SPATIAL AND TEMPORAL VALIDATION OF FIRE-SCAR FIRE HISTORIES

by

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DEDICATION

To Kerry, Tamsen, and Fletcher and Bodie: Nobody suffered more during this process.

To my parents: I wish my father was still around to see this.

"I'm staying, I'm finishing my coffee." -- Walter Sobchak

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ABSTRACT

Accurate information about historical fire regimes is needed to understand the long-term effects of fire and climate on ecosystem dynamics and guide ecosystem restoration. Fire scars are used widely to reconstruct historical fire regimes around the world but few empirical validation studies have been conducted. This dissertation consists of three integrated studies aimed at addressing the following questions: (1) how accurate are fire-scar fire histories compared to known patterns of fire occurrence; (2) how do these relationships vary spatially and temporally; (3) how representative statistically are search-based (“targeted) fire-scar sampling techniques? I utilized an empirical corroboration approach to validate fire-scar reconstructions against documentary fire perimeters for a 2,780 hectare ponderosa pine landscape in Saguaro National Park, Arizona (USA). Resampling statistics and spatial modeling were used to quantify interactions between spatial scale, sample size, and fire size. Statistical properties of targeted sampling were assessed by analyzing three case studies containing paired examples of targeted and non-targeted sampling (i.e., systematic and census). I found strong linear relationships between fire-scar synchrony (samples scarred in a given year) and annual area burned. Fire-scar derived estimates of fire frequency metrics, such as Mean Fire Return Interval and Natural Fire Rotation, did not differ significantly from the documentary record, and there was strong spatial coherence between fire frequency maps interpolated from fire-scar data and documentary maps. Scale and sample size dependence of fire-scar detection probabilities were variable for small fire years but relatively weak for widespread fires. This resulted in consistent and predictable influences on fire frequency

reconstructions: statistical measures dependent on area burned were relatively stable and robust across a range of scale, sample size, and fire size. Targeted sampling did not differ statistically from non-targeted datasets, but targeted fire-scar data contained proportionately greater sample depth and longer temporal records with fewer samples. These results demonstrate collectively that key temporal and spatial fire frequency parameters can be reconstructed accurately from point-based fire-scar data. They also reaffirm general interpretations and management implications from past fire history research indicating that frequent, widespread burning was an important component of pre-settlement fire regimes in Southwestern ponderosa pine.

CHAPTER 1: INTRODUCTION

Explanation of Problem

Fire scars are used widely around the world to reconstruct fire histories in forests where surface fires are a component of the fire regime. Like all forms of paleo-data, fire scars provide incomplete evidence of past fires and are patchily distributed due to the stochastic factors that influence their formation and preservation (Dieterich and Swetnam 1984, Swetnam and Baisan 1996a, Falk 2004). The presence of an individual fire scar provides irrefutable evidence of a fire in a particular year at a specific point on the landscape (i.e., tree bole), but the absence of a fire scar is ambiguous as it could indicate any of the following: 1) a fire didn't burn up to the base of the tree that year (even if there was a fire throughout the general area); 2) a fire burned up to the base of the tree but did not form a scar; 3) a fire scar was formed but was destroyed by subsequent fires or other disturbance or decay processes (Baker and Ehle 2001, 2003, Fulé et al. 2003, Van Horne and Fulé 2006, Shapiro-Miller et al. 2007, Collins and Stephens 2007). Fire historians therefore must rely on inferences about fire spread based on the spatial and temporal distribution of scars in a network of multiple samples.

Having reliable information about historical fire regimes is necessary to ensure an accurate understanding of long-term fire-climate relationships and ecosystem dynamics. A considerable body of knowledge about historical fire regimes is based on fire-scar reconstructions using different sampling and analytical approaches. There has been debate over the years about the best ways to collect and analyze fire-scar data to reconstruct historical fire regimes (Johnson and Gutsell 1996, Swetnam and Baisan 1996a, Minnich 2000, Baker and Ehle 2001, 2003, Fulé et al 2003, Stephens et al. 2003, Van Horne and Fulé 2006, Collins and Stephens 2007). These studies illustrate how different inferences and interpretations of fire-scar data can result in disparate conclusions about historical fire regimes. It has been argued, for example, that published estimates of fire frequency and extent in ponderosa pine throughout the West have been overestimated by several orders of magnitude (Baker and Ehle 2001, Minnich et al. 2000). Such discrepancies in interpretation could have major implications for forest restoration and fire-climate research.

Much of the debate about fire-scar reconstructions is due to a lack of empirical comparisons with independently derived documentary data. Modern calibration is an integral part of dendrochronology. Dendroclimatologists, for example, use instrumental records (based on rain gauges, thermometers, etc.) to calibrate and verify the relationships between climate and tree growth and then extend the climate record back through time. For fire history reconstructions the best available source of modern "instrumental" records are ground-based documentary fire maps. Quantitative comparison of fire-scar reconstructions with independently mapped fire perimeters is difficult to accomplish because there are few landscapes in the United States where multiple overlapping fires have occurred in the 20th and 21st centuries when documentary-based maps are available. Some pine-dominated forests in Mexico have burned frequently during the 20th century as shown by fire-scar data (e.g., Baisan and Swetnam 1995, Heyerdahl and Alvarado 2003, Stephens et al. 2003, Fulé et al. 2005), but independent documentary maps with annual resolution are generally lacking in this region.

Another challenge is that fire-scar sampling methods often involve search-based (or “targeted”) methods because the occurrence and quality of fire scars is highly variable in space and time, and primary goals have generally been to efficiently obtain lengthy and complete records for small study areas (Swetnam and Baisan 1996a). For various reasons involving fire-scar formation and preservation processes that are not well understood, some fire-scarred trees (living or dead) preserved the record of past fires with a relatively high degree of completeness and temporal length, whereas many others provide incomplete and/or short records. This characteristic of relative “rarity” of complete and lengthy fossil (or sub-fossil) records is common to paleontological, paleoecological and paleoclimatic records, and has commonly led to targeted sampling approaches in paleostudies (Swetnam et al. 1999). Because targeted sampling has been employed in many fire-scar studies, the spatial resolution of fire extent estimates (in absolute terms, i.e., hectares (ha) per fire event, or estimated perimeter locations) and statistical representativeness of these spatially distributed reconstructions have not been determined. Providing such spatial resolution and representativeness estimates requires more rigorous systematic/random sampling approaches (e.g., Heyerdahl et al. 2001, Falk 2004), and testing with independent fire history data. Typically, corroboration of fire-scar reconstructions of past timing, frequency, and extent of fires have been largely anecdotal, and limited to one or a small number of fire events.

The goal of this research was to conduct a comprehensive, empirical corroboration of fire-scar fire histories using empirical approaches. I add to the small body of work in this area by presenting the most comprehensive corroboration and fire-scar datasets conducted to date. I address key assumptions and methods used to collect and analyze fire-scar data. In addition to addressing how well fire-scar reconstructions represent actual fire regimes (as derived from documentary records), this research contributes to fundamental geographic questions about how to predict synoptic, broad-scale spatial processes from point data, and the relationship between search-based and probabilistic sampling approaches for analyzing past conditions with fragmented, paleo-data sources.

Our specific objective can be summarized into three overarching questions: (1) how well do fire-scar reconstructions represent documented spatial parameters of the fire regime (Appendix A); (2) how do these relationships vary in space and time (Appendix B); (3) how are these relationships influenced by sampling method (Appendix C)?

Approach

This research utilized an empirical "corroboration" approach to validate fire-scar reconstructions using the best and most accurate source of documentary data available – ground-mapped fire perimeters with annual resolution. Like fire-scar data, documentary data are also subject to various types of imprecision and inaccuracy, requiring certain assumptions and interpretations (Morgan et al. 2001, Rollins et al. 2001, Hessl et al. 2007, Shapiro-Miller et al. 2007). Hence, we consider this to be a form of "corroboration," achieved by comparison of two independent estimates, rather than a pure "validation," which might erroneously imply that one of the data types is the complete or absolute "truth" (see Turner et al. 2001, page 58). I additionally used GIS modeling and statistical resampling techniques to simulate partial fire-scar datasets of varying sample size and spatial scale.

