an incorrect number of fires was reconstructed. Also, the error associated with careful laboratory counts on well-prepared surfaces was minimal (mean error of 1.5 years) even when cross dating was not conducted. We recommend that future fire history studies in the Pacific Northwest employ cross dating.

Introduction

Tree-ring studies are used to reconstruct fire history over centuries, or for as long as the oldest trees survive. Cross dating, the matching of tree-ring patterns to determine absolute dates for tree-ring series (Stokes and Smiley 1968, Fritts 1976), is a valuable technique for precisely determining years of fire injury or tree origin that can then be used to date wildfires. Cross dating can also be used to extend the length of fire records using tree-ring series from snags, stumps, and other remnant (dead) materials (e.g., Baisan and Swetnam 1990, Kitzberger and Veblen 1997). Since cross dating is laborious and time consuming, many fire history studies have relied on non-cross-dated ring counts. Only 22 of 116 (19%) published fire history studies conducted in the western United States prior to 1995 used cross dating (Heyerdahl et al. 1995).

Some current ecosystem management and science problems require studies of fire history over scales of landscapes to regions (Christensen et al. 1996, Cissel et al. 1998, Cissel et al. 1999). For some ecosystems, this necessitates extensive field sampling, where many samples must be obtained and little time and resources are available for each sample. Landscape-level studies require a challenging balance between intensive and extensive sampling, where intensive sites provide temporal precision through cross dating, and extensive sites provide greater spatial coverage (Taylor and Skinner 1998). The majority of fire history studies emphasizing the temporal dimension (e.g., effects of climate variation) may continue to focus on study areas of one to several stands. The costs, labor and time required for cross dating fire history over whole landscapes might be prohibitive for all but the most well-funded research projects.

The necessity for cross-dated fire history reconstructions may thus limit the development of broad-scale fire regime characterizations in some ecosystems. Yet, the necessity for cross dating has been little explored for research questions that are general, and more concerned with fire regime variation in space than over time. Little is known about the level of accuracy for non-cross-dated

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studies of a given ecosystem and fire regime type. Few studies have quantified the error associated with non-cross-dated tree-ring counts in a fire history study (Madany et al. 1982, Means 1989). Furthermore, none has quantified the error for fire histories where tree-ring counts were made on minimally prepared stump surfaces in the field, even though many fire history studies that have used non-cross-dated ring counts have conducted these counts on minimally prepared cross sections or cores under field conditions (e.g., Hemstrom and Franklin 1982, Teensma 1987, Masters 1990, Morrison and Swanson 1990, Impara 1997, Weisberg 1998). Such quantification of dating error is important for prudent interpretation of fire history analyses (Swetnam et al. 1983).

In the Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco) forests of the Pacific Northwest (PNW), the application of cross dating (or any fire dating

sus cross dating; (2) laboratory ring counts on well-prepared cross sections (i.e., "laboratory counts") versus cross dating; and (3) fire frequency estimates derived from field counts, laboratory counts, and cross dating.

Methods

Field Methods

Four sampled clearcut sites are located within the Blue River study area (Weisberg 1998), which occupies approximately 450 km^2 in the central western Oregon Cascades (Figure 1, Table 1). Elevations range from 316 m to 1645 m, in an area of steep and dissected terrain. Annual precipitation averages about 2300 mm (Bierlmaier and McKee 1989, Greenland 1994), with periods of extended drought common during the summer months. The combination of summer drought,

