COMPARING METHODS OF RECONSTRUCTING FIRE HISTORY USING FIRE SCARS IN A SOUTHWESTERN PONDEROSA PINE FOREST

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ABSTRACT

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Fire scars have been used extensively to understand the historical role of fire in ponderosa pine (*Pinus ponderosa* Dougl. ex Laws.) ecosystems. However, the sampling methods and interpretation of fire scar data have been criticized as statistically invalid, biased, and leading to exaggerated estimates of fire frequency. We tested alternative sampling schemes by comparing “targeted” sampling, random sampling, and grid-based sampling to a complete census of all 1,479 fire-scarred trees in a one square kilometer study site in northern Arizona. The effects of sample size and area sampled on fire frequency estimates were also tested. Given a sufficient sample size, we concluded that all tested sampling methods result in reliable estimates of the true fire frequency, with mean fire intervals very similar to the census. We also investigated the usefulness of three techniques developed to compensate for spatial uncertainties: 1) fire intervals from individual trees, 2) the interval between the tree origin and the first scar, and 3) filtering, a technique used to classify large fires. The seasonality distributions of the census and targeted sample were also compared. Quantification of the differences in sampling approaches cannot resolve all the limitations of fire scar methods, since scarred trees are inherently point-sources of data. But measurement of sampling uncertainty did reduce the scope of uncertainty in interpretation of fire regime statistics.

ACKNOWLEDGMENTS

I would like to recognize my committee chair, Pete Fulé, for his support of this project and his continued dedication to improving the science of ecological restoration. I also appreciate the other members of my committee, Tom Swetnam, Carolyn Hull Sieg and Tom Kolb, for their input, patience and words of encouragement. They all contributed different, yet necessary, pieces of the puzzle. After three years of specimen collection, preparation, crossdating and data entry of the largest fire scar collection I know of, all the staff and students at the Ecological Restoration Institute deserve recognition for their endless efforts. A special thanks to Daniel Fairbairn who dedicated an entire summer to crossdating, Nevin Yepa and Ethan Hulme who spent more time collecting and sanding than I did, and Don Normandin for helping me manage this whole process. I had the privilege of spending time at the Laboratory of Tree-Ring Research at the University of Arizona during my dendrochronological infancy. The staff and students there were instrumental in my progress and continued to support me throughout this study. Rudy King (USDA Forest Service Rocky Mountain Research Station) provided sound analytical advice. Thanks to the School of Forestry Mission Research program for funding this project, and J.J. Smith and the Centennial Forest for permitting this study and providing the gold mine of fire scars. This work could not have been completed without the heckling from my peers, constantly asking how many more specimens I had to crossdate and if I could at least take a lunch break away from the microscope. Thanks to my family for always supporting my chosen direction in life. And thank God for my good eyesight.

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PREFACE

This document was written in manuscript format so that Chapter 3 may be submitted for publication in a scientific journal, so the reader may encounter some repeated information in this chapter. The conclusions of the whole thesis are contained in Chapter 3 since it is the only manuscript chapter. To reduce redundancy, there is one Literature Cited section (Chapter 5) that includes references from the whole thesis. The plural pronoun “we” in Chapter 3 refers to the collaborating authors of the manuscript, who will be added when the manuscript is submitted for publication.

CHAPTER 1

Introduction

Crossdated fire scars provide concrete evidence of the presence of fire in an exact year and location. Fire scars have been used extensively in the southwestern United States as evidence of the natural frequent fire regime. However, uncertainties associated with sampling and interpreting fire scar data have led to criticisms of these methods. The uncertainties include the inherent limitation that fire scars are imperfect recorders of fire, so while a fire scar proves the presence of fire, the absence of a fire scar does not necessarily mean that fire did not burn in that location. Scars destroyed by subsequent fires or decay, and error introduced when sampling are also sources of uncertainty. Sampling error is one of the major topics of criticism because targeting, the standard method of fire scar sampling, is based on recovering historic evidence of fire in the natural record, not a statistical design. Therefore, targeting has no measure of accuracy or precision and was said to lead to overestimates of fire frequency. Other criticisms focus on the interpretation of fire interval distributions, unscarred trees adjacent to scarred trees, and the unscarred portion of trees before the first fire scar.

These uncertainties and criticisms are detailed in Chapter 2 along with a review of the literature relevant to the fire history of ponderosa pine forests in the Southwest and how fire regimes are studied. Chapter 3 addresses the issues of fire scar sampling and interpretation raised in Chapter 2 by collecting and mapping the entire population of trees scarred before Euro-American settlement in a representative case study area. Targeted, random, area-based and grid-based sub-samples of the population are then compared to the census to determine how well the sample mean fire intervals (MFIs) represented the population MFI. We also investigated the usefulness of several techniques developed to compensate for the uncertainties: fire intervals from individual trees, the interval between the tree origin and the first scar, and filtering, a technique used to classify the large fires.

Chapter 4 outlines the management implications of this thesis, including social and ecological considerations.

CHAPTER 2

Literature review

Fire Regimes

Ponderosa pine (*Pinus ponderosa* Dougl. ex Laws.) forests of the southwestern United States are known to have burned predominantly in a surface fire regime, characterized by frequent, low-intensity fires (Covington & Moore 1994; Pyne et al. 1996; Moore et al. 1999). Fire history studies from a range of elevations in the southwestern ponderosa pine reported fire return intervals from 2-17 years (Swetnam & Baisan 1996). Historical documents, photographs and other ecological studies support the theory that the fire regime in the ponderosa pine forests helped to maintain a relatively open forest structure with large trees and a diverse and productive understory (Weaver 1951; Cooper 1960; Moore et al. 1999).

In the last century, a combination of events led to a radical change in the fire regime and consequently an increase in tree density and fuels (Covington & Moore 1994; Fulé et al. 1997). Overgrazing of domestic livestock during Euro-American settlement in the late 1800's and fire suppression throughout the 1900's are often identified as the causes of this change (Cooper 1960; Dieterich 1980; Madany & West 1983), but researchers caution against this simple assumption as climate change is also a powerful force that can cause similar changes (Allen et al. 2002; Swetnam & Baisan 2003). Millar and Woolfenden (1999) highlight the challenges of interpreting ecological changes because climate is a possible confounding factor. However, in the southwestern United States, researchers have concluded that grazing and fire suppression are primarily responsible for the shift from a frequent, low-intensity fire regime to one with infrequent, high-intensity fires (Swetnam et al. 1999).

Understanding the historical fire regime is critical for those managers who want to restore an ecosystem or model management prescriptions and desired outcomes after natural processes and conditions (Fulé et al. 1997). This brings up the question of how to define "natural." Since there is a suite of conditions that could be considered natural, the terms "reference conditions" and "range of natural variability" are often used to describe what is natural (Fulé et al. 1997; Moore et al. 1999). This description often includes the structure, composition and function of an ecosystem and must be defined for a specific region and a period of time (Stephenson 1999). In the southwestern United States, reference conditions are typically determined for the time prior to Euro-American settlement (Fulé et al. 1997; Moore et al. 1999; Allen et al. 2002).

Ponderosa pine is one of many species known to sustain scars from fire while remaining alive (Weaver 1951). A fire scar appears within the annual growth ring in which it occurred, so by using crossdating techniques an accurate date of the fire event can be determined from the scar (Stokes & Smiley 1968; Arno & Sneck 1977; Dieterich 1980; Madany & West 1983). Taken in combination with other fire scars on the tree, one can compute a mean fire interval (MFI), a point-based estimate of fire frequency (Agee 1993).

Uncertainty

Fire scars provide a valuable and precise way to study fire history, but uncertainties are inherent when using fire scars to estimate fire frequency and spatial patterning of fires for three main reasons: 1) fire scars are not necessarily recorded consistently on individual scarred trees so they are an incomplete point source of data (Dieterich & Swetnam 1984), 2) more recent fire events may have consumed remnant fire records, and 3) error is introduced by the process of sampling the population of fire scars (Fall 1998). These uncertainties frame a discussion over the correct application of MFIs, how to interpret unscarred trees, and the sampling methods used in fire history research, including the possibility of correcting for any bias introduced in sampling. Few researchers have attempted to quantify the extent of uncertainty in fire scar studies, yet most acknowledge that the problem exists (Fall 1998). Baker and Ehle (2001) suggested "bracketing" MFIs with correction factors to compensate for the perceived uncertainties. They assessed 18 studies in ponderosa pine forests that reported MFI values of 5-21 years. When their bracketing methods were applied, they calculated the MFI to be 22-308 years. In contrast, Fall (1998) argued that current methods are biased in the opposite direction, towards under-representing fire occurrence because many unscarred trees may have actually burned but failed to scar. It is likely that uncertainties in fire-scar formation and their preservation through time have resulted in both of these views being appropriate in different areas at different times.

Interpretation of fire interval distributions

Dieterich and Swetnam (1984) studied a single tree with 42 fire scars in which none of the four cross-sections from the tree, taken individually, recorded all 42 scars. To calculate fire frequency based on a single cross-section from a single tree would underestimate the true fire frequency of the whole stand because of unrecorded fire events and loss of fire scars from decay, breakage, and subsequent fire events. Since tree rings are imperfect recorders of fire, Dieterich (1980) compiled fire dates from many trees in an area to produce a master fire chronology and a composite MFI more representative of the entire study area than a single tree.

A composite, or whole site, MFI typically results in a much shorter interval compared to that of an individual tree, or point fire interval. While Baker and Ehle (2001) suggested that the composite MFI overestimates fire occurrence and is not area-explicit, the point MFI is likely to underestimate fire occurrence because of unrecorded fires. A composite is most useful when applied to homogeneous areas (Dieterich 1980) because different burning patterns occur on different landscape features (Arno & Petersen 1983). More fires are encountered as the study area increases in size (Kilgore & Taylor 1979; Falk & Swetnam 2002), so temporal and spatial heterogeneity of fires are difficult factors to capture with one estimate of fire frequency (Lertzman et al. 1998). Some approaches to resolving this problem include filtering the composite to exclude the fires that occur on fewer than a determined percentage of trees (Grissino-Mayer 1995), or using the median fire interval which is less affected by the skewed distribution of intervals than the mean (Taylor & Skinner 1998). A different method, called the annual fire frame, attempts to capture the spatial variability by expanding a “frame” over the study area until the MFI reaches the maximum of one fire per year (Swetnam & Baisan 2003; Falk 2004).

Another potential source of uncertainty is the period of time between tree germination and the first fire scar, called the origin-to-scar (OS) interval (Baker 1989). It was argued that for a ponderosa pine tree to survive, it must have experienced a fire-free interval of at least 50 years and therefore this fire-free interval must be included in the population MFI (Baker and Ehle 2001). Alternatively, Stephens et al. (2003) asserted that it is impossible to know the true fire-free interval since many trees survive fires without scarring. Most trees are much older than 50 years when they scar for the first time, and many are younger. Another argument in opposition to the OS interval when calculating MFI is one of the basic sources of uncertainty mentioned earlier, that fire scars may be burned away by subsequent fires, so the true OS interval cannot be quantified (Stephens et al. 2003).