The success of such an approach depends largely on the quality of the "reference" dataset (i.e., documentary maps). I took advantage of an extraordinary 20th century landscape located in the Rincon Mountains in the Saguaro National Park Wilderness in southern Arizona (USA). The Mica Mountain study area contains an unusually high frequency of overlapping 20th century fires (including both lighting-ignited wildland fires and prescribed fires) and a relative long and complete documentary record of those fires (including many ground-mapped perimeters). The study area also contained independent fire-scar data collected using targeted sampling (Baisan and Swetnam 1990). Datasets from two additional Southwestern study areas containing independent examples of targeted and systematic or census sampling were used in combination with the Rincon Mountain data to complete this study (Baisan and Swetnam 1990, Touchan et al. 1995, Falk 2004, Van Horne and Fulé 2006).

The sequence of the methodological approach was as follows: 1) corroborate the relationship between fire-scar fire history reconstructions and documentary maps, 2) use bootstrapping and spatial modeling to examine the relative influence of spatial scale, sample size, and fire size on the corroboration for 20th century and pre-20th century fire regimes, and 3) utilize multiple case studies to compare the relative accuracy of search-based, or "targeted," sampling approaches against systematic and random sampling.

Organization of the Dissertation

This dissertation consists of three related studies designed to test key assumptions and analytical approaches for reconstructing fire histories from fire scars. The first study focuses on the relationship between spatial and temporal fire history parameters reconstructed from fire-scar data and documentary fire maps. The second study expands on these results to explore how the relationship between fire scars and documentary maps vary as a function of spatial scale, sample size, and fire size. The third study compares statistical agreement between search-based sampling (i.e., "targeted") and independently collected systematic, random and census sampling.

The three studies are presented as stand-alone research papers in Appendices A, B, and C. Chapter 2 (Present Study) provides a brief summary of each study. Each Appendix was prepared in the form of a publishable paper to be submitted to a peer reviewed journal. Each paper follows a standard scientific structure consisting of an Introduction, Methods, Results, Discussion, and References section.

Appendix A, titled "Spatial and temporal corroboration of a fire-scar based fire history reconstruction in a frequently burned ponderosa pine forest in Arizona." was prepared for submission to *Ecological Applications*. The paper has been accepted for publication, but the publication date is unknown as of this writing. This paper was co-authored by Christopher Baisan, Donald Falk, Stephen Yool (committee member), and

Thomas Swetnam (committee member). All are affiliated with the University of Arizona. As lead author I was responsible for the experimental design, planning and overseeing field data collection, assisting with laboratory work, conducting all data analysis and initial interpretation of results, and writing the complete first draft of the manuscript. C. Baisan contributed extensively with all phases of field work and laboratory processing. All authors provided technical advice throughout the project and participated in reviewing and revising the final manuscript. C. Baisan was 2nd author because of extensive field and laboratory assistance. S. Yool and T. Swetnam were listed as the last two authors to reflect their roles as committee members and co-chairs.

Appendix B, titled "Empirical corroboration of scale and sample size dependence of fire-scar data under different fire regimes" was prepared for the *International Journal of Wildland Fire* or *Landscape Ecology*. I plan to submit that paper in the spring of 2010. The authorship of this paper and the roles of the co-authors are the same as Appendix A.

Appendix C, titled "Targeted fire-scar sampling can accurately and efficiently estimate past fire regime patterns in Southwestern ponderosa pine forests" was prepared for submission to *Canadian Journal of Forestry*. The paper is currently in peer review. The research utilizes data from three case studies, one of which included original data I collected for Appendix A and B and two of which are from previous studies. I co-authored this paper with Pete Fulé and Megan Date (who publishes under the name Megan Van Horne) of Northern Arizona University, and Donald Falk, Christopher Baisan, and Thomas Swetnam of the University of Arizona. As lead author I developed the experimental design, the conceptual and analytical framework, performed the data analysis and initial interpretation of results, and wrote the draft manuscript. P. Fulé and M. Van Horne provided data for the Centennial Forest study area and M. Van Horne provided additional assistance with data management; D. Falk and T. Swetnam collected and provided data for the Monument Canyon study area; C. Baisan collected and provided data for the original Mica Mountain study area. All co-authors provided technical advice and assistance and helped revise the manuscript. M. Van Horne is listed as second author because of her added data management role; all other authors are listed in alphabetical order, except for T. Swetnam who is listed last to reflect his role as a committee chair (the only co-author on my committee).

CHAPTER 2 – PRESENT STUDY

This chapter provides a brief overview of the three studies that comprise this dissertation. For the full content and detailed methodology and results of each study see the Appendices. These three studies collectively represent the most comprehensive empirical assessment yet conducted on the relative accuracy of landscape-scale fire history reconstructions from fire scars.

Appendix A – "Spatial and temporal corroboration of a fire-scar based fire history reconstruction in a frequently burned ponderosa pine forest in Arizona"

Fire scars are used widely to reconstruct historical fire regime parameters in ponderosa pine and mixed conifer forests in the southwestern United States and elsewhere. Because fire scars provide incomplete records of past fire occurrence at discrete points in space, assumptions must be made to reconstruct fire frequency and extent across landscapes using spatial networks of fire-scar samples. Assessing the relative accuracy fire-scar fire history reconstructions has been hampered due to a lack of empirical comparisons with independent fire history data sources.

In this study we compared fire histories reconstructed independently from fire scars with a comprehensive documentary fire history on Mica Mountain, southern Arizona (USA). Unlike other pine-dominated landscapes in the United States, the 2,780 hectare study area contained an unusually rich and well documented contemporary fire history, with some stands having burned at least 9 times during the 20th century. The

National Park Service (NPS) has kept detailed fire records since 1937, including ground-mapped fire perimeters for most burns (hereafter referred to as NPS fire atlas). We used these data to test the relationship between annual area burned and fire-scar synchrony derived from 60 systematic 1-hectare plots, compare the relative accuracy of spatially explicit reconstructions of fire frequency, compare widely used temporal fire frequency summary statistics, and validate predictions of fire seasonality inferred from intra-annual scar positions in tree rings.

We found that fire-scar data provided spatially representative and complete inventories of all major fire years (>100 ha) in the study area, but failed to detect the majority of small fires. Combining or "compositing" records from multiple fire-scar samples at the stand level (i.e., within plots) improved the completeness of fire-scar inventory of major fire years. There was a strong linear relationship between the percentage of samples recording fire scars in a given year (i.e., fire-scar synchrony) and total area burned for that year ($y = 0.0003x + 0.0087$, $r^2 = 0.96$, $p < 0.001$). The spatial coherence between fire-scar interpolated fire perimeters and fire frequency maps and NPS fire atlas was very strong. Widely used fire frequency summary statistics, including the Mean Fire Return Interval (MFI) and Natural Fire Rotation (NFR), did not differ significantly between datasets. Seasonal timing of past fires was reconstructed accurately using the intra-annual ring position of fire scars and knowledge of local tree growth.

These results demonstrate clearly that representative, landscape-scale fire histories can be reconstructed from spatially distributed fire-scar networks. This study also provides the first empirical test of key analytical fire-scar inferences used by fire historians, such as the relationship between area burned and fire-scar synchrony. We illustrate how the values of different fire frequency summary statistics can differ for a single set of fires of known origin and extent and discuss implications for interpreting fire history studies.

Appendix B - “Empirical corroboration of scale and sample size dependence of fire-scar data under different fire regimes”

Fires, and the physical proxy evidence created by them (e.g., fire scars), are patchily distributed in space and time. The first study (Appendix A) assessed corroboration between fire-scar reconstructed fire histories and documentary maps for a single spatial scale (the entire study area), for a single sample size (full set of 60 plots), and for a single temporal period and corresponding fire frequency regime (1937 to 2000, which encompasses the fire suppression era). A logical outgrowth of the first study therefore was to ask how sensitive fire-scar reconstructions are to the interacting influences of scale, sample size, and fire size (annual area burned). Understanding this variability is important because fire history studies exhibit considerable inconsistency in these parameters. Rarely is it practical for researchers to conduct intensive systematic sampling landscapes as large as we analyzed in the first study. An improved understanding of scale, sample size, and fire size on fire-scar reconstructions is necessary to interpret changes between historic (ca. pre-20th century) and contemporary fire regimes and between different study areas or sampling schemes.