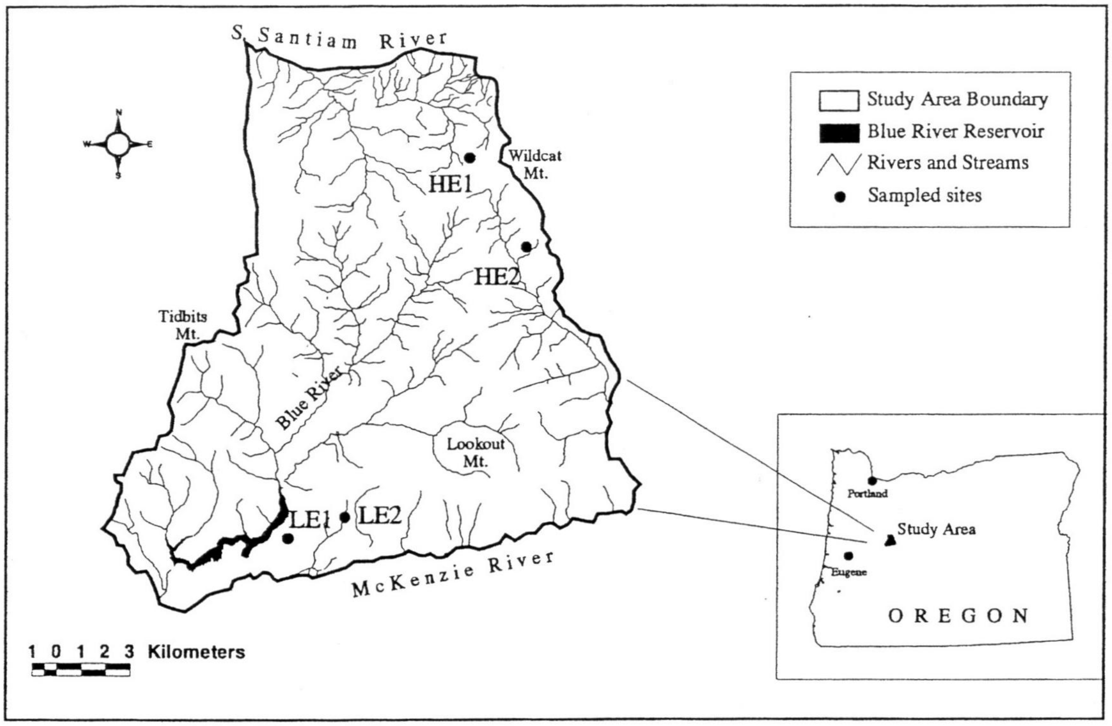


Figure 1. Map of the Blue River study area (Weisberg 1998), showing the four cross-dated fire history sites.

TABLE 1. Environmental characteristics of the four fire history sites, sampled in 1997. Elevation, slope position, and approximate UTM coordinates were derived from GIS data layers; the other variables were measured in the field. Forest type refers to forest series classification determined for standing forest adjacent to the clearcut sites (Franklin and Dyrness 1988).

Site	UTM Coordinates	Harvest Year	Elevation (m)	Slope Aspect	Slope Steepness	Forest Type
LE1	559465, 4892245	1989	740	Flat	Low	Western Hemlock
LE2	562225, 4893265	1991	575	203	Moderate	Western Hemlock
HE1	568405, 4911085	1992	1269	271	Low	Pacific Silver Fir
HE2	571225, 4906645	1986	1187	222	Moderate	Pacific Silver Fir

conditions (Table 1). It was expected that trees at higher elevation sites would have narrower rings and a greater incidence of tree-ring anomalies, such as missing, partial, or double rings, because of site conditions (e.g., persistent snow cover, low temperatures, immature soils) leading to greater stress and lower productivity.

At each clearcut site an area of approximately two hectares was searched for sound stumps of fire-scarred trees. Fifteen Douglas-fir stumps were sampled at each site, for a total of 60 trees. Sampling was limited to Douglas-fir, a species commonly used for fire history reconstruction, because it establishes after fire and can retain a distinctive fire history record. For each stump, fire scar and pith years were estimated in the field by counting tree rings under 3X, 10X, or 16X magnification, after stump surface preparation with hand tools (wire brush, scrapers, surform planer). The stump surface was then collected as a complete cross section or as a wedge encompassing the area immediately adjacent to the fire-scarred portion of the bole, depending on tree diameter.

Laboratory Methods

Cross sections were air-dried, mounted on wooden boards, planed, and sanded until cell structure was clearly visible (to 320 - 600 grit sandpaper). Dates of tree rings containing scars or pith years were estimated by counting backwards from the outermost ring, which corresponded to a known harvest year. All counts were checked independently by a second researcher. After this check, laboratory-counted fire year estimates were recorded. Fire years were then determined precisely by cross dating all tree-ring series using standard dendrochronological procedures (Stokes and Smiley 1968). An existing master tree-ring chronology from other sites within the H.J. Andrews Experimental Forest was used as a dating control[1].

Skeleton plotting was used to match ring-width patterns against the master tree-ring chronology, and against skeleton plots of already cross-dated tree-ring series (Stokes and Smiley 1968, Dieterich and Swetnam 1984). Since the master tree-ring chronology was not useful prior to ca. 1600 due to insufficient sampling depth, skeleton plots for those trees with ring series extending before 1600 were matched with each other, allowing cross-dated fire scar and pith year dates from as early as 1513. Earlier scar and pith years could not be cross dated.