Interpretation of Unscarred Trees

A crossdated fire scar indicates the presence of a fire in a specific year. A nearby fire scar in the same year may lead the observer to infer that the area between the trees also burned if the fuels, topography and absence of natural fuelbreaks are consistent with this inference. A different interpretation is that only a small patch, ignited by lightning, burned around the base of each tree (Minnich et al. 2000). In the case of small patches of discontinuous fire, Minnich et al. (2000) argued that a composite MFI based on the fire scars would overestimate the actual fire frequency since it does not account for the unburned area. Other studies that use composites (Dieterich 1980) use the definition of MFI to explain that every unit of ground is not necessarily burned at that average interval (Romme 1980; Swetnam & Baisan 2003). Because trees are imperfect recorders of fire, the absence of a fire scar does not necessarily indicate the absence of a fire, so it is impossible to know how much area was left unburned in each fire year in a densely fire-scarred area. This type of uncertainty can never be completely resolved, but some authors have reported mean and median fire intervals at several spatial scales with different filters to show the variability in patterns of fire (Swetnam & Baisan 1996; Stephens et al. 2003).

Sampling

A standard approach to sampling fire scars is to systematically search an area for trees showing multiple scars and long records of fire to compile a complete inventory of fire years in that area (Arno & Sneck 1977; Agee 1993; Swetnam & Baisan 1996; Swetnam & Baisan 2003). This method, called “targeting,” has been criticized as undesirable and statistically invalid because it is not a random sample from a well-defined population (Johnson & Gutsell 1994). Because it is partially subjective and there is currently no statistical validation for targeting, it is said to lead to estimates of fire frequency where neither the accuracy nor the precision are known (Johnson & Gutsell 1994). Swetnam and Baisan (1996) argued that random sampling would not result in a complete or unbiased record of fire in frequent surface fire regimes unless very large numbers of trees were sampled. They supported the targeting method based on the argument that trees are a natural archive of historical data and not consistently reliable recorders of fire, so they should not be treated “as if they all belong to the same statistical population”. However, Swetnam and Baisan (2003) recognize that “statistical descriptions and tests of fire interval distributions are inherently limited in objectivity, resolution and reliability”, and should be complemented with other historical description of fire occurrence and forest conditions.

A different approach to estimating fire frequency is by area-based measurements, one of which is the natural fire rotation (Heinselman 1973). This method calculates the time it takes for an area of interest to burn completely (Romme 1980), and is equivalent to fire cycle and fire return period (Li 2002). Based on time-since-fire maps and such parameters as stand age and species composition, this measure of fire frequency is most appropriately applied to high-severity fire regimes (Agee 1993). The low-intensity, surface fires in the southwestern ponderosa pine forests maintain uneven-aged stands and do not generally result in new stand initiation, so the stand characteristics necessary to make area-based estimates for the pre-documentary period do not exist (Dieterich 1980; Brown & Sieg 1996).

Johnson and Gutsell (1994) assert that time-since-fire maps are the only statistically valid method of reconstructing fire events and calculating fire frequency since they can account for spatial and temporal variability. Baker and Ehle (2001) showed the identity of the fire interval and the fire rotation. However, applying the fire rotation methods to fire intervals assumes that the fire-scarred trees constitute the entire area burned in a given year (Minnich et al. 2000). Instead, targeting is a method used in high frequency, low intensity surface fire regimes where time-since-fire maps cannot easily be constructed (Brown & Sieg 1996). The effects of other sampling strategies, such as grid-based (Arno et al. 1995; Heyerdahl 1997) and random sampling, are also unknown.

Given the variety of opinions about appropriate sampling methods and interpretation of fire scar data, we propose that a thorough practical investigation is needed of the uncertainties and criticisms detailed here. In the following chapter, we do so.

CHAPTER 3

Comparing Methods of Reconstructing Fire History Using Fire Scars in a Southwestern Ponderosa Pine Forest

Abstract

Fire scars have been used extensively to understand the historical role of fire in ponderosa pine (*Pinus ponderosa* Dougl. ex Laws.) ecosystems. However, the sampling methods and interpretation of fire scar data have been criticized as statistically invalid, biased, and leading to exaggerated estimates of fire frequency. We tested alternative sampling schemes by comparing "targeted" sampling, random sampling, and grid-based sampling to a complete census of all 1,479 fire-scarred trees in a one square kilometer study site in northern Arizona. The effects of sample size and area sampled on fire frequency estimates were also tested. Given a sufficient sample size, we concluded that all tested sampling methods result in reliable estimates of the true fire frequency, with mean fire intervals very similar to the census. We also investigated the usefulness of three techniques developed to compensate for spatial uncertainties: 1) fire intervals from individual trees, 2) the interval between the tree origin and the first scar, and 3) filtering, a technique used to classify large fires. The seasonality distributions of the census and targeted sample were also compared. Quantification of the differences in sampling approaches cannot resolve all the limitations of fire scar methods, since scarred trees are inherently point-sources of data. But measurement of sampling uncertainty did reduce the scope of uncertainty in interpretation of fire regime statistics.

Introduction

Fire scars provide a valuable and precise way to reconstruct fire history, but uncertainties are inherent when using fire scars to estimate fire frequency and spatial patterning of fires for three main reasons: 1) fire scars are not necessarily recorded consistently on individual scarred trees so they are an incomplete point source of data (Dieterich & Swetnam 1984), 2) more recent fire events may have consumed remnant fire records, and 3) error is introduced by the process of sampling the population of fire scars (Fall 1998). These uncertainties frame a discussion over the correct application of mean fire intervals (MFI), how to interpret unscarred trees, and the sampling methods used in fire history research, including the possibility of correcting for any bias introduced in sampling. Few researchers have attempted to quantify the extent of uncertainty in fire scar studies, yet most acknowledge that the problem exists (Fall 1998). Baker and Ehle (2001) suggested "bracketing" MFIs with correction factors to compensate for the perceived uncertainties. They assessed 18 studies in ponderosa pine forests that reported MFI values of 5-21 years. When their bracketing methods were applied, Baker and Ehle (2001) calculated the MFI to be 22-308 years. In contrast, Fall (1998) argued that current methods are biased in the opposite direction, towards under-representing fire occurrence because many unscarred trees may have actually burned but failed to scar. It is likely that uncertainties in fire-scar formation and their preservation through time have resulted in both of these views being appropriate in different areas at different times.

Interpretation of fire interval distributions

To calculate fire frequency based on a single cross-section from a single tree would probably underestimate the true fire frequency of the whole stand because of unrecorded fire events and loss of fire scars from decay, breakage, and subsequent fire events. A composite (Dieterich 1980), or whole site, MFI typically results in a much shorter interval compared to that of an individual tree, or point fire interval. Composites are used to capture the complete record of fire in an area and because temporal and spatial heterogeneity of burning is impossible to capture from a single tree. While Baker and Ehle (2001) suggested that the composite MFI overestimates fire occurrence and is not area-explicit, the point MFI is likely to underestimate fire occurrence because of unrecorded fires. One approach to resolving this problem is filtering the composite, or including fire dates that occur on greater than a determined percentage of trees (Grissino-Mayer 1995). Ten percent and 25% filtered composites have been used to represent the fires that have a bigger influence on the study site, excluding small spot fires (Swetnam & Baisan 1996; Baker & Ehle 2001).

Another potential source of uncertainty is the period of time between tree germination and the first fire scar, called the origin-to-scar (OS) interval (Baker 1989). It was argued that for a ponderosa pine tree to survive, it must have experienced a fire-free interval of at least 50 years and therefore this fire-free interval must be included in the estimate of MFI (Baker & Ehle 2001). Alternatively, Stephens et al. (2003) asserted that it is impossible to know the true fire-free interval since many trees survive fires without scarring. Most trees are much older than 50 years when they scar for the first time and many are younger. Another argument in opposition to the OS interval when calculating

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Sampling

A standard approach to sampling fire scars is to systematically search an area for trees showing multiple scars and long records of fire to compile a complete inventory of fire years in that area (Arno & Sneck 1977; McBride 1983; Agee 1993; Swetnam & Baisan 1996; Swetnam & Baisan 2003). This method, called "targeting", has been criticized as undesirable and statistically invalid because it is not a random sample from a well-defined population (Johnson & Gutsell 1994). Because it is partially subjective and there is currently no statistical validation for targeting, it is said to lead to estimates of fire frequency where neither the accuracy nor the precision are known (Johnson & Gutsell 1994). Swetnam and Baisan (1996) argued that random sampling would not result in a complete or unbiased record of fire in frequent surface fire regimes unless very large numbers of trees were sampled. They supported the targeting method based on the argument that trees are a natural archive of historical data and not consistently reliable recorders of fire, so they should not be treated "as if they all belong to the same statistical population". However, Swetnam and Baisan (2003) recognize that "statistical descriptions and tests of fire interval distributions are inherently limited in objectivity, resolution and reliability", and should be complemented with other historical descriptions of fire occurrence and forest conditions.

Johnson and Gutsell (1994) assert that time-since-fire maps and fire rotation (the time required to burn over an area equal to the study area) are the only statistically valid method of reconstructing fire events and calculating fire frequency since they can account for spatial and temporal variability. Baker and Ehle (2001) showed the identity of the fire interval and the fire rotation. However, applying the fire rotation methods to fire intervals assumes that the fire-scarred trees constitute the entire area burned in a given year (Minnich et al. 2000). Instead, targeting is a method used in high frequency, low intensity surface fire regimes where time-since-fire maps cannot easily be constructed (Brown & Sieg 1996). The effects of other sampling strategies, such as grid-based (Arno et al. 1995; Heyerdahl 1997) and random sampling, are also unknown.

The critical discussion of fire scar data led us to design a study in which we sampled and mapped an entire population of ponderosa pine trees scarred before Euro-American settlement. In this study we ask the following questions:

1) Are targeting and other methods of sampling (random, grid-based) accurate?
2) How do sample size, area sampled and filtering affect MFI estimates?
3) Should OS intervals, “bracketed” intervals and point MFIs be included in fire history?
4) Previous fire ecology studies in this region concluded that surface fires were frequent and led to recommendations for thinning and burning for forest restoration. Are our results consistent with these interpretations?

Methods

Study site

This study was conducted on 100 ha in Northern Arizona University’s Centennial Forest approximately 20 km southwest of Flagstaff, Arizona; latitude 35°05’N, longitude 111°50’W. Figure 1 shows this study site in relation to other nearby fire history studies (Dieterich 1980; Davis 1987; Swetnam et al. 1990; Heinlein 1996; Fulé et al. 1997). This is a case study, but because of the comparable landscape features, stand conditions and land use history, these results may be applicable to much of the southwestern ponderosa pine forest type. Located north of the Mogollon Rim at 2,200 m elevation, this site was selected for its relatively low variation in vegetation and topography, and the lack of natural barriers to fire spread. Ponderosa pine is the dominant species with Gambel oak (*Quercus gambelii* Nutt.) in low abundance in the understory. Basal areas at this site were very similar to those across the extent of the northern Arizona ponderosa pine (Bell unpublished data; FIA 2004), ranging from zero to 45.9 m^2/ha, averaging 19.1 m^2/ha. Slopes range from 0 to 10%.