Two approaches were employed to address these questions. We first used the documentary fire maps (NPS fire atlas) to assess scale and sample size dependence along a gradient of increasing fire size. Bootstrapping procedures were used to simulate partial datasets of different sample size and spatial extent (Burrough and McDonnel 1998, Krebs 1998, Magurran 2004), and these were used to calculate detection probabilities of fire years with different amounts of annual area burned. Spatial scale in this study refers to a contiguous area of interest of a given size (ha) and sample size refers to the number of independent sample units (i.e., plots in this case). The two are somewhat related in that small areas will only support a few plots, but examining the two separately by holding sample density (plots / ha) constant yields useful insights into their relative influences. Secondly, we used the calibrated relationships obtained from the first study (Appendix A) as a basis to compare sample size and scale dependence between 19th century and 20th century fire regimes in the study area. The 19th century fire regime was characterized by free burning fires constrained only by weather and fuels prior to fire exclusion. This comparison allowed us to assess the consistency and robustness of reconstructed fire frequency parameters for periods with differing fire frequency-area distributions.

We found that sample size and scale dependence of fire-scar data was primarily a function of small fires. Relatively few samples and small spatial scales were required to provide complete inventories of fire years with large, widespread burns. The relationship between fire-scar synchrony and area burned was consistently strong across a broad range of scales and sample sizes. This large-fire detection bias has a consistent and predictable influence on the estimation of fire frequency parameters. Fire frequency summary statistics that are based on area burned, such as filtered MFI and NFR, appear to be estimated robustly across a very wide range of scales, sample sizes, and fire sizes. Moreover, because large fires are proportionately more common in small areas than large areas, all fire frequency metrics were generally similar at fine spatial scales <100 ha. Consistent with these findings, the 19th century fire regime data showed remarkably little variation among and between different metrics. Scale dependence of area-based fire-scar metrics like the NFR and filtered MFI was due primarily underlying scale dependence of documentary fire occurrence rather than detection bias or inference error.

Our findings suggest that previously published estimates of large fire occurrence are robust across a range of spatial scales and sample sizes, particularly for pre-settlement fire regimes in the Southwest which were typically characterized by large fire extents. In Appendix 2 we present detailed comparisons of pre-settlement fire frequencies from this study with other fire-scar networks across the Southwest to demonstrate these points. Differences between the proportion of small and large fire years could reflect actual fire regime conditions or differences in detection of small fire years due to large sample sizes or scales. We discuss the implications for sampling and interpreting new and existing fire-scar datasets.

Appendix C – “Targeted fire-scar sampling can accurately and efficiently estimate past fire regime patterns in Southwestern ponderosa pine forests”

Subjective sampling is a common method in paleo-sciences because of the fragmented spatial and temporal distribution of relatively rare, ancient fossil and sub-fossil specimens. Fire historians typically employ various forms of search-based sampling to "target" tree-ring specimens containing visible evidence of well-preserved fire scars. The purported advantage of targeted sampling is that experienced researchers can efficiently locate high quality specimens, thereby increasing the likelihood of obtaining more complete inventories of fire events and lengthy records, especially of widespread events that tend to constitute the majority of area burned (Swetnam and Baisan 1996a, Van Horne and Fulé 2006). Despite the practical efficiency and widespread use of targeted sampling in fire history research, the validity of the approach for obtaining unbiased estimates of fire history parameters has been challenged based on the assumption that areas with higher scar densities may have burned more frequently (Johnson and Gutsell 1994, Minnich et al. 2000, Baker and Ehle 2001, 2003).

In this study we took advantage of three unique case studies consisting of independent, spatially overlapping targeted and non-targeted fire-scar sampling: the 100 ha Centennial Forest (CEN) study area in northern Arizona (Van Horne and Fulé 2006); the 256 ha Monument Canyon Research Natural Area (MCN) study area in central New Mexico (Touchan et al. 1995, Falk 2004); and the 2,780 ha Mica Mountain (MIC) study area in southern Arizona (Baisan and Swetnam 1990, Farris 2009 Appendix A). Using the same fire history reconstruction methods field-tested in the first two chapters, we compared pre-20th century fire frequency parameters derived from targeted and non-targeted fire-scar data. The three case studies are distributed across a wide geographic range of ponderosa pine-dominated ecosystems in the Southwest, they range in area from

100 ha to 2,780 ha, and they represent some of the most intensive non-targeted "reference" datasets currently available in the Southwest.

Targeted and non-targeted fire-scar samples recorded fire years in nearly equal proportions at all three study areas, which is strong evidence against an inherent bias in targeted sampling. Categorical inventories of major fire years identified from targeted and non-targeted data showed strong overlap, ranging from 93% at CEN to 99% at MIC. Differences between targeted and non-targeted Mean Fire Return Intervals and Natural Fire Rotations at each study were small and not statistically significant: the range of the targeted and non-targeted values were 2.5-4.5 to 1.8-4.1 years respectively for MFI_{all}; 2.9-6.5 to 2.7-7.4 years respectively for $MFI_{10\%}$; 5.0-7.3 years to 5.3 -10 years respectively for $MFI_{25\%}$; and 8.4-14.1 years to 9.0-16.5 years for NFR. Consistent with theoretical expectations, targeted fire-scar data provided clear advantages in terms of overall sample depth and efficiency. Temporal length of the fire-scar record was similar or longer for targeted data despite having a small fraction of total samples. Although there were more fire scars per century on targeted fire scars, these did not represent unique large-fire years.

These results demonstrate that targeted sampling can produce accurate estimates of temporal and spatial fire history parameters similar to those derived from intensive non-targeted sampling. There was no evidence of a systematic bias associated with the targeted samples. This is due in part because targeted sampling efforts in these studies were relatively broadly distributed and representative of the landscape variability. Factors such as sample size and spatial distribution are probably most important for characterizing landscape-scale fire occurrence than the method of selecting scarred trees. Our results also reaffirmed conclusions from previous fire history research in Southwestern ponderosa pine forests that relatively widespread fires were a frequent occurrence (<15 years on average) prior to 20th century fire exclusion.

Summary

This research compared the relative accuracy of fire-scar fire histories using independent documentary data sources. These results demonstrate that representative fire histories can be constructed from fire-scar data if the assumptions and limitations are understood. Despite the fact that fire scars are formed at the scale of the individual tree bole, networks of fire-scar data are most accurate for representing the relative extent and frequency of widespread fires in a given area. Fire-scar synchrony is correlated closely with area burned for a wide range of scales, sample sizes, fire sizes, and sampling methods. This relationship forms the basis for accurately estimating the underlying fire frequency-area distribution. Spatially explicit patterns of fire occurrence (extent and frequency) corresponded closely to mapped fires, but there are minimum interpretable resolutions that can be inferred based on the sample density.

The statistical properties of search-based sampling approaches tested in this research did not differ significantly from systematic sampling or a complete census. Although not appropriate in all circumstances, “targeted” sampling provides an efficient and viable alternative for inventorying and characterizing major fire years. No single sampling method or analytical method will be appropriate for all fire history objectives or applications. The research objectives, available resources, and site-specific characteristics of the landscape in question can help determine which methods are appropriate.

Our findings reaffirm general interpretations of past fire history studies in Southwestern ponderosa pine and mixed conifer forests that widespread fires occurred at frequent intervals of less than 15 years prior to the 20^{th} century (see summaries by Swetnam and Baisan 1996a, 1996b, Swetnam and Baisan 2003). Pre-20^{th} century NFRs estimated from all non-targeted datasets were <15 years regardless of study area, sampling technique, scale, or sample size. These values are significantly lower than the hypothetical range of "corrected" NFRs (*sic* population mean fire intervals) proposed for western ponderosa pine by Baker and Ehle (2001), which range from a median of 52 years on the low end to 170 years on the high end. The pattern of frequent, overlapping fires also differs from pre-settlement fire regime model proposed by Minnich et al. (2000) which asserts that infrequent, widespread fires at intervals of ~50 years were the primary force shaping forest structure. Thus, the current ecosystem restoration emphasis of increasing resistance and resilience in Southwestern pine forests by reducing fuel load and tree density and restoring frequent fire as an ecological process (Allen et al. 2003) are supported strongly by our research. Fire-scar estimates of large-fire parameters such as NFR and filtered MFIs appear robust across a range of scale and sample size, suggesting that the results interpretations from existing fire history research are representative.

REFERENCES

Allen, C.D. 2002. Lots of lightning and plenty of people: An ecological history of fire in the upland southwest. In Western Wilderness: Fire, Native Peoples, and the Natural Landscape. Island Press, Covelo, CA. pp. 143-193.

Baisan, C.H. and T.W. Swetnam. 1990. Fire history on a desert mountain range: Rincon Mountain Wilderness, Arizona, U.S.A. Canadian Journal of Forest Research 20: 1559-1569.