Other cross-dating methods, that we did not apply, include the "list" method of cross dating, where marker rings are listed and compared between samples (Yamaguchi 1991), and statistical cross dating using computer-aided cross correlation among measured ring width series (e.g., Holmes 1983, Sheppard et al. 1988). The list method may be faster than skeleton plotting, and has been used to date volcanic eruptions and lava flows in the Mount St. Helens, Washington area (Yamaguchi 1983, Yamaguchi and Hoblitt 1995). Statistical cross dating provides a more objective test of dating consistency, and the measured ring width series can be further analyzed using a variety of dendroecological techniques for inter-site comparisons (Fritts 1976: Chap. 6).

Data Analysis

Scar and pith year estimates from field and ring counts were compared with cross-dated scar and origin years. Pith years were not corrected to stump height, and so refer to the year of accession to stump height (generally, 60 - 90 cm). Field-counted and laboratory-counted estimates were compared with cross-dated years using histograms showing the distributions of differences (i.e., "errors"). We calculated the mean, median, minimum, maximum, and standard deviation of dating errors. For calculating the mean, median, and standard deviation, the absolute value of the error was used, since errors could be positive or negative. Errors were not independent, since multiple scars often occurred on the same tree. An error in outer rings would propagate towards the pith, with the effect that a single counting error could affect multiple scar and pith year estimates.

Before calculating fire frequency indices, a fire history was reconstructed using field-counting, laboratory-counting, and cross-dating methods. Scars were considered to be of fire origin if they were oriented along a common radius, aligned with a zone of thin bark, and had a distinctive morphology characteristic of fire effects on thick-barked Douglas-fir (Morrison and Swanson 1990). For a fire to be detected using cross dating, at least 10% of all trees, within a site, that were old enough to have been scarred during a given year had to have recorded that scar year. Further, at least two scars on different trees had to be present for each detected fire year. The purpose of these rules was to reduce the possibility of including scars from non-fire sources (e.g., mechanical injury, animal damage) in the fire chronology, under the assumption that fire scars were more likely than scars from non-fire sources to occur in the same year (Agee 1993). Another outcome of these criteria was that some small fires were likely excluded.

The same criteria were used to reconstruct fire history for the field-counting and laboratory-counting methods, but were applied to scar-year estimates clustered in time (*sensu* Teensma 1987, Weisberg 1998). The maximum duration of scar-year clusters was 8 years for 1800-1996, 10 years for 1700-1799, and 12 years for 1500-1699. Longer intervals were used for earlier time periods when scar year estimates were fewer and subject to more counting errors. Also, the scar-year cluster was split when two scars close in time were counted on the same radius of a single tree, indicating that two fires had occurred. The average scar-year within a scar cluster was used to estimate the fire year.

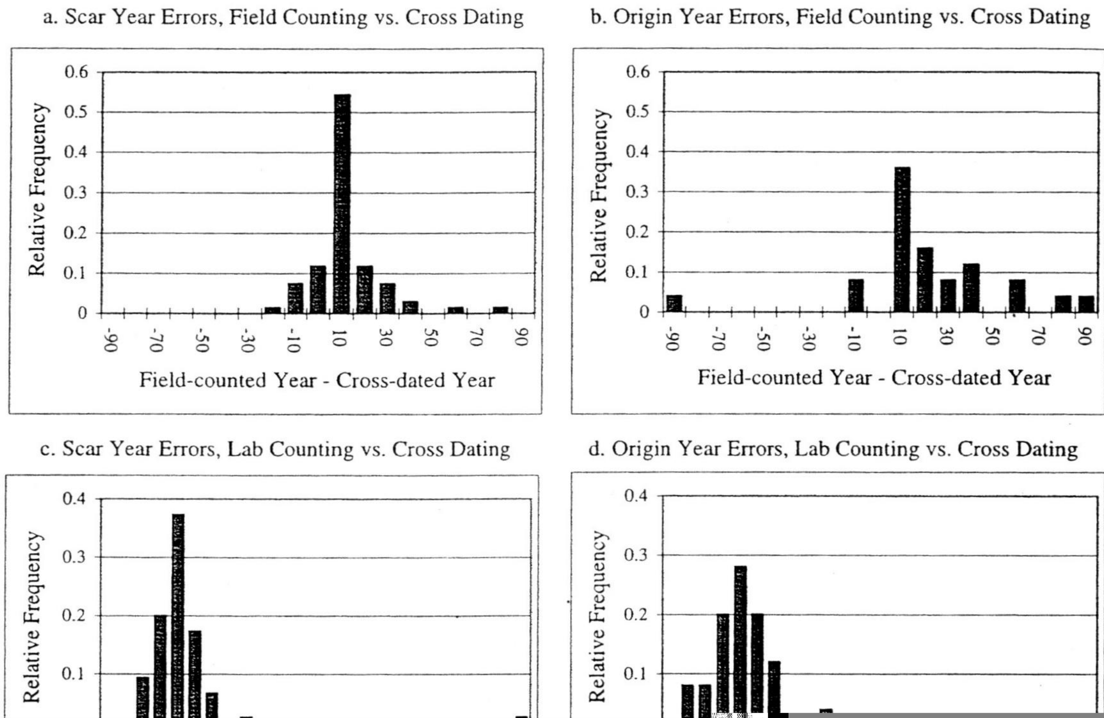
Because Douglas-fir may establish over at least 40 years following high-severity fire (Hemstrom and Franklin 1982), we identified a fire year from counted and cross-dated pith years if at least two pith years occurred within a 40-year period prior to 1600, or three pith years within a 40-year period following 1600, even in the absence of scar