The average annual precipitation in Flagstaff is approximately 54 cm (1950-2004) with most of the precipitation falling in late winter and late summer (Western Regional Climate Center 2004). The soils are predominately sandy loams and loams (Abella 2005) with basalt cinders and limestone parent material (Miller et al. 1995).

Timber extraction began in the site and surrounding areas during railroad construction in the 1880's, and at about the same time overgrazing led to widespread exclusion of fire (Dieterich 1980; Fulé et al. 1997). Sporadic logging activities and fire suppression continued throughout the 20th century. The most recent activity in the site was timber harvesting and burning piles of logging slash in the 1980's and 1990's.

Field methods

The boundaries of the study area were marked. To test the effect of different sampling methods, the targeted sample was collected first. We systematically walked through the site examining each fire-scarred tree we encountered for number of visible scars and soundness. Forty trees with multiple scars and long records of fire distributed spatially throughout the sampling unit were selected to comprise the targeted sample. These specimens were identified for the targeted sample in the field and preferentially chosen over other fire-scarred trees. After completing the targeted sample collection, a 5 by 5 cell grid overlaid on the 100 ha study site was flagged to delineate boundaries for organized collection and analysis of the census. The grid consisted of 25 4-ha cells. The entire population of trees with visible fire-scar evidence comprised the census. Cross-sections from all remaining fire-scarred trees were collected (those not collected in the targeted sample) in the census using the same procedures as the targeted sample. Several specimens were too deteriorated to collect, so the catface was documented and mapped.

We recognized that buried scars may have existed on the site, but we did not deliberately sample for them. The stands within the site were primarily second-growth with old cut stumps remaining. All the stumps were examined for evidence of fire-scarring including buried scars, but trees with no visible evidence of fire-scarring were not sampled. The likelihood of missing a buried scar was low since a fire-scarred tree would probably not be able to heal over considering the high frequency of fire. Judging from the high number of fire dates encountered on the site, any buried scars that may have occurred would probably not yield any new fire dates. However, some point locations of established fire dates may have been excluded because we did not sample for buried scars.

Scarred trees included living trees, snags, logs, and stumps. Full cross-sections from stumps and logs, and partial cross-sections from live and standing dead trees were collected, a standard technique that can be done without killing live trees (Arno & Sneck 1977; Heyerdahl & McKay 2001). A 5-cm thick cross-section was extracted from the region of the tree that appeared to have the most complete fire record using a chainsaw. In cases where multiple sides or heights on the catface appeared to have recorded different fires, multiple cross-sections from that tree were extracted. In a preliminary assessment of the study site, we noticed that all the older (>100 yrs) fire-scarred trees had been harvested, but fire scars were still evident on many stumps of these trees. Thus, no living old growth trees were sampled. The only living trees with fire scars were young trees clustered around burned slash piles and appeared to be scarred within the last 25 years. Since we were primarily interested in the fire regime before Euro-American settlement, we only collected samples from about 70% of these trees to verify that the fire date was outside our time frame of analysis. However all these trees were measured and mapped in the field.

Each fire-scarred tree was documented by recording the diameter at stump height, the number of cross-sections taken, the number of pieces per cross-section, the number of visible scars on the specimen, the aspect of the catfaces, the height of the cross-sections on the bole, and the UTM coordinates from a Garmin® global positioning system (GPS), accurate to within 15 m. The condition of the tree was also recorded: living, snag, stump or log.

Laboratory methods

All specimens were mounted on plywood and surfaced using an electric belt sander with increasingly fine sandpaper until the cells were clearly visible. Initially a ring-width chronology from Gus Pearson, Arizona (Graybill 1987) was used to crossdate the targeted specimens. The targeted specimens supplemented with 20 tree cores were then used to build a master ring-width chronology specific to the study site. All remaining specimens were crossdated with the site master ring-width chronology, according to standard procedures (Stokes & Smiley 1968). All specimens were visually crossdated when possible. COFECHA software (Holmes 1983) was used to assist with dating difficult specimens. The rings on the difficult specimens were measured with an Acu-Rite glass scale and encoder with 2 μm precision and Measure J2X software. The COFECHA outputs were checked carefully against the cross-sections to verify the dating. Many specimens remained undated even after COFECHA was employed. If a specimen had an injury that could not be unquestionably identified as a fire scar, we did not include the date of that injury. If a fire scar could not be dated to an exact year, we did not include the estimated year. Specimens that contained no fire scars, or had fire scars where the exact year could not be determined, were not crossdated.

The season of fire occurrence was identified using the following categories based on the relative position of the fire scar within the annual ring: early earlywood (EE), middle earlywood (ME), late earlywood (LE), latewood (L), dormant (D), and undetermined (U) (Baisan & Swetnam 1990). Radial growth generally occurs between May and September in northern Arizona ponderosa pine (Pearson 1924; Gaylord 2004), representing the range of fire-scar seasonality categories from EE to L. Dormant season scars were dated to the year following the scar, indicating an early season fire before radial growth commenced, because fall fires are rare in this region (Baisan & Swetnam 1990). All the targeted specimens and 40% of the entire collection was checked by other dendrochronologists to independently verify the dates of the wood specimen, the fire dates and seasons of the fire events. Any unresolved discrepancies were considered undateable. We also identified the years in which each tree with dateable fire scars was recording. A tree is considered “recording” after the initial injury when it is susceptible to be rescarred by subsequent fires, excluding any years in which decay or other fires may have destroyed a fire scar (Grissino-Mayer 1995).

Data analysis

The data were analyzed in groups based on targeting, random selection or location. Each individual fire-scarred tree will be called a specimen (even if more than one cross-section was collected from that tree) and each group of specimens analyzed will be a sample. FHX2 software (Grissino-Mayer 1995) was used to analyze combinations of fire history data from specimens. Since FHX2 analysis is limited to 255 specimens, the composite fire chronology for each sample that exceeded this limitation was run in FHX2.

The 200 year period from 1682 to1881 was used in all analyses for consistency unless otherwise stated. The minimum number of trees recording in this period was 39 trees in 1881. This is a sufficient number of trees with which to conduct this analysis (Falk and Swetnam 2003). The year 1881 is the last year of analysis because it was the last fire year in the study area before grazing and fire suppression interrupted the natural fire regime. Prior to the late 1600’s, the results would be confounded by the lack of fire scar data. The year 1682 was chosen to make an even 200 year period of analysis. Although it is somewhat arbitrary, 1682 is a reasonable date to begin the analysis.

For each sample, the MFI for all scars (no filter) and for 10%- and 25%-scarred filters was computed in FHX2 (Dieterich 1980; Swetnam & Baisan 1996). Filters only include those fire years that are recorded by the determined minimum percentage of recording trees, and can be used to infer fire size; no filter includes fires of all sizes whereas a 25% filter only includes the larger fires. There are many relevant descriptive statistics for fire interval distributions, but the MFI is reported for all the samples as a basis for comparison (Baker & Ehle 2001). These samples are subsets of the census data, so the same specimens may be included in multiple samples. Because of lack of independence and spatial autocorrelation, we are not testing for statistically significant differences of the means. Instead, graphical and tabular representations of the means are used to show the effect of sampling methods. Ranges and standard deviations (SD) of fire intervals are also discussed.

A geographic information system (GIS) was used to map the locations of the samples by the UTM coordinates recorded in the field to assist with the spatial interpretations. The original UTM coordinates were used except where the trees falsely appeared to be out of the study area due to the GPS error. UTM coordinates of these trees were moved to the site boundary nearest to the original location.

Sampling method

The analyses outlined above were applied to the census and the following samples.

1) *Census.* The census provided a baseline to test the effect of all other sampling methods. The census fire history was assembled using *all* scars and represented the most complete possible fire-scar-based fire history of the site.
2) *Targeted sample.* The targeted sample was analogous to other fire history studies in the region and was conducted to test the effect of this standard method of sampling in

ponderosa pine forests. The targeted sample consisted of 40 specimens with multiple scars and long records of fire.

3) *Sample size (random samples).* Random samples were used to test the effect of increasing sample size. Eight sample sizes were tested: 10, 20, 30, 40, 50, 60, 70 and 80 specimens. Within each random sample, all crossdated specimens with fires were randomly sampled without replacement. Sampling with replacement occurred at the scale of the separate samples, but not within a single sample. For each sample size, the MFIs for ten random samples were averaged. These samples were also used to compare random sampling against the census data.
4) *Area sampled.* The study area was spatially subdivided into 25 grid cells of equal size. This analysis considered 6 areas of different sizes to test the effect of increasing the size of the study area on MFI. The areas tested were 4 ha (1 cell), 8 ha (2 cells), 16 ha (4 cells), 32 ha (8 cells), 64 ha (16 cells) and 100 ha (25 cells). All dated fire scars were included in this analysis. The 100-ha sample is equivalent to the census. The MFI for each area was calculated as an average of the MFIs for each combination of that size. That is, there are four combinations of 16 adjacent cells arranged in a square. Those four combinations were averaged to get the 16-cell MFI; however the MFI for each of the four combinations is shown graphically.
5) *Grid-based samples.* This analysis explored two alternative grid-based sampling approaches (Arno et al. 1995), and can be thought of as systematic targeting (Heyerdahl 1997; Fulé et al. 1997). Grid 1 had a spacing of 141 m arranged diagonally over the study area yielding 41 plots (see Figure 2a). The spacing of these plots was determined by the original 25 cell grid, locating one plot in the middle of

each cell and one plot at the corner of 4 adjacent cells. Each sample included 1-4 specimens with the highest number of observed scars in the field from within three search radii, 20 m, 40 m and 60 m. The samples consisted of different numbers of specimens per plot to approximately mimic the size of the targeted sample (n=40). There were two samples assessed within the 40 m radius, sample (a) with one specimen per plot, and sample (b) with two specimens per plot. Grid 2 is a checkerboard with 100-1 ha blocks (see Figure 2b). MFIs were calculated using the specimen with the highest number of observed scars in the field from each of the 50 white cells, then the 50 black cells. The number of observed scars in the field was recorded at the time of specimen collection. These samples were constructed using the field data in a GIS.

Origin-to-first scar intervals and point MFIs

The analyses of the origin-to-first scar (OS) interval and the individual, or point, MFI addressed the interpretation of fire intervals rather than sampling issues. The point MFIs were calculated for each specimen in the census then plotted in comparison to the census composites with the three levels of filtering. The OS interval distribution of all 154 specimens with piths was analyzed and the proportion of OS intervals less than 50 years reported (Baker & Ehle 2001). The OS interval was also determined for the 47 specimens having piths within the 200 year period of analysis and OS intervals less than the point MFI. These 47 specimens were mapped and the dates of the OS intervals were compared to the fire dates of their nearest recording neighbors to determine if the OS interval was truly fire-free, based on adjacent trees.