Baisan, C. H., and T.W. Swetnam. 1995. Historical fire occurrence patterns in remote mountains of Southwestern New Mexico and northern Mexico. Pages 153-156 in J. K. Brown, R.W. Mutch, C.W. Spoon, and R.H. Wakimoto, editors. Proceedings: Symposium on Fire in Wilderness and Park Management. Missoula, MT, March 30-April 1, 1993. General Technical Report INT-GTR-320. USDA Forest Service, Intermountain Research Station.

Baker, W.L. and D. Ehle. 2001. Uncertainty in surface-fire history: the case of ponderosa pine forests in the western United States. Canadian Journal of Forest Research 31: 205-1226.Dieterich, J. H., and Swetnam, T.W. 1984. Dendrochronology of a fire scarred ponderosa pine. Forest Science 30(1):238-247.

Baker, W.L. and D. Ehle. 2003. Uncertainty in fire history and restoration of ponderosa pine forests in the western United States. In Conference proceedings: fire, fuel treatments, and ecological restoration. Edited by P.N. Omi and L.A. Joyce. USDA Forest Service, RMRS-P-29. Fort Collins, CO. pp. 319-334.

Burrough, P.A. and R.A. McDonnel. 1998. Principles of geographic information systems (2nd edition). Clarendon Press, Oxford, England.

Collins, B.M. and S.L. Stephens. 2007. Fire scarring patterns in Sierra Nevada wilderness areas burned by multiple wildland fire use fires. Fire Ecology 3(2):53-67.

Falk, D.A. 2004. Scaling rules for fire regimes. PhD. Dissertation. University of Arizona, Tucson.

Fulé, P.Z., T.A. Henlein, W.W. Covington, and M.M. Moore. 2003. Assessing fire regimes on Grand Canyon landscapes with fire scar and fire record data. International journal of Wildland Fire 12(2):129-145.Heyerdahl, E.K., L.B. Brubaker, and J.K. Agee. 2001. Spatial controls of historical fire regimes: a multiscale example from the Interior West, USA. Ecology 82:660-678.

Hessl, A., J. Miller, J. Kernan, D. Keenum, and D. McKenzie. 2007. Mapping paleo-fire boundaries from binary point data: comparing interpolation methods. The Professional Geographer 59(1):87-104.

Heyerdahl, E.K. and E. Alvarado. 2003. Influence of climate and land use on historical surface fires in pine-oak forests, Sierra Madre Occidental, Mexico. In Fire and climatic change in temperate ecosystems of the western Americas. Springer-Verlag, New York, NY. pp.196-217.

Johnson, E.A. and S.L. Gutsell. 1994. Fire frequency models, methods and interpretations. Advances in Ecological Research 25:239-287.

Krebs, C.J. 1998. Ecological Methodology. Benjamin-Cummings (2nd ed.). 576 pp.

Magurran, A.E. 2004. Measuring biological diversity. Blackwell Publishing, Malden, MA. 256 pp.

Minnich, R. A., M.G. Barbour, J.H. Burk, J. H., and J. Sosa-Ramírez. 2000. California mixed-conifer forests under unmanaged fire regimes in the Sierra San Pedro Mártir, Baja California, Mexico. Journal of Biogeography 27: 105-129

Morgan, P., C. Hardy, T.W. Swetnam, M.G. Rollins, and D.G. Long. 2001. Mapping fire regimes across time and space: Understanding coarse and fine-scale patterns. International Journal of Wildland Fire 10 (3-4): 329-342.

Rollins, M.G, T.W. Swetnam, and P. Morgan. 2001. Evaluating a century of fire patterns in two Rocky Mountain wilderness areas using digital fire atlases. Canadian Journal of Forest Research 31(12): 2107-2123.

Shapiro-Miller, L.B., E.K. Heyerdahl, and P. Morgan. 2007. Comparison of fire scars, fire atlases, and satellite data in the northwestern United States. Canadian Journal of Forest Research 37:1933-1943.

Stephens, S.L., C.N. Skinner, and S.J. Gill. 2003. Dendrochronology-based fire history of Jeffrey pine-mixed conifer forests in the Sierra San Pedro Mártir, Mexico. Canadian Journal of Forest Research 33:1090-1101.

Swetnam, T. W. 2005. Fire histories from pine-dominant forests. Rocky Mountain Research Station. Rocky Mountain Research Station. Pages 35-43 *in* G.L. Gottfried, B.S. Gebow, L.G. Eskew, and C.B. Edminster, editors. Proceedings of the Conference: Biodiversity and Management of the Madrean Archipelago II: Connecting Mountain Islands and Desert Seas, Tucson, AZ, May 11-15. General Technical Report RMRS-P-36. USDA Forest Service.

Swetnam, T.W., C.D. Allen, and J.L. Betancourt. 1999. Applied Historical Ecology: Using the Past to Manage for the Future. Ecological Applications 9(4):1189-1206.

Swetnam, T. W. and C.H. Baisan. 1996a. Historical fire regime patterns in the Southwestern United States since AD 1700. Pages 11-32 *in* C.D. Allen, editor. Proceedings of the Second La Mesa Fire Symposium, Los Alamos, New Mexico, March 29-31. General Technical Report RM-GTR-286. USDA Forest Service.

Swetnam, T. W. and C.H. Baisan. 1996b. Fire histories of montane forests in the Madrean Borderlands. Rocky Mountain Research Station. Pages 15-36 *in* P.F. Ffolliott, L.F. DeBano, M.B. Maker, Jr., G.J. Gottfried, G. Solis-Garza, C.B. Edminster, D.G. Neary, L.S. Allen, editors. Effects of fire on Madrean Province Ecosystems, A symposium proceedings. General Technical Report RM-GTR-289. USDA Forest Service.

Swetnam, T.W. and C.H. Baisan 2003. Tree-ring reconstructions of fire and climate history in the Sierra Nevada and Southwestern United States. In Fire and Climatic Change in Temperate Ecosystems of the Western Americas, Ecological Studies Vol. 160. Edited by T. T. Veblen, W. Baker, G. Montenegro, and T. W. Swetnam. Springer, New York, N.Y. pp. 158-195.

Touchan, R., T.W. Swetnam, and Grissino-Mayer, H.D. 1995. Effects of livestock grazing on pre-settlement fire regimes in New Mexico. In Proceedings: symposium on fire in wilderness and park management. Edited by J. Brown, R.W. Mutch, C.W. Spoon, and R.H. USDA Forest Service General Technical Report INT-GTR-320. pp. 268-272.

Turner, M.G., R.H. Gardner, and R.V. O'Neill. 2001. Landscape Ecology in Theory and Practice. Springer-Verlag, New York, NY.

Van Horne, M.L. and P.Z. Fulé. 2006. Comparing methods of reconstructing fire history using fire scars in a southwestern USA ponderosa pine forest. Canadian Journal of Forest Research 36(4):855-867

APPENDIX A

SPATIAL AND TEMPORAL CORROBORATION OF A FIRE-SCAR BASED FIRE HISTORY RECONSTRUCTION IN A FREQUENTLY BURNED PONDEROSA PINE FOREST IN ARIZONA

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Spatial and temporal corroboration of a fire-scar based fire history reconstruction in a frequently burned ponderosa pine forest in Arizona

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Abstract

Fire scars are used widely to reconstruct historical fire regime parameters in ponderosa pine and mixed conifer forests in the southwestern United States and elsewhere. Because fire scars provide incomplete records of past fire occurrence at discrete points in space, inferences must be made to reconstruct fire frequency and extent across landscapes using spatial networks of fire-scar samples. Assessing the relative accuracy fire-scar fire history reconstructions has been hampered due to a lack of empirical comparisons with independent fire history data sources. We carried out such a comparison in a 2,780 hectare ponderosa pine forest on Mica Mountain in southern Arizona (USA) for the time period 1937 to 2000. Using documentary records of fire perimeter maps and ignition locations, we compared reconstructions of key spatial and temporal fire regime parameters developed from documentary fire maps and independently collected fire-scar data. We found that the fire-scar data provided spatially representative and complete inventories of all major fire years (>100 ha) in the study area, but failed to detect most small fires. There was a strong linear relationship between the percentage of samples recording fire scars in a given year (i.e., fire-scar synchrony) and total area burned for that year ($r^2 = 0.96$). There was also strong spatial coherence between cumulative fire frequency maps interpolated from fire-scar data and ground-mapped fire perimeters. Widely used fire frequency summary statistics, such as the Mean Fire Return Interval (MFI) and Natural Fire Rotation (NFR), differed by less than 3 years between fire-scar data and mapped fires. The known seasonal timing of past fires based on documentary records was furthermore reconstructed accurately by observing intra-annual ring position of fire scars and using knowledge of tree-ring growth phenology in the Southwest. Our results demonstrate clearly that representative landscape-scale fire histories can be reconstructed accurately from spatially distributed fire-scar samples.