the study area initiated cohorts of Douglas-fir, but left few surviving, scarred trees. Fire-year estimates based solely on pith year data likely underestimated the actual age of the fire because: (1) pith years were not corrected for growth to stump height, a correction of at least several years; and, (2) an unknown number of years had elapsed between the fire and establishment of the earliest recorded regeneration tree (Goldblum and Veblen 1992). Fire frequency was calculated for each site as mean, median, and maximum fire interval, and the number of fires, using reconstructed fire interval distributions from both cross-dated and field-counted data sets.

Patterns of cross dating success for pith years were similar, as expected, since fire scar and pith years were taken from the same set of tree-ring series. We were able to cross date 26 of 35 (74%)

prepared stump surfaces, and incorrect estimates of the fire scar or pith year. We detected 11 scars (i.e., 12% more) on prepared cross sections that were not detected on the same surfaces in the field. Many of these scars were difficult to detect because they were small and/or located in sections of narrow rings. Others were super-imposed on scars from earlier fires, where the cambial layer had been repeatedly injured along the same radius, corresponding with bark fissures (Morrison and Swanson 1990). Such scars may be difficult to distinguish from patterns of healing over previous scars, even with appropriate magnification.

Errors in fire scar or pith year estimation were


a. Scar Year Errors, Field Counting vs. Cross Dating
Relative Frequency
Field-counted Year - Cross-dated Year
b. Origin Year Errors, Field Counting vs. Cross Dating
Relative Frequency
Field-counted Year - Cross-dated Year
c. Scar Year Errors, Lab Counting vs. Cross Dating
Relative Frequency
d. Origin Year Errors, Lab Counting vs. Cross Dating
Relative Frequency