Season and direction of scarring

Seasonal distribution of fires from the census and targeted sample data was plotted and a chi-square goodness of fit test was performed to determine if these distributions differed.

Gutsell and Johnson (1996) stated that fire scars only form on the leeward side of a tree because vortices of hot gasses accumulate there causing local cambial mortality. To test this hypothesis, directions of all catfaces were plotted in a circular histogram and the Rayleigh test (Zar 1984) was conducted to test for an angular concentration of catfaces.

Results

Collection summary

A total of 1,479 fire-scarred trees were documented and mapped (Figure 3), of which 1,246 (84%) were collected. Of the 233 (16%) specimens that were not collected, 189 (13%) had a high level of decay preventing us from collecting a viable specimen. The remaining 44 (3%) were not collected because they were young (<100 yrs) living trees with one scar clustered with other living recently-scarred trees that we sampled. The following percentages were computed based on the 1246 collected specimens. We were able to crossdate 777 (62%) specimens and identify their fire dates, 67 (5%) of which were from live trees. Of the 459 (37%) collected but not crossdated, 303 (24%) contained no fire scars that could be dated to an exact year. The remaining 156 (13%) had clearly visible fire scars, but we failed to crossdate them because of decay, and short or complacent ring series. Ten (<1%) of the collected specimens are missing.

During the period of analysis (1682-1881), the percentage of recording trees varied between 16% and nearly 100% of the total sample depth (Figure 4). The total sample depth peaked between 1725 and 1750, whereas the number of recording trees were greatest between 1800 and 1820. Both sample depth and recording trees declined sharply approaching the end of the period of analysis. The fires that scarred more than 25% of the recording trees were clustered together in time. Primarily large fires and few small fires occurred between 1784 and 1813, with longer fire intervals occurring between 1784-1788 and 1788-1794. Conversely, fires scarring fewer trees occurred almost annually from 1831 to 1850, but few large fires were recorded during this period. There was also a notable lack of fires recorded between 1873 and 1881.

Sampling method

Composite MFIs of all the sampling methods were within 2.18 years of each other and within 2.75 years of the census (Table 1).

Census and targeted sample. The census with no filter represented the maximum possible number of fire dates, so the census MFI was the shortest computed in this study. The targeted sample was slightly longer than the census with no filter and a 10% filter, but slightly shorter than the census with a 25% filter. The targeted sample captured the one specimen with the most scars in the whole study, and included many more highly-scarred specimens than the other samples. The SD of the census with no filter was 0.7 years with fire intervals ranging from 1 to 4 years. The targeted sample SD was 1.1 years with fire intervals from 1 to 6 years.

Sample size (random samples) and area sampled. Mean MFI decreased towards an asymptote as the sample size increased for no filter and a 10% filter, while the mean MFI filtered at 25% remained fairly constant (Figure 5a). The variability within each set of 10 runs of each unique combination of sample size and filter level increased as the filter level increased. These trends were similar for area sampled (Figure 5b). The 25% filtered means of MFI were very similar between small and large areas sampled. The MFIs decreased as area sampled increased for the less restrictive filters. Within the different samples of the same-sized area, variability was highest in the 25% filter MFIs and lower for the less restrictive filters.

As the sample size increased, the variability of fire intervals within a single sample decreased. SD of fire intervals in the random data sets of at least 40 specimens with no filter ranged from 1.1 to 1.87 years. The maximum fire intervals in the same data sets ranged from 7 to 12 years. The minimum fire interval for these data sets was one year. Variability of SD and ranges of fire intervals increased with more restrictive filters.

Grid-based samples. In the samples based on Grid 1, the longest MFIs resulted from the 20 m and 40 m search radii where the sample size was about 30. The other two samples, one with a larger search radii and both with bigger sample sizes, resulted in shorter MFIs. The MFIs from the black and white cells in Grid 2 were very similar (Table 1).

Point and origin-to-first scar intervals

The census composite MFIs with filters varied between 1.66 and 6 years. The variability of point MFIs was much greater, with a mean of 12 years and range from 2 to

133 years (Figure 6). The targeted point MFI was 1.2 times shorter than the point MFI from the census data.

The average OS interval was 101.5 years. The distribution of OS intervals increased until the 61-80 interval class, then declined (Figure 7). There were 36% of all the specimens with pith that scarred before age 70; 19.5% of these specimens scarred before age 50. The distance from a tree with an OS interval to its nearest neighbor scarred within the tree's OS interval ranged from 1 to 72 m, averaging 25 m. Of the fire-scarred neighbors, 87% were the closest recording neighbor to the tree in question. Many trees that scarred later in their lives remained unscarred during the most extensive fire years, including 1737 and 1794 (Figure 8).

Season and direction of scarring

Most fires burned in the early part of the growing season (Figure 9). Although the patterns of seasonality were similar between the targeted sample and the census, there was a statistically significant difference (chi-square goodness of fit test, $p<0.05$) between these distributions.

Catfaces formed in all directions; however the distribution was unimodal and weighted towards the North and East (Figure 10). The Rayleigh test confirmed that there was an angular concentration ($p<0.001$).

Discussion

Are targeting and other methods of sampling (random, grid-based) accurate?

We needed to establish criteria in the absence of statistical testing in order to assess how well the sample MFIs represented the census MFI. We chose three different levels at which to determine similarity. The most restrictive criterion was a 95% confidence interval (C.I.) of the census MFI. Since the range of fire intervals was only 1 to 4 years in the census, the 95% C.I. is very small, 0.13 years, so the threshold for similarity is 1.79 years. None of the samples fell within this C.I., and one could conclude that none of the samples reliably represent the true fire history. A threshold at the other extreme would include MFIs less than 25 years, the maximum interval considered to represent a frequent fire regime (Pyne et al. 1996). This assessment would lead to the conclusion that all methods of sampling, including the point estimate, are adequate representations of the fire frequency. An intermediate approach to the question of reliability is to assume that all MFIs within one year of the census MFI are similar enough to represent the true fire frequency. One year is a reasonable threshold for ecological and management considerations as well. The threshold for samples is then 2.66 years. Samples with similar MFIs to the census include the targeted sample, random samples of at least 50 specimens, areas of at least 16 ha, and grid-based samples with at least 35 specimens. We will use the intermediate criterion to conclude that all sampling methods tested in this study, given a sufficient sample size, will result in a reliable estimate of the true fire frequency.

How do sample size, area sampled and filtering affect MFI estimates?

We have shown through our random samples of increasing size, and others have shown with fire scar accumulation curves (Falk & Swetnam 2002; Stephens et al. 2003) that there is a mathematical threshold at which little new information is gained with additional specimens. This threshold was approximately 50 randomly sampled specimens in this study. However, a similar MFI resulted from a smaller sample of targeted and grid-based specimens because we selected the specimens with the most fire dates in these samples. Swetnam and Baisan (1996) were correct that a larger sample size is needed to accumulate the same fire history data in a frequent surface fire regime when using random sampling than when using targeted sampling.

Sample size and area sampled are linked. The sample sizes in the 4- and 8-ha areas fell below the 50 specimen threshold, so the longer MFIs in these samples, 3.49 and 2.79 years, respectively, may be a product of the small sample size, not necessarily a factor of area sampled. The same relationship was present in the 20 m and 40 m samples, n = 29 and 31, respectively, based on Grid 1. Even though there appeared to be an inverse relationship between search radius and MFI, these instances of longer MFIs, 3.52 and 3.13 years, respectively, seem to be a function of sample size, not necessarily search radius.

The MFIs with a 25% filter were remarkably consistent as sample size or area sampled increased. This means that the large fires were captured with fewer specimens in a smaller area, but smaller fires continued to be discovered with more samples over a larger area. Some researchers were concerned that fire scar methods were weighted towards small fires (Minnich et al. 2000; Baker & Ehle 2001), but filtering proved to be an effective technique, finding stability across spatial scales at the 25% level. Filtering at other levels accounts for greater spatial variability. At the fine scale, fires burned every 1 to 2 years. A slightly coarser scale (10% filter) showed that widespread fires burned about every 3 years, and a very coarse scale (25% filter) showed that large fires averaged every 6 years. One level of filtering can be useful for some applications, but filtering is most effective at detecting spatial differences in fires when more than one level is applied. Filtering MFIs is just one way to account for variability.

Ranges and standard deviations of MFIs are also important to consider in terms of the spatial patterns of fire and the ecological significance of variability that occurs within a site. The range (1 to 12 years) and SD (1.1 to 1.87 years) of fire intervals in random data sets of at least 40 specimens indicates that a single point on the landscape probably burns at a different frequency than the composite MFI (2.28 to 2.82 years). Ecologically, this mosaic of fire frequencies allows for shifting patterns of understory vegetation and tree regeneration.

Should OS intervals, "bracketed" intervals, and point MFIs be included in fire history?

Two arguments were made in the literature that attempted to explain why most trees are older than 50 when they scar for the first time: 1) fires killed the young trees instead of scarring them, leaving no lasting evidence of the fire's presence, and 2) fire was absent around the seedling during its establishment (Baker 1989; Gutsell & Johnson 1996; Keeley & Stephenson 2000; Baker & Ehle 2001). While these are both logical explanations, a third possible conclusion missing from this list is that fire was present, but failed to leave a scar. The maps of widespread fire years (Figure 8) show that it is highly likely that most trees experienced more than one fire without scarring, especially since some scarred trees are only 1 m away from a tree during its unscarred OS interval. The distribution of OS intervals in this study (Figure 7) was similar to Baker and Ehle's (2001)

Figure 3 for ponderosa pine, except all measures of central tendency were approximately 20 years longer in this study.

It has been noted that in frequent fire regimes where post-fire regeneration does not typically occur in even-aged cohorts, the pith of a tree is not a surrogate for fire occurrence, so assuming that the OS interval is the same as a fire interval is incorrect (Baker 1989). The same argument can be made for the first scar. Thus far, it has been assumed that hot, passing fires are the only cause of initial scarring, but this discussion would be lacking without investigating other possible causes of initial scarring. In the Southwest, where lightning strike densities are some of the highest in the country, many trees become susceptible to fire scarring after a lightning strike wound. Deep fuelbeds with large branches that accumulate and ignite and smolder at the base of older trees are another likely cause of initial scarring. Other agents of scarring include humans, other animals, physical processes and disease (Agee 1993). Like the pith, the first scar may not be a good indicator of a typical fire, or fire at all, leading to greater uncertainty about the true meaning of the OS interval. Further uncertainty and overestimation of the OS interval is likely when considering the possibility of the first scar being burned away, broken or decayed over time.

The point MFI may be useful metric of the maximum fire interval at the scale of individual trees (Baker & Ehle 2001). Even though individual trees did not necessarily scar with every fire, as shown by Dieterich and Swetnam (1984) comparing both sides of the same catface, they still recorded fires on average every 12 years in this study. This is longer than all the composite MFIs regardless of sampling method, yet still indicative of a frequent fire regime (<25 years). While the OS interval and other bracketing techniques are derived somewhat arbitrarily, the point MFI is an exact interval between two recorded fires and may be a useful measure for some purposes. Unlike a composite of fire years, the point MFI is strongly affected by the quality (number of fires) per specimen. Targeted sampling yields higher quality samples which may overestimate the point MFI and would not be appropriate for quantifying the maximum fire interval. In this study, the targeted point MFI was overestimated by a factor of 1.2 (<2 years). Although this was a small difference, if the point MFI is used to represent the maximum fire interval in other studies, a random sample of fire-scarred remnants should be used to quantify this interval. We caution against applying this factor as a bracketing factor to all fire scar studies.