Key words: fire scar, fire history, ponderosa pine, empirical corroboration

Introduction

Reliable information about historical fire regimes is required to understand the long-term effects of fire and climate on ecosystem dynamics and to help guide fire and forest restoration planning (Agee 1993, Swetnam et al. 1999, Swetnam and Anderson 2008). High resolution fire mapping and documentation is being obtained for current fires using remote sensing technology (e.g., Key and Benson 2006, Miller and Thode 2007), but key parameters of historical fire regimes, such as fire frequency, size, seasonality, and spatial patterning must be reconstructed from limited proxy evidence left behind by past fires (Baisan and Swetnam 1990, Swetnam et al. 1999). Fire scars are the primary source of physical evidence used to date past fires and estimate fire frequency in ponderosa pine and mixed conifer forests of the western U.S. over the past several centuries (e.g., Baisan and Swetnam 1990, Everett et al. 2000, Heyerdahl et al. 2001, Veblen 2003, Taylor and Skinner 1998, 2003, Stephens and Skinner 2003, Fulé et al. 2003, Brown and Wu 2005, Brown et al. 2001, Swetnam and Baisan 1996a, Sherriff and Veblen 2007, Iniguez et al. 2008, Collins and Stephens 2007).

The presence of a fire scar provides irrefutable evidence of past burning at a single point in time and space (tree bole), but interpretation of the absence of a fire scar is ambiguous because not all fires form scars on trees, not all scars persist through time, and not all trees may have burned (Dieterich and Swetnam 1984, Swetnam and Baisan 1996a). Fire-scar data thus provide only a partial record of past fires at discrete points on the landscape. Any broader understanding of the extent and timing of past burning between sampled points requires inferences about fire spread based on the spatial and temporal synchrony of fire-scar years across a network of sampled points. Empirical studies are needed to test key assumptions and interpretations used in fire-scar fire history reconstructions and to better understand the accuracy and uncertainty associated with reconstructed fire regimes (Baker and Ehle 2001, 2003, Fulé et al. 2003, Van Horne and Fulé 2006, Shapiro-Miller et al. 2007, Collins and Stephens 2007).

Fire historians have debated about the best ways to collect and interpret fire-scar data to represent historical fire patterns on landscapes (Johnson and Gutsell 1996, Swetnam and Baisan 1996a, Minnich 2000, Baker and Ehle 2001, 2003, Fulé et al 2003, Stephens et al. 2003, Van Horne and Fulé 2006). Beyond issues of potential bias related to sampling strategies (e.g., “targeted” versus systematic or random sampling), much of the uncertainty in fire history reconstructions is due to a lack of systematic corroboration of fire-scar data with independently derived fire histories (e.g., mapped fires in documentary or digital forms). We use the term “corroboration” here in the sense of an empirical comparison of two independent estimates of fire history. Like fire-scar data, documentary data are also subject to various types of imprecision and inaccuracy, requiring certain assumptions and interpretations (Morgan et al. 2001, Rollins et al. 2001). Hence, we consider comparisons between fire-scar data and documentary fire maps to be a form of corroboration, achieved by comparison of two independent estimates, rather than a “validation,” which might erroneously imply that one of the data types is the complete or absolute “truth” (see Turner et al. 2001, page 58)

Spatially explicit corroboration of fire-scar data using independent, documentary fire history is a major challenge because it requires the co-occurrence of two relatively rare criteria. A landscape first must have enough modern fires to provide an adequate sample size (i.e., number and spatial extent of fire events) and serve as a reasonable analog to past fire regime conditions (overlapping fires). A landscape secondly must have accurately mapped documentary records derived from direct observation (e.g., dates of occurrence, causes, locations and perimeters, etc.). In the United States, contemporary documentary records are relatively complete during the past two to three decades but few ponderosa pine forests have burned multiple times (Fulé et al. 2003). In Mexico, some pine-dominated forests have burned frequently during the 20th century as shown by fire-scar data (e.g., Baisan and Swetnam 1995, Heyerdahl and Alvarado 2003, Stephens et al. 2003, Fulé et al. 2005), but independently mapped fire records with annual resolution are generally lacking. Consequently, corroboration of fire-scar reconstructions of past timing, frequency, and extent of fires have been largely anecdotal, limited typically to one or a small number of fire events. In the most comprehensive spatially explicit corroboration published to date, Collins and Stephens (2007) found that convex hulls drawn around opportunistically sampled fire-scar locations underestimated fire extent and total area burned statistics of overlapping 20th century fires in Yosemite (n = 5 fires) and Sequoia National Parks (n = 4). In a similar analysis, Shapiro-Miller et al. (2007) reported the relative accuracy of convex hulls from systematically sampled fire-scar locations varied depending on the source (e.g., fire atlas or remote sensing) and resultant quality and resolution of the documentary fire maps used. Fulé et al. (2003) found that fire-scar data detected all large 20th century documentary fires >8 ha in a northern Arizona ponderosa pine forest and showed good agreement between inferred timing from intra-annual ring position of fire scars and the known dates of fires. To the best of our knowledge, no published study to date has simultaneously compared multiple spatially explicit fire frequency summary statistics, or tested the accuracy of widely used analytical assumptions for reconstructing landscape-scale fire histories from fire scars.

A landscape with a contemporary fire regime suitable for comprehensive, spatially explicit fire-scar corroboration with documentary records is the Rincon Mountains of southern Arizona (Figure 1). The ponderosa pine dominated forests on Mica Mountain in Saguaro National Park (the larger of two major peaks in the Rincon Mountains) have experienced an unusually high frequency of 20th century fires relative to similar forests elsewhere in the United States. Based on 20th century fire maps maintained by the National Park Service (NPS), stands on Mica Mountain have burned at least nine times between 1937 and 2000. Numerous multiple-burn polygons have been mapped and the high spatial and temporal heterogeneity of the documentary fire record provide a variety of fire frequency and extent comparisons with the tree-ring reconstructed fire history. The forests in this designated wilderness area have never been logged commercially or developed, with the exception of a primitive road (now grown over) and two log cabins (ranger stations) constructed at the summit in the early 1900s (Baisan and Swetnam 1990). This combination of extensive tree-ring records, documentary fire records, and a frequently burned landscape provides a rare opportunity to corroborate fire-scar fire history reconstructions against independently derived documentary fire maps.

The primary purpose of our research was to test basic assumptions and analytical approaches used by fire historians to reconstruct landscape-scale fire histories from point-based fire scars. We compared spatial and temporal fire history parameters derived independently from fire-scar data and NPS fire maps to accomplish this goal. We additionally addressed long-standing uncertainties about inferring fire spatial patterns and geographic extents from distributed plots. For this research we assumed ground-mapped fire perimeters within the study area provided sufficiently complete and accurate data to corroborate fire histories reconstructed from fire scars (for reasons we discuss below in more detail).

We sought answers to the following research questions: How effective are fire-scar data at providing a complete inventory of fire years recorded in the documentary data? What is the relationship between fire-scar synchrony and annual area burned? How similar/dissimilar are the reconstructed quantities of burned areas estimated from fire scars and ground-mapped burned areas? How similar/dissimilar are spatially explicit fire frequency maps interpolated from fire scars and documentary perimeter maps? How much do fire frequency summary statistics differ between fire-scar and documentary data and between different methods of calculation? How accurately do intra-annual positions of fire scars represent the timing of past fires as known from documentary records? These questions are designed to address broader issues of spatial and temporal uncertainty associated with the interpretation of point data.

Twentieth Century Documentary Fire Records

The National Park Service (NPS) has maintained detailed records and maps of fires on Mica Mountain since 1937. The intent was to map as many fires as possible and record information about fire size, cause, origin date, and control actions. Older fires less than 30 hectares (ha) were generally mapped as points (at their origin) but most fires greater than 30 ha were mapped as perimeter polygons. These fire records were maintained in a database updated annually, referred to hereafter as the "NPS fire atlas" (Swantek 1999a 1999b, Saguaro National Park 2002). Some large fires prior to the 1990's were ground-mapped by government survey crews or by fire crews immediately after burning. More recent fires were mapped using Global Positioning System (GPS) technology and satellite remote sensing (Henry and Yool 2002). A valuable feature of the NPS fire atlas for our analyses was the abundance of overlapping burn polygons (fire perimeters) representing areas that have burned at different frequencies, from once to as many as nine times between 1937 and 2000.