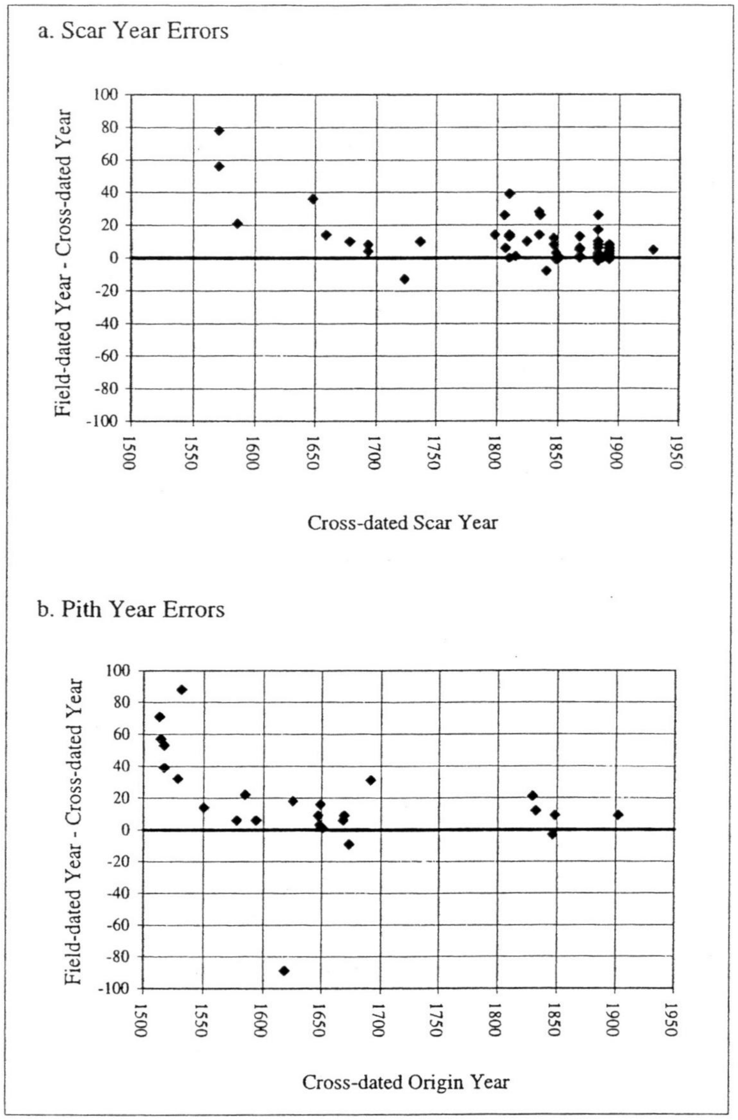


Figure 3. Errors in field-counted estimates for (a) fire scar years, and (b) tree pith years, shown over time. Errors are pooled among the four sites.

consistently dated as having occurred more recently than they actually did based on the field-counted data set. Spurious fires were reconstructed from field-counted data for sites LE1 and HE2, although the 1815 fire in the HE2 field-counted

Fire frequency was similar among cross-dated, ring-counted, and field-counted dates where the number of fires detected was the same, but differed considerably where a different number of fires was detected (Table 3). For example, where

TABLE 2. Fire history reconstructions developed using the three fire dating methods, for each of four fire history sites. The symbol "X" indicates a fire was dated to a certain year (row) by a certain method (column). The symbol "S" indicates a spurious fire according to the Field or Lab Counting methods, that did not occur or was not detected using the Cross Dating method.

Site	Cross Dating	Lab Counting	Field Counting
LE1			
1550	X		
1557		X	
1564			X
1834	X	X	
1846	X	X	
1850			X
1860			X
1883	X		
1884		X	
1886			X
1897			S
LE2			
1647	X		
1649		X	
1651			X
1868	X	X	
1872			X
1892	X	X	
1893			X
HE1			
1513	X		
1515		X	
1551			X
1810	X	X	
1826			X
1892	X	X	
1894			X
HE2			
1570		X	
1571	X		
1584			X
1807		S	
1815			S
1848	X	X	
1849			X
1882		X	
1883	X		
1884			X

TABLE 3. Estimates of fire frequency (years) for each of four fire history sites, for cross-dated, laboratory-counted, and field-counted methods of fire history reconstruction.

	Cross-Dated	Lab-Counted	Field-Counted
Site LE1			
Mean Fire Interval	109	110	83
Median Fire Interval	75	75	19
Maximum Fire Interval	284	277	286
Number of Fires	4	4	5
Site LE2			
Mean Fire Interval	116	116	115
Median Fire Interval	104	104	103
Maximum Fire Interval	221	219	221
Number of Fires	3	3	3
Site HE1			
Mean Fire Interval	161	160	149
Median Fire Interval	104	104	102
Maximum Fire Interval	297	295	276
Number of Fires	3	3	3
Site HE2			
Mean Fire Interval	142	107	103
Median Fire Interval	113	78	74
Maximum Fire Interval	277	237	231
Number of Fires	3	4	4

Time Expenditures

More time was required to obtain laboratory-counted and cross-dated fire scar and pith year dates than to obtain field-counted dates. Field-counted dates for the four sites were obtained in 24 person-hours. The cross-dated dates required nearly 530 person-hours to obtain, distributed as:

(1) 12 hours (one person) to locate and mark scarred stumps of maximum suitability;

(2) 57 hours (three people at 19 hours each) to remove and transport cross-sections;

(3) 340 hours (one person) to trim, mount and sand the cross-sections; and,

(4) 120 hours (two people) to count, cross-date, and check for accuracy.