Bracketing includes such useful techniques as filtering and point fire intervals which we have already discussed. It also includes the OS interval, an erroneous estimate of fire intervals, such as stated by Baker and Ehle (2001) "Targeting likely decreases the mean composite FI by a factor of two to three times," which we have shown to be untrue. Baker and Ehle's (2001) bracketed estimate, 22-308 years, implies that ponderosa pine forests can persist over generations with MFIs that characterize stand-replacing fire regimes. We have seen in recent years that even a fire interval of ~100 years in ponderosa pine can lead to type conversion (Friederici 2003; Savage & Mast in press). It is important to recognize that occasional torching of trees led to local patches of mortality, but the purpose of an estimated MFI is to describe the dominant trends in fire frequency. Considering many frequency estimates from filtered and unfiltered composites, and individual trees, gives enough evidence as to the nature of the fire regime to negate the need for any further bracketing.

How does this study relate to other fire history studies in the region and the management of these forests?

The previously published fire history studies from the region of our study site also reported high fire frequency before Euro-American settlement. Dieterich (1980) reported MFIs of 2.4 years at Chimney Springs and 1.8 years Limestone Flats; sites on the San Francisco Peaks had an MFI of 5.2 years (Heinlein 1996); Fulé et al. (1997) reported a 3.7 year MFI for Camp Navajo (Figure 1). These studies also reported a similar end to the frequent fire regime, from 1876 at Chimney Springs (Dieterich 1980) to 1883 at Camp Navajo (Fulé et al. 1997).

The pattern of large synchronous fires, recorded on this site between 1784 and 1813, has been noted in different sites around the southwestern United States and Mexico, and other regions of the world (Stephens et al. 2003). This trend occurred in the mid-19th century in Colorado, USA and Patagonia, Argentina (Veblen & Kitzberger 2002), and in the early 19th century in Mexico (Stephens et al. 2003). Attributed to shifting climatic patterns, other indicators of this gap in the fire regime are decreasing fire frequencies, and a shift in the season of burning (Swetnam & Baisan 2003). Dieterich (1980) reported a period of very frequent fires in his nearby Chimney Springs study between 1850 and 1865, similar to the pattern found in this study from 1831 to 1850. It is unclear if the varied frequency of large fires over time in this study is a function of multi-decadal climate variability or other factors.

Through our findings, showing that targeted, grid-based, and even random methods are robust and unbiased at this study site, we are confident in the results of previous studies and their recommendations for management. Since this is a case study, our results may not be entirely representative of other studies, especially because we tested sampling methods within a single site. Other patterns are likely to emerge if these methods were tested across landscapes (Falk 2004; Grissino-Mayer et al. 2004). However, even given perfect knowledge of the historic fire regime, it is unlikely that managers would implement equally frequent, widespread fires because of other constraints of budgets, risk of escaped fires and smoke impacts on nearby communities.

In recent years, wildfires in the Southwest have dramatically increased in size and severity, resulting in undesirable ecological effects (Agee 1993; Kolb et al. 1994; Swetnam et al. 1999) and increased costs of suppression and rehabilitation (National Fire Plan 2004; GAO 2004). Recent legislation has encouraged thinning to reduce the hazards of the increased fuel loads as one way to mitigate the severity of these fires (Healthy Forest Restoration Act 2003). As the cost of wildfires continues to increase, policy makers are eager for information to help guide management policy. Since management recommendations are based partially on historic forest conditions and fire frequencies, it is important to have information collected in such a way that accurately represents the true historic conditions.

One area for managers and researchers to explore is the pattern of unburned patches within a fire boundary. Although large strides are still necessary to attain the means of reintroducing fire in some areas, replicating the spatial patterns of burning may be a key to promoting natural variation within the ponderosa pine ecosystem. Modern calibration of fire regimes (Farris et al. 2003; Fulé et al. 2003), evolutionary ecology (Moore et al. 1999) and historical documentation (Cooper 1960) support the understanding of the changes in the fire regime and forest structure that occurred in the last century. It is this understanding of the historical context that will lead to its judicious application.

Season and direction of scarring

There was a statistically significant difference of the seasonal distributions of fire scars between the census and targeted sample, but there would be no difference in the application of either data set. Both lead to the conclusion that early season fires dominated the fire regime. The statistical difference does, however, highlight the quality of the targeted specimens since the season of fire scars was identified 5.6% more times in the targeted sample than in the census.

The hypothesis that catfaces *only* form on the downwind side is not substantiated by our data since scars formed in all directions. The angular concentration of catfaces corresponds to the downwind side of trees with respect to the prevailing winds out of the southwest during fire season, as Gutsell and Johnson (1996) explained. However, the formation of catfaces in other directions leads to the conclusion that while vortices of hot gasses on the lee side of trees are likely causes of many catfaces, other environmental and causative factors must be considered in future research.

Conclusion

We acknowledge that while some of the research questions can be answered by our data, others are issues of interpretation and are inherently unknowable. The uncertainty and related criticism that targeting and other sampling methods have an unknown effect on estimates of fire frequency have been resolved at this study site. We think that all methods of sampling outlined in this study are reliable given a sufficient sample size, and that any 50 specimens would yield a fair estimate of the fire frequency. Targeting is preferred because it requires the smallest sample size, yields the same results as other sampling methods and is likely to result in longer reliable records of fire. There is no perfect interpretation of fire intervals, but a useful portrayal of the fire regime can be gleaned by combining a number of the results reported in this study. The minimum MFI in this 100 ha study site is 1.66 years (census MFI), and the maximum estimate is 12 years (point MFI). Relatively widespread fires occurred every 2.83 years (census MFI with 10% filter) on average, and the largest fires had an average frequency of 6 years (census MFI with 25% filter).

The other uncertainties, highlighting the imperfections of the fire scar record, will never entirely be resolved. An issue, central to Baker and Ehle’s (2001) argument although not stated in this way, is simply the definition of a fire. Is a fire the outer perimeter of a burn, including both burned and unburned areas (Swetnam & Baisan 1996)? Or is a fire only the surface area actually burned above some threshold of intensity? Baker and Ehle (2001) insisted on the latter definition by claiming the identity between fire interval and fire rotation and by arguing that the period of tree-origin-to-first-scar must be a fire-free interval. The fundamental problem is the interpretation of fire occurrence between the fire-scarred trees. All researchers agreed that fire scars are point data, that fires include a range of burning intensities and unburned areas within their perimeters, and that the absence of scarring is not necessarily equated with absence of fire. Swetnam and Baisan (1996) suggested that when 25% of more of the sample trees dispersed over a landscape with no natural fuelbreaks were scarred in a given year, it could be assumed that one or more fires burned over much of the study site. Minnich et al. (2000) and Baker and Ehle (2001) essentially adopted the opposite perspective, suggesting that burning could be clearly associated only with the scarred tree locations. By assuming that previously unscarred trees would have been killed by a fire, Baker and Ehle (2001) interpreted unscarred trees in the intervening spaces between scarred tree locations as evidence of fire absence, contributing to their long (22-308 year) bracketing of ponderosa pine fire intervals.

The census of fire-scarred trees in this study provides a fine-grained approach to addressing interpretation of unscarred trees. We have shown mapped evidence that many trees remained unscarred through many fire events before incurring their first scar. There will always be unscarred trees within a fire boundary and areas between scarred trees with no remaining evidence of fire. We propose that the definition of a fire remains as the area within the perimeter of a fire boundary, although it is understood that fires burn in a mosaic of intensity and severity within their perimeters. Compensating, or bracketing, for this type of uncertainty using unreliable factors is unnecessary and confuses the application of this data.

Some researchers rely solely on mathematical models to avoid subjectivity, but Agee (1993) warned that “mathematical models, which usually have rigid assumptions about the nature of the system, can be just another form of storytelling if they are not carefully interpreted”. The definition of a MFI is widely understood and infers some variability in microsites that may have burned with varying frequencies due to subtle differences in topography or vegetation (Romme 1980; Dieterich 1980).

When recommending and implementing prescribed burn plans, scientists and managers should be aware of the uncertainties inherent in fire scar data and base their decisions on more than an estimated MFI. Ecological, historical and photographic records support evidence of a predominantly frequent fire regime in the Southwest. Instead of quantitatively compensating for uncertainties, we should simply take care when interpreting MFIs and be thorough in our investigations of reference conditions.

Table 1. Mean fire intervals (years) for all sampling methods at Centennial Forest, northern Arizona (1682-1881). The filter categories include all fire years in which scars were present (all), fire years in which at least 10% of the recording specimens scarred (10%), and fire years in which at least 25% of the recording specimens scarred (25%). *see Figure 2 for grid layout maps.

Filter	Census	Targeted
All	1.66	2.23
10%	2.83	3.00
25%	6.00	5.43

	Random Sample Size							
Filter	10	20	30	40	50	60	70	80
All	4.41	3.71	3.05	2.82	2.43	2.58	2.46	2.28
10%	4.41	3.82	3.21	3.05	2.98	3.11	3.16	3.14
25%	4.94	5.87	6.00	6.25	6.84	5.95	6.28	5.66

	Sampled Area				
Filter	1 cell	2 cells	4 cells	9 cells	16 cells
All	3.49	2.79	2.41	2.07	1.85
10%	3.66	3.24	3.08	2.98	2.89
25%	5.52	5.44	5.51	5.67	5.86

GRIDS*	Search Radius (m)				Checkerboard	
Filter	20	40(a)	40(b)	60	black	white
All	3.52	3.13	2.54	2.28	2.28	2.54
10%	3.52	3.4	2.91	2.71	2.87	2.96
25%	4.87	5.24	6	6.39	4.71	4.95
n	29	31	67	39	44	35
specimens per plot	all (1-4)	1	2	1	1	1