Although the NPS intended to document all fires that occurred in the Rincon Mountains, it is quite likely that some small lightning-ignited fires, common during the Arizona "monsoon" season (i.e., early July through August), were not recorded. Such small fires were often extinguished by rain before being detected or were not managed or mapped. Another limitation of the NPS fire atlas was that no unburned areas (or severity levels) were mapped within individual fire perimeters (polygons) for most burns. It is known from experience in these forest types that some areas enclosed within mapped perimeters generally remain unburned. The positional accuracy of some small fires mapped as points prior to GPS technology are unknown, but considerable effort was made by NPS personnel to describe in detail the locations of even small fires. All large fire perimeters are considered reasonably accurate (the largest of which were surveyed), but it is quite likely that there are some mapping errors in the database.

Summary of Twentieth Century Fire Occurrence on Mica Mountain

The NPS fire atlas documented 414 fires within the study area between 1937 and 2000 for an average of 6.5 fires/year (Table 1). Multiple fires occurred every year. Total area burned by all fires during the 64 year period was 6,636 ha. Most years had only small fires that burned less than 40 cumulative ha. There were, however, 21 large fires that burned more than 100 ha each (and up to about 1,600 ha) distributed across 12 different fire years. These 12 years accounted for 19% of the 64 fire years during the study period and 97% of the 6,636 ha burned. The overlapping fire perimeters formed multiple-burn polygons consisting of many combinations of individual fire years and extents across the landscape.

Lightning-ignited fires accounted for 93% of all fires and 86% of the total area burned during the study period, consistent with the findings of Baisan and Swetnam (1990). There were six management-ignited prescribed burns that comprised most of the remaining 14% of burned area. Human-caused wildfires accounted for 6% of all fires but less than 1% of total burned area.

Fires on Mica Mountain were managed by the U.S. Forest Service from 1906 to 1933 and by the National Park Service from 1933 to the present. Rugged terrain and poor access in the study area enabled many spring and arid foresummer fires to grow relatively large (>200 ha) before being suppressed. A prescribed natural fire (termed "wildland fire use" today) program was implemented briefly between 1972 and 1994 to allow some lightning ignitions in the wilderness fires to burn under certain conditions. Three lightning fires during this period were allowed to grow to more than 200 ha before being eventually suppressed.

Methods

Study Area Description

The study area is located in the Rincon Mountains in Saguaro National Park Wilderness Area just east of Tucson, AZ, USA (Figure 1). The Rincon Mountains are a Sonoran Desert "Sky Island," rising from the desert floor at an elevation of 940 m to the forested summit of Mica Mountain at 2,641 m. The mountain harbors extensive coniferous forests at the high elevations (Bowers and McLaughlin, 1987). The study area polygon is 2,780 ha and traces the extent of the coniferous forest belt on Mica Mountain. The polygon was delineated prior to field sampling using aerial photography to map the lower forest ecotone. Ponderosa pine (*Pinus ponderosa* P.& C. Lawson) or Arizona pine (*Pinus ponderosa* var. arizonica) is the dominant tree species above 2,100 m. Southwestern white pine (*Pinus strobiformis* Engelm.) is a ubiquitous co-dominant above 2,300 m. Gambel oak (*Quercus gambelii* Nutt.) occurs as isolated individuals or in small clusters on cooler aspects throughout this zone. White fir (*Abies concolor* (Gord. & Glend.) Lindl. ex Hildebr) and Douglas-fir (*Pseudotsuga menziesii* (Mirbel) Franco) form small, isolated mixed conifer stands with ponderosa and Southwestern white pine on some north aspects in the northern part of the study area. Ponderosa pine decreases in dominance at lower elevations and becomes locally absent near the lower study area boundary. Alligator juniper (*Juniperus deppeana* Steud.), border pinyon (*Pinus discolor* D.K. Bailey & Hawksworth), Arizona white oak (*Quercus arizonica* Sarg.), and silverleaf oak (*Quercus hypoleucoides* A. Camus) are common at the lower elevations near the lower forest ecotone (below 2,200 m).

Average annual precipitation varies strongly with elevation, ranging from approximately 33 cm at the base of Mica Mountain (800 m elevation) to approximately 89 cm near the summit at Manning Camp (2,438 m elevation). The seasonal distribution of precipitation is bimodal. About 58% falls as rain between May and September and peaks in July and August during the wet summer monsoon season. The remainder falls as rain or snow between October and March and peaks in December and January. Fire season typically occurs between April and September. Maximum area burned peaks during June, whereas the maximum number of ignitions is in early July, coincident with the monsoon and peak lightning occurrence season (Baisan and Swetnam 1990, Crimmins and Comrie 2004). Most 20th century fires were ignited by lightning (Table 1, Baisan and Swetnam 1990). Lightning fires are common during the monsoon season in July and August but rarely become widespread before being extinguished by rain.

Fire-scar data

We sampled fire scars from sixty 1-ha plots using a two-phase systematic and random sampling approach. The purpose was to provide a uniform distribution of sample plots with variable densities completely independent of the fire atlas. An initial plot was established randomly within the study area. From this plot, a 1.2 km grid was generated with a 45 degree orientation to maximize the number of grid cells within the study area. Twenty-four plots were systematically generated during the first phase within the center of each 1.2 km grid (Figure 1). Thirty-six additional plots were located randomly between initial grid points during the second phase to increase the sampling density and create greater variation in lag distances between points. When plots were located on rock outcrops or barren ground they were moved to the nearest forest stand. Some low elevation grid cells had a lower plot density because forest cover was sparse near the ecotone.

Within each plot we collected 3 to 14 fire-scarred cross sections from living trees and remnant wood (i.e., logs, stumps, snags). Of the 405 fire-scarred cross sections sampled, 202 had tree-ring records encompassing part or all of the corroboration period (1937 to 2000). In many cases we collected all of the fire-scarred material that was present within each 1-ha plot. Where there was an abundance of material, we sampled trees with well-preserved fire scars that provided a combination of records from both young and old specimens to maximize the length and completeness of the temporal record. All cross sections were prepared and cross-dated in the laboratory using standard dendrochronology techniques (Stokes and Smiley 1968). All fire scars were assigned a calendar year, and where possible, an intra-annual ring position to determine the approximate seasonal timing of fires (Dieterich and Swetnam 1984, Baisan and Swetnam 1990).

Because trees may not record (or preserve) all fires that burned the bole, all fire-scar years within individual plots were combined to form a composite master fire chronology for each plot (*sensu* Dieterich 1980). Vegetation and topography were typically homogeneous within the plots, so the composite plot chronologies are reasonably assumed to be relatively complete inventories of fire events within the 1-ha sampling areas during the time spans encompassed by the tree-ring specimens. The composite fire records from each plot were analyzed collectively as a "point," and we made no inference or assumptions about within-plot spatial or temporal heterogeneity. The number of plots capable of recording fires each year (referred to subsequently as "sample depth") was $\geq$57during the analysis period and varied little due to the use of plot-level compositing and the recent time period of the study.

Data Analysis

Fire Year Inventory

A common objective of fire history research is to obtain a complete inventory of fire years within a given area, particularly "major" fire years with widespread burning (Swetnam and Baisan 1996, Van Horne and Fulé 2006). We calculated the proportion of documented fire years in the study area (from the NPS fire atlas) detected by the fire-scar network. To assess how fire-scar detection varied as a function of area burned, we used three different sets of documented fire events: all fire years, years with at least 40 ha burned, and years with at least 100 ha burned.

We constructed a 2x2 error matrix to quantify potential ranges of fire-scar detection error based on the error typology described in Falk (2004). In this case, Type I error occurs when a fire-scar plot within a mapped fire perimeter fails to detect that corresponding fire, and Type II error occurs when a fire-scar year is detected within a plot where there is no documentary fire year shown. Only "extensive fires," which we define here as a mapped fire perimeter large enough to encompass at least two fire-scar plots, were evaluated in the analyses. This is because small "spot" fires were mapped as discrete points with varying spatial accuracy over time, and it would be impossible to determine with any certainty whether plots and mapped spot fires actually intersected at that scale. The failure of fire-scar data to "detect" small fires between sample locations moreover would be due to sampling resolution rather than Type I error.

Combining fire-scar years from multiple samples within a specified area, or a composite fire chronology (*sensu* Dieterich 1980), is assumed to result in a more complete inventory of fire events because not all samples record (or preserve) all fire years. To assess the relative importance of compositing on the detection of extensive fires that burned through each plot, we calculated the proportion of extensive fire-scar years in each plot that required compositing to detect.