Our record-keeping was not detailed enough to estimate precisely the length of time required to obtain laboratory-counted data, which required from 410–529 person-hours. These times might vary greatly among studies, depending upon the skill and experience of the dendrochronologists, the size of the samples to be transported and sanded, transport distances for carrying and driving samples, and the quality of laboratory facilities.

Discussion

The Context of Fire-Dating Error in Fire Regime Analysis

Error in dating fire events is but one of many sources of error and uncertainty for fire history analysis. Other significant sources include the erasure problem, where trees carrying fire evidence are killed and decompose over time; problems of sampling methodology, where an incomplete sample of the population of trees and sites with fire evidence is collected; errors associated with determining which scars result from fire rather than other scarring agents; and limitations of analytical methods for characterizing fire regimes (Molnar and McMinn 1960, Agee 1993, Brown and Swetnam 1994, Johnson and Gutsell 1994, Kipfmeuller and Baker 1998, Lertzman et al. 1998, Weisberg 1998). These factors vary in importance and tractability among tree species and fire regime types.

While field-counted scar and pith year estimates may include large errors (Figures 2a and 2b) and result in incorrect estimates for fire frequency descriptors (Table 3), these errors may be small compared to other error sources. Especially important is the inability to consistently and objectively determine which scars represent fire scars, due to the scarcity of recorder trees with open catfaces in mesic forests, such as those of the western Cascades. Studies in the mixed-severity fire regime of the central western Oregon Cascades do not allow unequivocal determination of which scars are fire scars, and so must rely upon somewhat arbitrary criteria to define fire events from the population of sampled scars. Differences in fire history reconstruction and fire regime characterization associated with such criteria may exceed errors associated with field counting rather than cross dating. For example, 17 of 69 (~25%) of cross-dated scar years were not used to date fire episodes using the 10% criterion, where at least two or three trees per site were needed to interpret a fire episode. If it were known that all sampled scars were of fire origin, the criterion for detecting a fire would be a single scar, and many more fires would be detected. Resulting estimates for fire frequency descriptors (Table 3) would differ greatly from those obtained using the 10% criterion. For example, the cross-dated Mean Fire Interval would be 74, 70, 42, and 53 years for sites LE1, LE2, HE1, and HE2, respectively, if all sampled scars were used.

Are Field Counts of Tree Rings Accurate Enough for Fire History Reconstruction?

The utility of field-counted fire history studies is determined by the study objectives and the fire regime under consideration. In the central western Cascades, fires were generally infrequent with mean fire intervals ranging from 80 to 300 years (Hemstrom and Franklin 1982, Teensma 1987, Garza 1995, Morrison and Swanson 1990, Weisberg 1998). However, fires of the past 400 to 500 years were not evenly distributed over time. Fires were clustered from the 1400s to the early 1600s, and from the 1800s to the early 1900s (Weisberg 1998). Within these periods, fire intervals were often short (i.e., within 50 years). If research objectives require differentiation of fires that occur within 20 years of each other, field-counted studies may not provide sufficient accuracy. Although most fire scar years were estimated to within 20 years of their correct value, the 13% that were not may cause fires to be undetected, and other fires to be falsely detected.

Large errors in counts of individual scar and pith years (Figures 2a and 2b) were reduced at the fire reconstruction stage of analysis (Table 2). However, recording an erroneous fire in one of four sites would not be suitable for most fire history research objectives in a fire regime where sites experience just two to eight fires over the period of record (Weisberg 1998). Reconstruction of an incorrect number of fires leads to greater errors for fire frequency descriptors when fire intervals are long relative to the total length of record.

A more consistent effect of field-counted error is the temporal offset of reconstructed fire years. All fire years at all four sites were estimated to have occurred more recently than they likely did (Table 2). In most cases (e.g., site HE2 fires 1848/1849, 1883/1884) the offset was minor. For a few cases (e.g., site LE1 fires 1834/1850, 1846/1860) it exceeded a decade. This source of error is sufficient to make field-counted studies unreliable for studies of interannual climate effects on fire occurrence, or for other studies where accurate estimates of fire years are important.