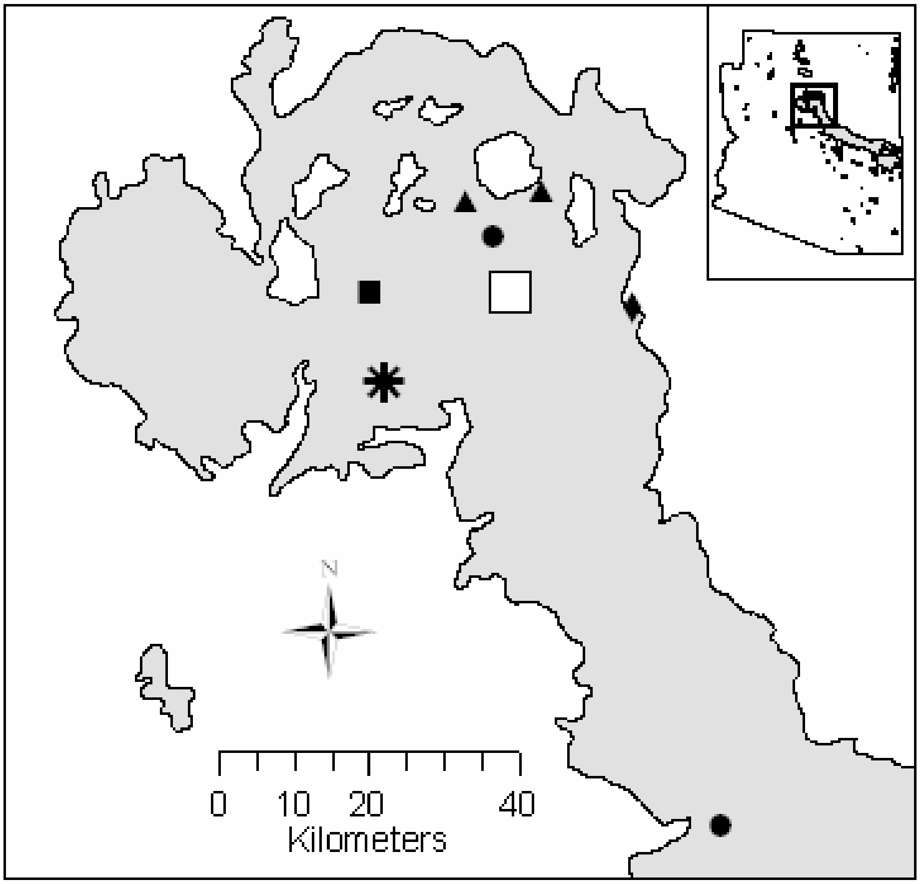


Figure 1. This study site (✱), Flagstaff (□) and other fire history study sites including Dieterich 1980 (●), Davis 1987 and Swetnam *et al.* 1990 (♦), Heinlein 1996 (▲) and Fulé *et al.* 1997 (■) are shown in the ponderosa pine forest type (shaded area) in northern Arizona.

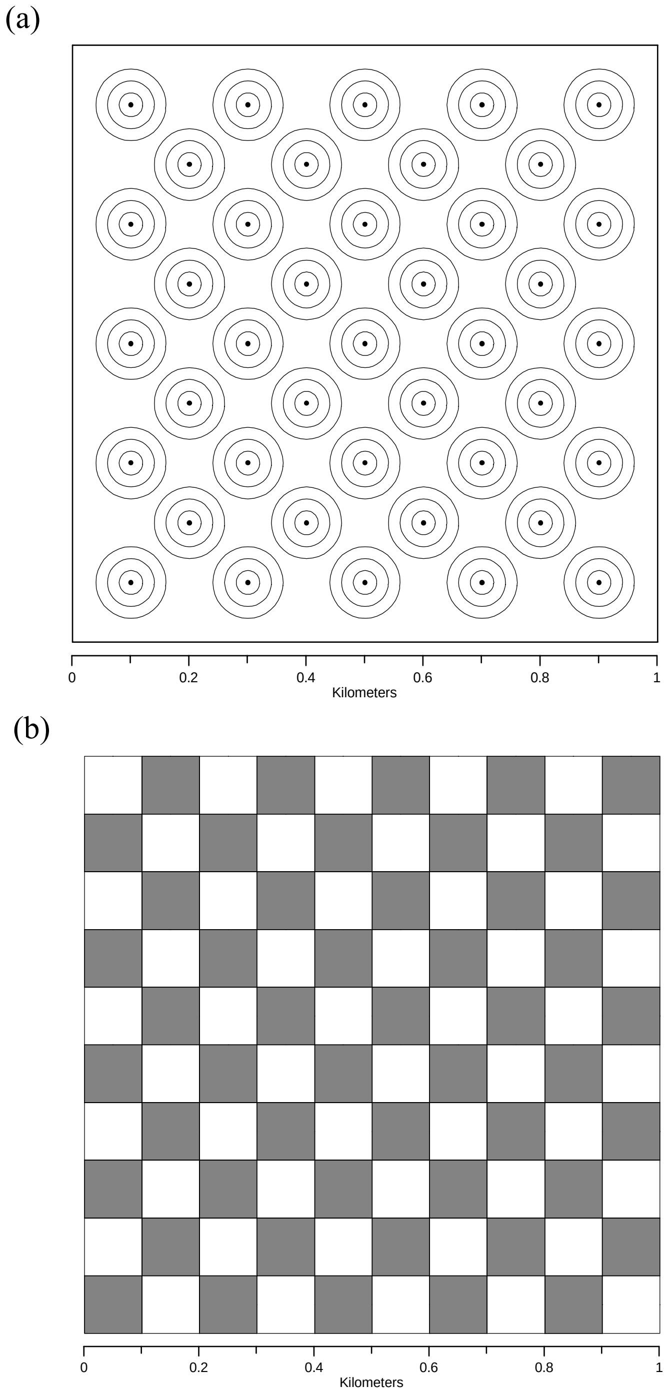


Figure 2. Maps of sampling grids used to test the effect of grid-based methods of sampling. (a) Sampling grid 1 had 41 plots spaced at 141 m. Concentric circles are 20, 40 and 60 m search radii. Mean fire interval (MFI) was compared between samples taken from the three search radii. (b) Sampling grid 2 was a checkerboard with 100-1 ha cells. MFI of the black cells was compared to MFI of the white cells using the specimen in each cell with the most fire scars.

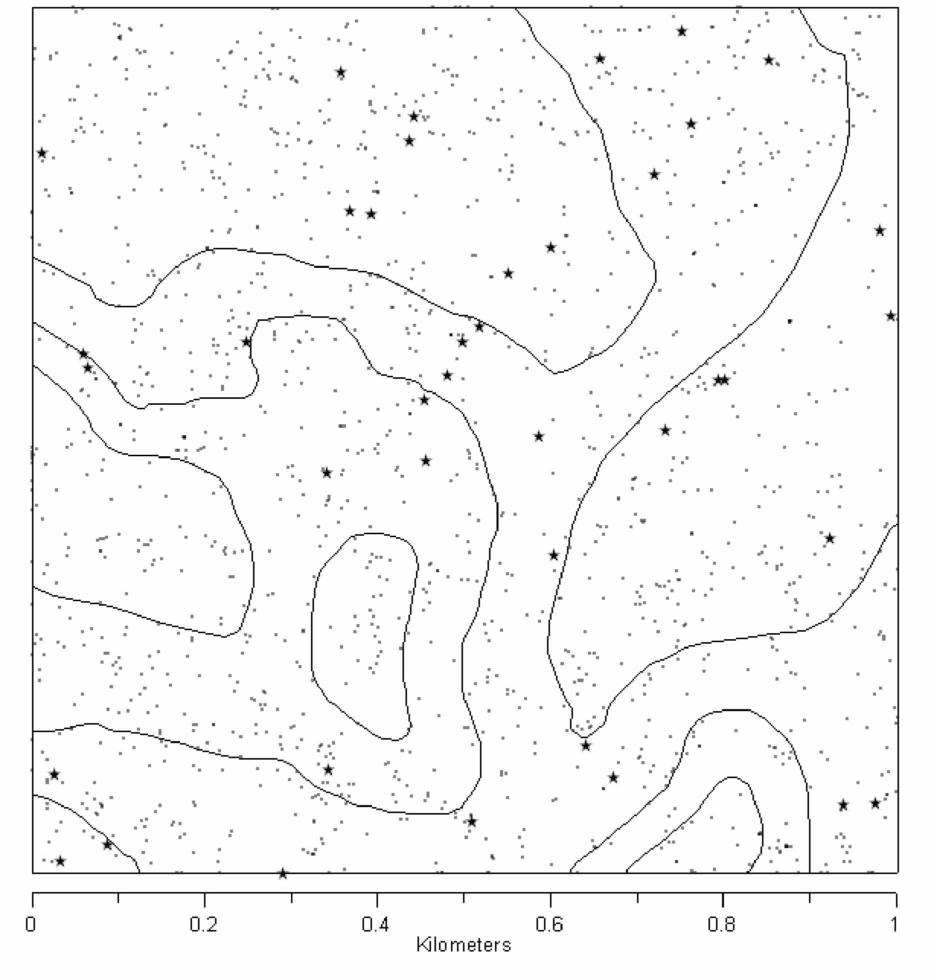


Figure 3. Study area map showing the 1,479 census (points) and 40 targeted sample (stars) specimen locations. Lines are 5 m contours.