Percent Scarring and Area Burned

Annual fire-scar synchrony, or the proportion of sample units (i.e., plots in our study) that record a fire in a given year, has been used widely by fire historians as a relative index of total area burned (e.g., Swetnam 1993, Taylor and Skinner 1998, Morrison and Swanson 1990). We tested this assumption by regressing the percentage of plots scarred annually against the corresponding area burned (ha) documented independently by the NPS fire atlas data. In many fire-scar studies, percent scarring of samples has been sorted – or "filtered" – into categories based on a specified percentage scarring threshold. This is intended to eliminate the influence of "smaller" fires that scar only small numbers of trees. Although any threshold percentage can be used, filtering at the ≥10% and ≥25% level has been reported most widely in the fire history literature to represent larger burns. To assess the validity of this approach for representing relative area burned, we compared the average annual burned area (ha) for fire years in which ≥10% and ≥25% of the plots recorded a scar with the average for all fire years.

Spatial Pattern Interpolation

We used Thiessen Polygon tessellations, known also as Voronoi diagrams (Burrough and McDonnel 1998), to interpolate fire-scar data into spatially explicit fire perimeter maps. Based on spatial autocorrelation inherent in most spatial datasets, the Thiessen Polygon approach rests on the simple assumption that the presence/absence of a fire event at an unsampled location is predicted best by the presence/absence of a fire event at the nearest data point reference. The Thiessen approach was selected for our study for three reasons: First, Thiessen Polygon tessellations closely resemble qualitative, expert knowledge-based techniques used commonly by fire historians whereby perimeters are drawn between scarred and unscarred plots. Second, this approach required the least amount of parameterization and subjective user input, which was important in this study to prevent bias because the fire locations were already known. Third, this approach is well suited for interpolating binary data (such as fire maps) from broadly distributed data points.

Two rules were used to determine which fire-scarred plots were interpolated and how exact fire boundaries were determined: 1) at least two adjacent plots had to be scarred in a given year for a fire to be interpolated, and 2) if a polygon lacking a fire scar in a given year at a centroid plot was 100% surrounded by burned polygons in that year, it was classified as burned. The first rule was conservative and assumed that fire-scar years restricted to single plots or widely separated plots did not burn beyond the plot boundary (or boundaries). The second rule assumed conversely that when a single unscarred plot was completely surrounded by scarred plots, fire burned throughout a significant proportion of the polygon, as in the adjacent polygons. It is likely that unburned areas sometimes occurred within larger burned areas, but the second rule is consistent with assumptions associated with the NPS fire atlas maps (i.e., all areas within NPS mapped polygons were assumed to have burned). Both assumptions were consistent with the overall goal of mapping external perimeters of fires and total areas encompassed, rather than internal heterogeneity (burned and unburned sub-areas) of polygons.

Individual fire perimeters interpolated from fire-scar plots were combined to create a single, spatially explicit fire frequency map for the study area. A similar fire frequency map was created from the NPS fire atlas data and compared with the fire-scar based map. Pearson's cross-correlation coefficient (Zar 1999) was calculated between the two maps to compare the correspondence of fire frequency values (30 m grain). The proportion of the study area occupied by each fire frequency class was compared between fire-scar data (predicted) and NPS fire atlas data (expected) using a two-sample Kolmogorov-Smirnov Test ($\alpha = 0.05$) (Zar 1999).

Annual Area Burned

Annual area burned is an important fire regime parameter and is used to calculate fire frequency statistics such as the Natural Fire Rotation (Agee 1993). Area burned can be estimated using a spatially explicit interpolation procedure such as Thiessen Polygons or spatially implicit procedure such as the relationship between fire size and fire-scar synchrony. The former uses the spatial coherence of scarred plots and the latter assumes each actively recording sample unit represents some fixed proportion of the landscape. We estimated annual area burned from fire-scar data using examples of both approaches: (1) we calculated the area of interpolated Thiessen Polygon fire perimeters described previously, and (2) we assumed the annual percentage of distributed plots scarred in a given year (fire-scar synchrony) was equivalent to the percentage of the study area burned (i.e., 1:1 ratio). We plotted fire-scar estimates of annual area burned against documentary area burned extracted from the NPS fire atlas to assess the relative accuracy of each approach.

Fire Frequency Summary Statistics

The two summary statistics reported most widely in the literature to summarize the fire frequency-area distribution are the composite Mean Fire Return Interval (MFI) and the Natural Fire Rotation (NFR). The composite MFI is the average number of years between fires of any size that occurred within a specified area (Romme 1980). Note that unless otherwise stated, all detected fire years are included in the calculation of the composite MFI regardless of their size. This is because compositing was intended to be used in relatively small or homogenous areas where fire spread is assumed, and/or where any fire is determined to be of significance or interest (Dieterich 1980). It has become customary therefore to add a relative area burned component to the MFI to determine the mean interval between larger fire years. This is done by calculating mean intervals only for fire years that scar a minimum percentage of samples, which has the effect of "filtering out" intervals between presumably smaller and isolated fire years (Swetnam and Baisan 1996). Filtering at the 10% and 25% level is most common, meaning that only intervals of fire years recorded by $\geq$10% or $\geq$25% of recording samples respectively, are used in the calculation. We denote the level of filtering hereafter with a subscript (e.g., $MFI_{10\%}$, $MFI_{25\%}$, or MFI_{all} for "all fire years").

The NFR is defined as the average number of years required to for an area *equivalent* to the study area to burn (e.g., 2,780 ha for the Mica Mountain study area) (Romme 1980, Agee 1993). The value of the NFR is theoretically analogous to the Fire Cycle (Agee 1993), which is estimated from stand age distributions, and the population mean fire interval (*sensu* Baker and Ehle 2001). The NFR is based on cumulative area burned for a specified time period rather than the frequency of fire years.

We compared the fire-scar MFI_{all}, $MFI_{10\%}$, and $MFI_{25\%}$ with the corresponding NPS fire atlas values for the study area. Only scar-to-scar intervals were included for fire-scar calculations because of ambiguity of the period before the first scar (see Van Horne and Fulé 2006). The unfiltered MFI_{all} was directly comparable between fire scars and maps because it is based solely on the presence or absence of any fire year. Filtered MFI values were not directly comparable between datasets because fire-scar data consisted of points whereas fire atlas maps consisted of area polygons. It was necessary therefore to convert point-based fire-scar data to area-based perimeter maps for a standardized comparison. For fire atlas maps, we calculated filtered MFI values for fire years in which $\geq$10% and $\geq$25% of the study area burned. For fire-scar data, we calculated both a point-filtered MFI from fire years in which $\geq$10% and $\geq$25% of the plots burned, and an area-based filtered MFI from fire years in which $\geq$10% and $\geq$25% of the study area burned as determined from fire-scar interpolated perimeter maps

We calculated the study area NFR for each dataset using the following equation:

(1) $NFR = T \div P$

Where *T* was the number of years (1937 to 2000 in this case) and *P* was the cumulative proportion of the study area burned (which can be greater than 100%). We calculated *P* for NPS fire atlas data by directly extracting area burned from GIS fire maps. We calculated *P* for fire-scar data using area burned estimated from both Thiessen polygons fire-scar synchrony ratios. All fire years were used for the latter approach even if they were recorded at only one plot.

Fire Seasonality

The relative intra-annual ring position of fire scars can be used to estimate the approximate seasonal timing of burning (e.g., Dieterich and Swetnam 1984, Baisan and Swetnam 1990, Fulé et al. 2003). The beginning and end date of each large fire was recorded in the NPS fire atlas so we were able to compare the predicted month of occurrence from fire scars with an actual documented month of fire occurrence. We constructed percent frequency histograms for the six fires with the largest number of clear, seasonally dated fire scars to determine if the observed modal ring position corresponded with the expected ring position based on known fire dates and the known tree growth phenology (i.e., timing of cambial growth initiation, rate, and cessation), for conifers in the Southwest (Fritts 1976, Baisan and Swetnam 1994, Craig Allen unpublished data).

Results

<u>Fire Year Inventory</u>

Twenty-seven years were detected by fire scars in the study area between 1937 and 2000, of which 14 were detected at multiple plots (range 2 to 35 plots) and 13 years were detected at only a single plot (Figure 2). The probability of a documented fire year being detected by fire scars increased strongly with increasing area burned: 43% of the 64 documentary fire years were detected by fire scars overall, but 100% of the 12 fire years with >100 ha or burned were detected by multiple plots (Table 2). Fire scars thus provided a complete inventory of all large fire years that resulted in >97% of the total area burned.