More problems arise when field-counted studies are used for evaluating fire extent and pattern. With imprecise fire dates, it is hard to interpret which sites burned in the same fire or even in the same decade. For example, cross-dated fire reconstructions show that the 1883 and 1892 fires were synchronous between LE and HE site pairs but not within them (Table 2), even though sites within these pairs are located within four kilometers (km), while site pairs are located approximately 10 km apart (Figure 1). A non-cross-dated field study that aggregated fire chronologies from individual sites to a single, study-area master fire chronology (e.g., Teensma 1987, Morrison and Swanson 1990, Impara 1997, Weisberg 1998) might have combined the 1883 and 1892 fires into a single "fire episode" (*sensu* Teensma 1987). Results from such a study may have led to the erroneous interpretation that a single widespread fire burned the whole study area sometime between 1883 and 1892. Alternatively, failure to aggregate non-cross-dated fire year estimates between sites may lead to erroneous interpretations of small fire extents when fires were actually large, since estimates for the same fire could differ between sites. Cross dating is thus important for valid interpretation of fire extent. Even with cross dating, it may be impossible to consistently distinguish separate fires that burned in the same season and year.

Despite these limitations, fire history reconstructions based on field-counted, fire-year estimates may be suitable for ecological objectives over coarse spatial and temporal scales. Such studies may be useful for: (1) providing a first look at patterns of fire regime over large areas and long time scales, that might then be fine-tuned with detailed dendrochronological studies over smaller areas; (2) comparing fire frequency between areas subject to different topographic and other environmental influences; and (3) interpreting temporal variation in area burned over increments of 30 years or longer.

Are Laboratory Counts on Well-Prepared Cross Sections Accurate Enough?

Non-cross-dated fire history data obtained from careful laboratory counts on well-prepared cross sections under a microscope should be suitable for many ecological objectives, for the fire regime and forest types considered in this study. Average errors on the order of one to two years do not preclude fire-interval analysis (Agee et al. 1990). However, most of the labor required for cross-dated fire history studies is used to prepare cross-section samples; once samples are prepared, it is little additional work to cross date. The added precision of cross dating allows for more powerful, higher-resolution fire history analyses. Even when fire history research objectives do not require annual precision, it is possible that a future study might (e.g., of weather conditions and climatic events leading to widespread fire, Swetnam 1993, Villalba and Veblen 1998). Also, cross-dated fire histories are more suitable for analyses of the spatial patterning of fire events (Heyerdahl et al., in press).

Implications for Past and Future Fire History Research

Cross-dated fire history studies commonly require great time, effort, and expense, and are difficult to conduct over landscape scales. In this study, it required more than 22 times the number of person-hours to carry out the cross-dating study than it did to obtain fire scar and pith year estimates by field counting. Despite this cost, we recommend that future fire history studies employ cross dating, or at least careful counts on finely-sanded, cross-sectional surfaces. While many sources of error in fire history studies cannot be resolved (Johnson and Gutsell 1994, Lertzman et al. 1998, Weisberg 1998), it seems prudent to resolve those that can be. Dating errors from field-counted cross sections can be significant, but can be resolved by cross dating. Landscape-scale questions might be approached through a careful hierarchical selection of sampled sites and trees within sites. Where logistical limitations preclude extensive cross-section collection and cross dating, we recommend that field-counted fire history studies begin with a pilot study where a subset of the study area is sampled using cross dating, and error between field-counted and cross-dated fire history reconstructions quantified. A second phase of extensive fire history sampling using field counting might be useful for mapping past fire events, if followed up with a third phase, where high-resolution dating is used to obtain accurate dates for particular events, areas, or research questions. Multiple studies at different scales might be necessary to obtain a complete and accurate picture of spatial fire patterns, and the environmental factors that influence them, over large landscapes or regions.

Fire history studies based on field counting alone provide data at too coarse a temporal resolution for testing many hypotheses involving fire frequency or extent. Fire events may be undetected by such studies, or falsely detected. Detected fires, often dated using a narrow range of fire-year estimates, are likely to be consistently shifted forward in time. Without such quantification of error as provided by this study, it is difficult to interpret results of field-counted studies at an appropriate resolution.

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Footnote

1. The tree-ring chronology was obtained from Peter Brown, Director, Rocky Mountain Tree-Ring Research, Inc., 2901 Moore Lane, Ft. Collins, CO. 80526, U.S.A., and is a compilation of Douglas-fir chronologies from the 1991 and 1997 Dendroecological Fieldweeks, H.J. Andrews Experimental Forest. The chronology uses a 60-year spline to filter low-frequency variation.

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