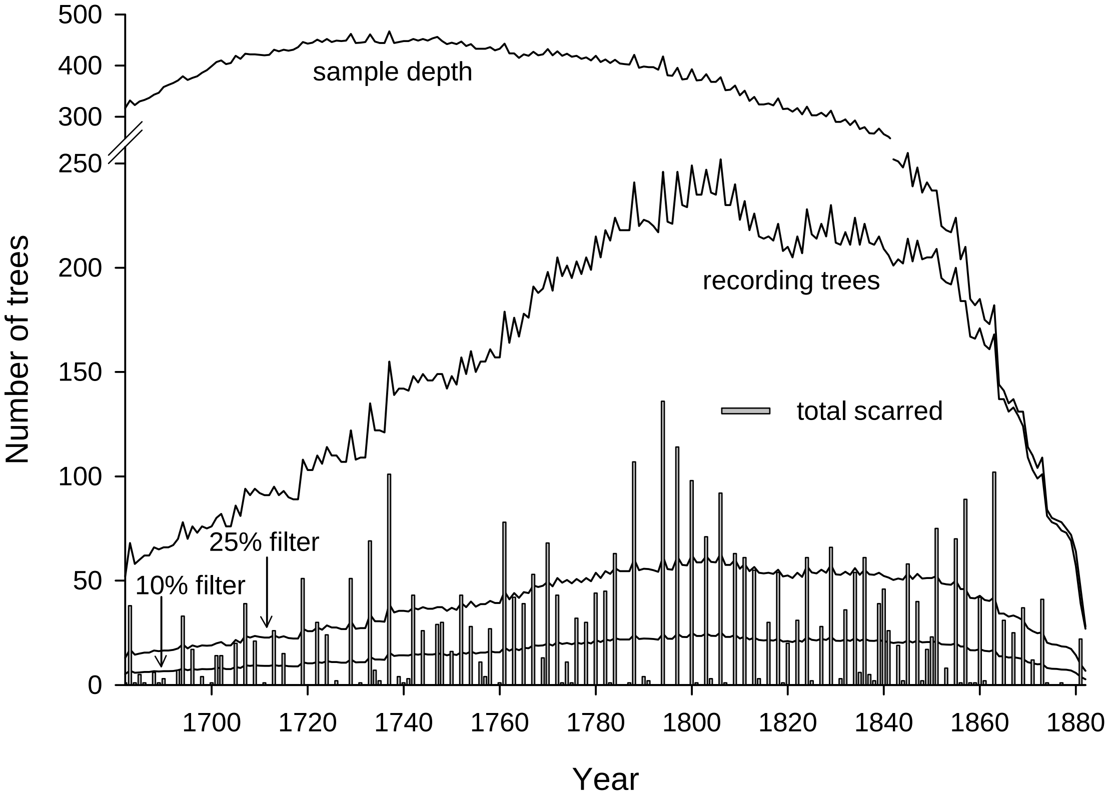
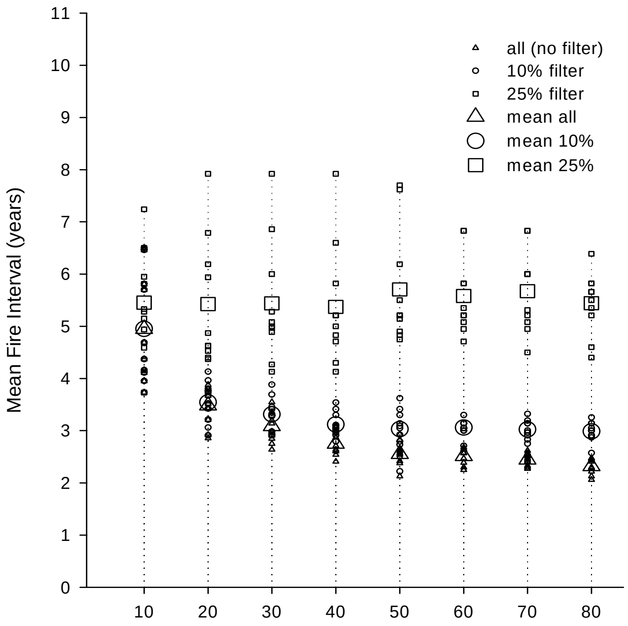
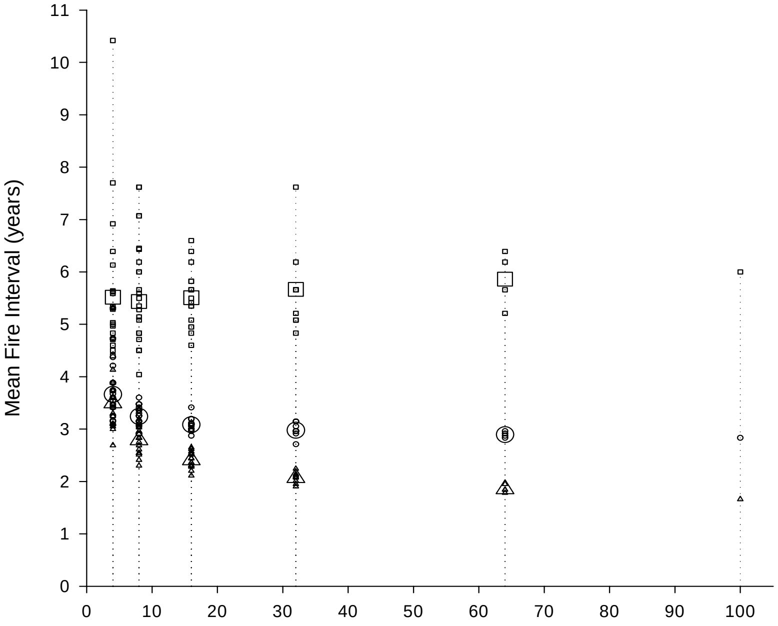


Figure 4. Composite fire history of all fire scarred trees (1682-1881) showing the number of trees scarred, number of trees susceptible to fire scarring (recording trees), and total number of fire-scarred trees present (sample depth) per year. The 10% and 25% filter lines indicate the minimum number of scarred trees required in that year to be included in the filter composite.



(a) Sample size



(b) Area sampled (ha)

Figure 5. Mean fire intervals (MFIs) (years) from several samples showing the effect of (a) sample size and (b) area sampled. (a) Random samples of different sizes were used to test the effect of sample size. 10 samples were taken per unique combination of sample size and filter level (MFIs displayed by the small shapes), and the means of the sample MFIs are shown by the large shapes. (b) MFIs were computed for all combinations of each area category (4, 8, 16, 32, 64 and 100 ha) and displayed by the small shapes. The large shapes indicate the means of the sample MFIs.

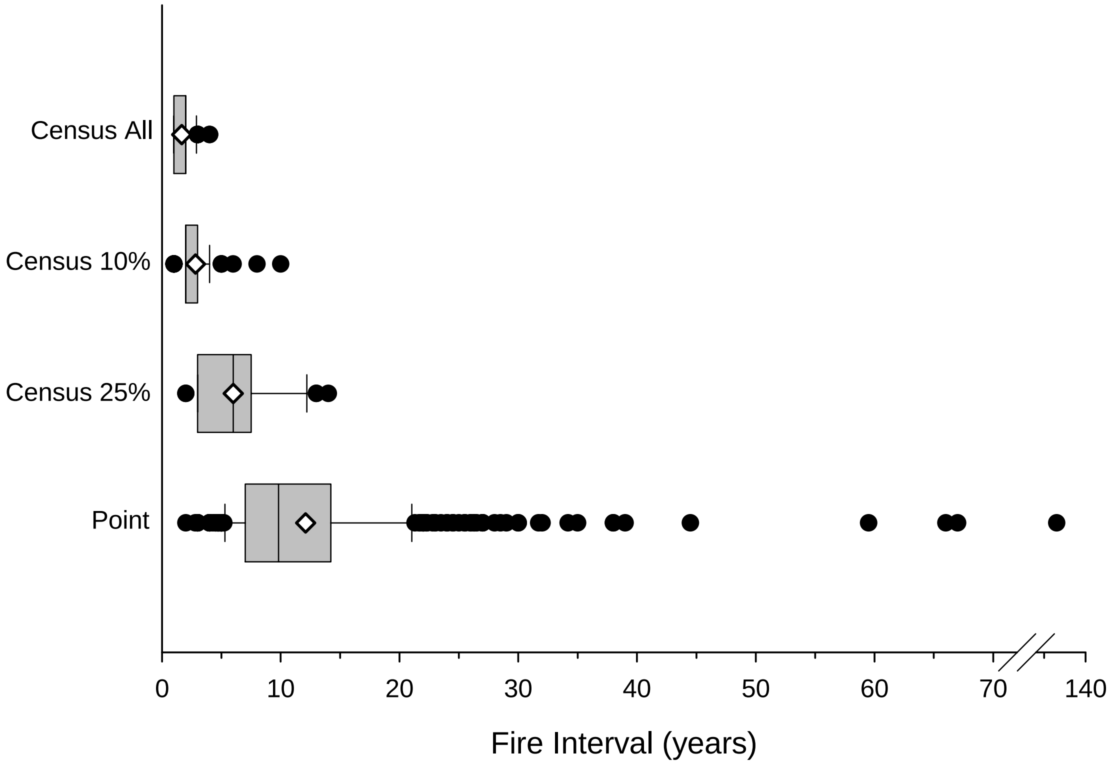


Figure 6. Distribution of individual fire intervals for the census data with three levels of filtering and the point (per tree) fire intervals. The 25th and 75th percentiles are denoted by either side of the shaded boxes with the median (vertical line) separating them. The whiskers extend to the 5th and 95th percentiles. The black dots are all the extreme values, and the white diamonds indicate the mean for each sample.

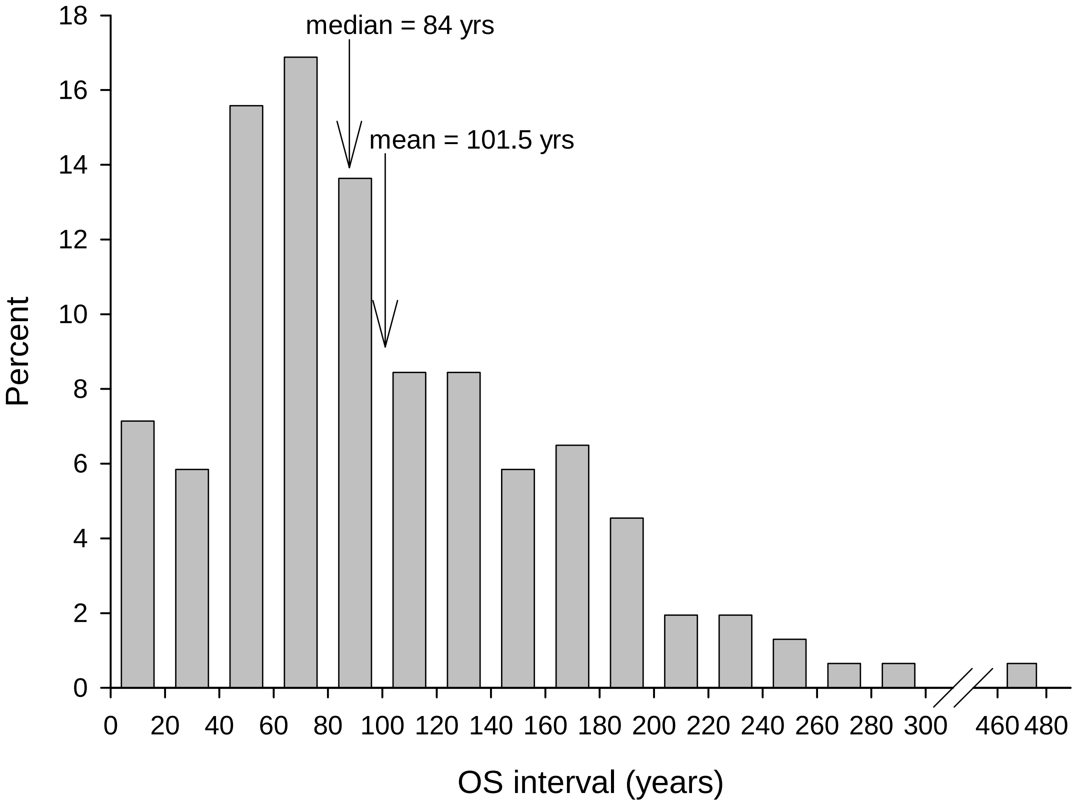


Figure 7. Origin-to-first scar (OS) interval for all trees with piths. This interval indicates the age of a tree when it received its first visible fire scar.

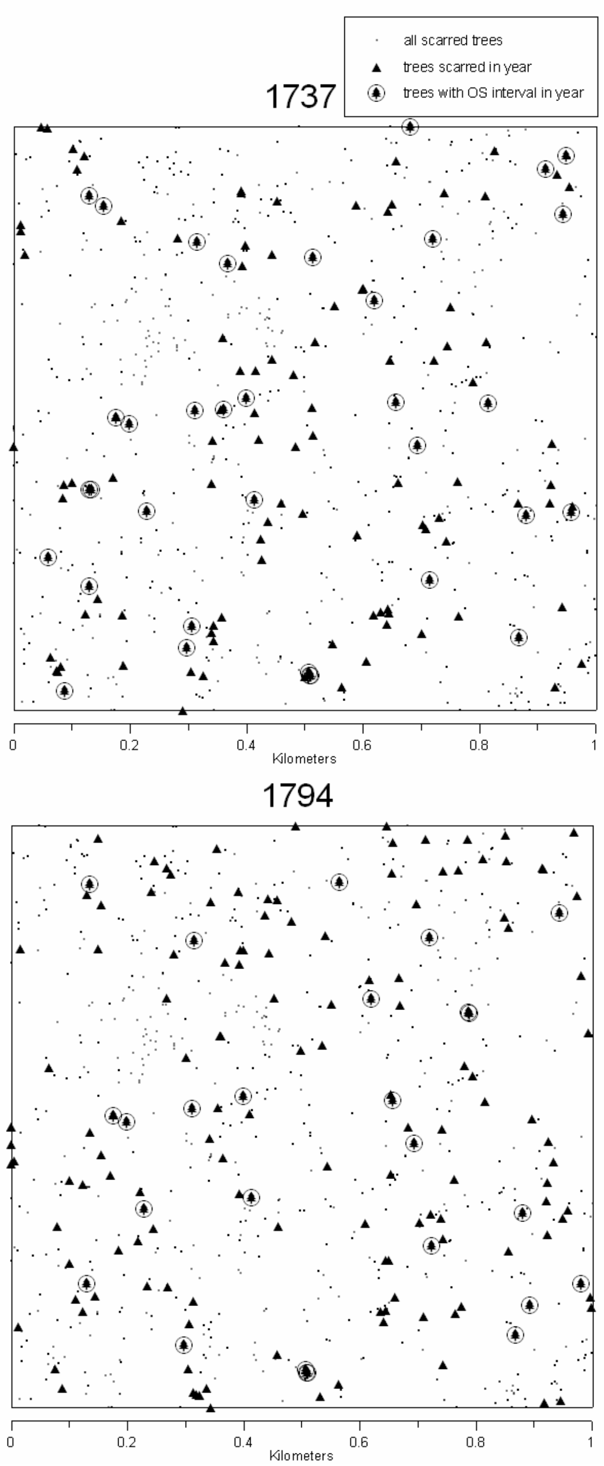


Figure 8. Trees with origin-to-first scar (OS) intervals occurred in close proximity to scarred trees during two major fire years, 1737 and 1794. OS trees are only mapped here if the OS interval overlaps the fire year shown.

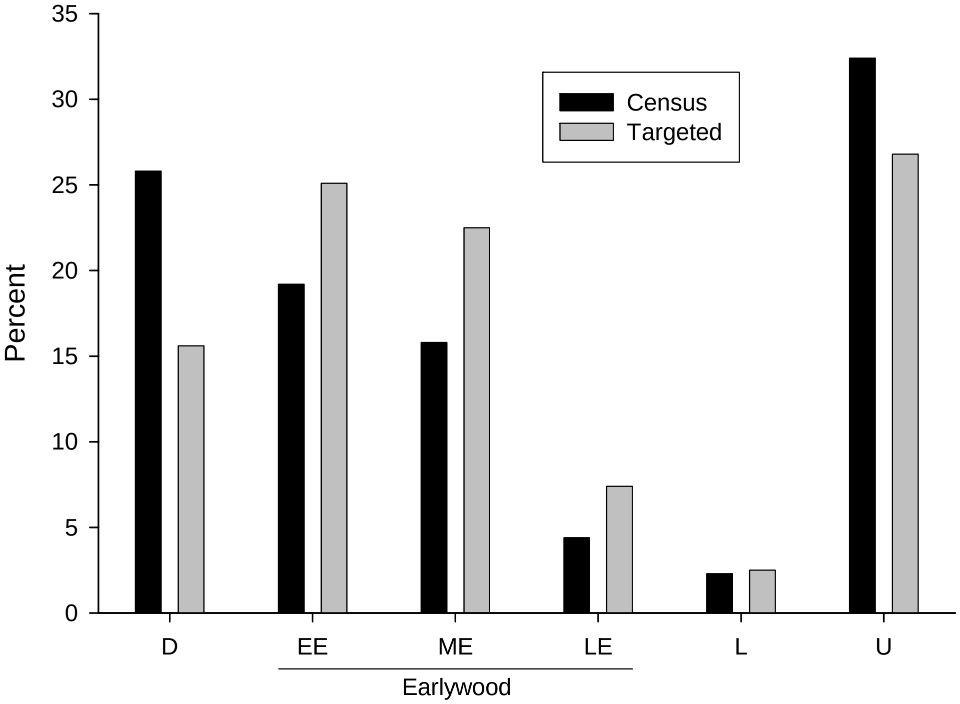


Figure 9. Seasonality distribution by percent of fire scars for the targeted sample and census. D – dormant, EE – early earlywood, ME – middle earlywood, LE – late earlywood, L – latewood, U – undetermined.

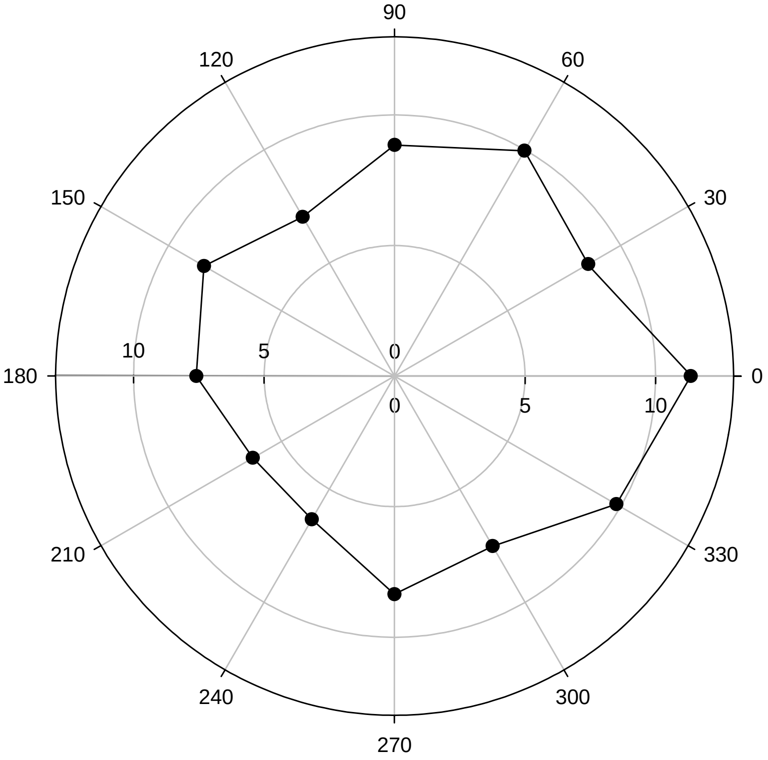


Figure 10. Percent of catfaces (radial axes) by direction of formation (angular axes in degrees). Note: this is not oriented like a compass.

CHAPTER 4

Management Implications

Social Implications

In recent years, wildfires in the Southwest have dramatically increased in size and severity, resulting in undesirable ecological effects (Agee 1993; Kolb et al. 1994; Friederici 2003) and increased costs of suppression and rehabilitation (National Fire Plan 2004; GAO 2004). Recent legislation has encouraged thinning to reduce the hazards of the increased fuel loads as one way to mitigate the severity of these fires (Healthy Forest Restoration Act 2003). Many agree that restoration of ponderosa pine ecosystems is necessary to avoid further losses because of increased susceptibility to crown fires, drought, insects and pathogens (Covington & Moore 1994; Allen et al. 2002; Fulé et al. 2004).

As the cost of wildfires continues to increase, policy makers are eager for information to help guide management policy. Policy makers are coming to understand that many ecosystems evolved with and depend on fire, and that continuing the fire suppression policy will only lead to greater losses (GAO 2004). Since management recommendations are based partially on historic forest conditions and fire frequencies, it is important to have information collected in such a way that accurately represents the true historic conditions. However, fire history is only one piece of the larger management puzzle. Managers must consider the risks of escaped fires and smoke impacts on nearby communities. The costs of restoring stand densities and frequent fire, including the possible loss of revenue from timber harvesting, must be weighed against the climbing costs of fire suppression and rehabilitation. A mosaic of treatments representing the range of natural variability can be applied across broad landscapes while monitoring and adaptively managing for the economic, social and ecological outcomes (Kolb et al. 1994; Allen et al. 2002).

Ecological Implications

Many studies suggest that decreasing ecosystem health is characterized by high intensity fire events, an increase in bark beetle and pathogen related mortality, a shift in understory dominance from native to exotic species, a decrease in nutrient cycling, altered hydrologic regimes, and a loss of wildlife habitat with an increase in tree density since the time of Euro-American settlement in the late 1800's (Weaver 1951; Kolb et al. 1994; Covington & Moore 1994; Swetnam et al. 1999; Covington 2003). Although there is broad consensus that many of these changes are at least partly a consequence of a century of fire exclusion, the solution remains under debate (Cooper 1960; Stephenson 1999; Moore et al. 1999; Allen et al. 2002). There is general agreement that restoring ponderosa pine ecosystems to similar conditions under which they evolved would allow their for long-term sustainability (Fulé et al. 1997; Moore et al. 1999).

Those who support ecosystem restoration debate between reintroducing the natural processes and rebuilding the structural aspects of the reference ecosystem. Process restoration considers type and frequency of disturbance, while structure restoration includes species composition and arrangement (Stephenson 1999). In the Southwest, this means the decision between reintroducing frequent fires and mechanically thinning dense stands of young trees before burning. In one case study in ponderosa pine, process restoration proved to be more cost effective, but was not as successful at thinning the dense young trees, while the structural approach restored more natural forest attributes, but was costly and resulted in soil damage and exotic species invasions (Fulé et al. 2004). Allen et al. (2002) recognize that it is unsafe to reintroduce fire without thinning in some areas with developments, but other remote areas may be good candidates for process restoration. Others support the reintroduction of fire as a key ecological process, but allege that structural restoration is premature, citing considerable uncertainties in the fire history and weak data describing reference conditions (Baker & Ehle 2001).

The ecological consequences of misdirected restoration activities are sometimes great and reference conditions are only attainable for fire regimes and forest structure (Stephenson 1999). Reintroducing fire in one heavily stocked stand in Northern Arizona killed many of the old-growth, legacy trees without affecting the general stand conditions (Sackett et al. 1995). The resulting structure may be imprecise and poorly suited for future climate conditions (Millar & Woolfenden 1999; Allen et al. 2002), but if failures are recognized and used for learning, they can lead to continued adaptation of restoration practices (Allen et al. 2002).

Many previous fire history studies using the targeting method reported high fire frequencies (<20 yr MFI, 10-100 ha sites) before Euro-American settlement (Swetnam & Baisan 1996). Fire scars are just one line of historical evidence indicating a frequent fire regime, yet it is still important to test the validity of these methods. Modern calibration of fire regimes (Fulé et al. 2003; Farris et al. 2003), evolutionary ecology (Moore et al. 1999) and historical documentation (Cooper 1960) support the understanding of the changes in the fire regime and forest structure that occurred in the last century. It is this understanding of the historical context that will lead to its judicious application.

CHAPTER 5

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