The number of actively recording fire-scar plots within each of the 21 mapped fire perimeters ranged from 1 to 39, for a cumulative total of 159 possible detections. Fire scars recorded the corresponding mapped fire 132 (83%) times, with a corresponding Type II error of 17% (Figure 3). This is a maximum (liberal) estimate fire-scar Type II error because in some cases a plot within a perimeter actually may not have burned. There were 6 cases out of a possible 600 in which a plot recorded an extensive fire even though it was located outside of the mapped perimeter. Although this technically constitutes a Type I error of 1%, all six detections were located <100m from the corresponding fire perimeter with the same date, so a false fire-scar detection or tree-ring dating error is unlikely in these cases, and it is more likely that the mapped perimeter was in error.

Compositing the fire-scar years from multiple trees was necessary to ensure a complete record of extensive fires that burned through individual plots, especially in plots that experienced high fire frequency (Table 3). In the 31 plots that recorded only 2 to 3 extensive NPS fire atlas fires, compositing was required to detect all years in 16% (5) cases (i.e., a single tree contained all fire years 84% of the time). However, in the 11 fire-scar plots that recorded ≥4 extensive fires, compositing was required to detect all extensive fire years in 55% (6) of the cases (i.e., a single tree contained all fire years only 45% of the time).

Fire-Scar Synchrony

There was a strong linear relationship between the percentage of fire-scar plots recording a fire year (fire-scar synchrony) and the amount of area burned ($r^2 = 0.96$; $y = 0.0003x + 0.0087$) (Figure 4a). Synchronous scarring of $\geq$2 plots in a given year resulted exclusively from one or more extensive fires that spread between plots; in no case did the simultaneous co-occurrence of small fires result in scars at more than two plots during the same year. In only two years – 1961 and 1964 – did two plots record fires known not to have spread between them (based on the NPS fire atlas data), and only in 1964 were the plots adjacent to each other.

Spatial Patterns of Fire Frequency

There was strong agreement of fire frequency spatial patterns between interpolated fire-scar maps and the NPS fire atlas (Figs. 5 and 6). Pearson's cross correlation between datasets was $r = 0.81$ ($p = 0.001$) reflecting the strong graphical correspondence between maps. Less than 15% of the total area in each map (fire-scar vs. NPS fire atlas estimated) differed by a frequency of more than one fire, and there were no consistent patterns of over- or underestimation that would indicate a strong bias in the fire-scar data or NPS mapped data (Fig 6c). The biggest difference between the predicted and mapped area of any fire frequency class was <5% and overall differences between classes were not statistically significant ($p = 0.97$).

Area Burned Estimation

Estimation of annual area burned from fire scars correlated closely with area burned derived from ground-mapped fire perimeters: $r^2 = 0.97$, $y = 0.819x + 35.5$, for Thiessen polygons; $r^2 = 0.96$, $y = 0.898x + 24.1$, for fire-scar synchrony ratio (Figure 7). As expected with a broadly distributed sampling distribution, results between the Thiessen Polygon and fire-scar synchrony ratio method were quite similar. Both techniques resulted in regression slopes close to 1.0, indicating a nearly 1 to 1 relationship. Given the broad spatial distribution of sample data in this study, spatially explicit interpolation and relativistic extrapolation methods both provided excellent estimates of area burned.

Fire Frequency Metrics

The fire-scar MFI_{all} for the study area was 2.2 years compared to 1.0 year for the NPS fire atlas (Table 4). Although not all fire years were detected by the fire-scar network, the difference in the MFI was small because the value asymptotically approaches 1.0 for large landscapes of this size (Falk 2004, Falk and Swetnam 2003), which is considerably larger than what unfiltered compositing was intended for. Filtered fire-scar MFI values corresponded very closely with the fire atlas values regardless of whether area or point based filtering was used (Table 4). The fire-scar and NPS fire atlas

$MFI_{25\%}$ were identical (25.5 years) because they incorporated the exact same fire years (Table 4). The NPS fire atlas $MFI_{10\%}$was 11 years compared to 9.2 years for comparable area-based fire-scar data. The point filtered fire-scar $MFI_{10\%}$ was slightly lower at 6.9 years because two extra fire years were counted that scarred 10.3% of the plots (points) but just slightly less than 10% of the study area.

The reference NFR calculated from NPS fire atlas maps was 26.8 years and differed by less than 3 years from the fire-scar NFR (Table 4). The interpolated fire-scar NFR was 29.6 years and the fire-scar NFR estimated using fire-scar synchrony (percent scarring) was 23.9 years. This value was slightly lower because, unlike Thiessen Polygon interpolations, we did not filter out fire-scar years that did not scar at least two adjacent plots (this added about 600 ha of cumulative area burned).

Fire Seasonality

The modal intra-annual fire-scar position matched the expected ring position according to the known seasonal occurrence of the fire in all cases (Figure 8). Due to variation in local site conditions, tree phenology, and our ability to visually discern intra-ring scar positions on some samples, each fire exhibited a range of intra-ring positions on samples rather than just a single expected position. Two late season fires that occurred after the monsoon (one lightning-caused and one prescribed burn) resulted in scars exactly on the ring boundary that were incorrectly assigned to the "dormant" position of the following year in a few samples. The positions of most scars those years were correctly assigned to the current year's latewood however, so there was no dating error in terms of assigning the correct calendar year. The 1997 prescribed burn occurred in late November which is well after large lightning fires typically occur in the region.

Discussion

This study is the most comprehensive empirical comparison (to the best of our knowledge) of fire history parameters reconstructed from fire scars and independently mapped fire perimeters yet conducted. Our results demonstrate clearly that broadly distributed fire-scar data can be used to characterize accurately numerous temporal and spatial aspects of past fire occurrence in landscapes. These data provide better understanding of how fire-scar reconstructions reflect patterns of actual fire occurrence across landscapes and provide a robust framework for interpreting historical fire regimes using fire-scar data.

Interpreting the Fire-Scar Record

Reconstructing representative fire histories from fire scars requires an understanding of how fire-scar sampling networks record fire years. Large fires have a much higher probability of being detected by fire-scar networks than smaller fires that are more numerous but burn little cumulative area. This pattern was illustrated clearly on Mica Mountain where every fire year >100 ha was detected by multiple samples compared to only 3.8% of the fire years <100 ha. Fulé et al. (2003) found a similar pattern in Grand Canyon National Park where fire scars provided a complete inventory only for the larger fires in the documentary fire atlas. Moreover, spatially distributed fire-scar data tend to record fire years in relative proportion to the amount of area burned. This was evident by the strong linear correlation between fire-scar synchrony and annual burned area on Mica Mountain. Estimation of fire-scar synchrony has been shown to be robust across a relatively wide range of sample size, sampling designs (e.g. opportunistic versus probabilistic sampling), spatial scales, and geographic settings in pre-settlement Southwestern pine forests (Van Horne and Fulé 2006, Farris 2009 Appendix C, and Farris et al. submitted). The results of this study thus provide strong empirical support for two key assumptions used by fire historians to reconstruct fire frequency parameters: (1) fire-scar synchrony is an accurate proxy for annual area burned, and (2) filtering based on scarring percentage provides a meaningful relative index of major fire years by eliminating small fires. Our results also confirmed that compositing increases the likelihood of obtaining complete inventories of major fire years in sampled stands even though individual trees are imperfect recorders. Compositing was particularly useful in areas with the highest fire frequencies and/or short-interval fire years where scar formation and retention could be quite variable (Collins and Stephens 2007).

Minnich et al. (2000) argued that the relationship between fire-scar synchrony and annual area burned is equivocal because numerous small fires may scar trees at multiple sample locations in the same year. They speculated that, in the Sierra San Pedro Mártir in northern Mexico, small “spot” fire (<5 ha) densities in mixed conifer forests may approach 1 per ha over a 52 year period (the estimated NFR), which might result in multiple fire scars from small fires in the same year. A conservative estimate of “spot” fire density on Mica Mountain based on the NPS atlas would be about 1 per 8 ha during a similar 52-year period. The actual value is likely higher due to unmapped monsoon season ignitions. If Minnich et al.'s (2000) point were applicable, we would expect to see numerous small fires recorded in separate sample locations given the large sample size and high ignition and lightning density on Mica Mountain and the Southwest (Allen 2002). We instead found that synchronous scarring at more than two sites resulted exclusively from widespread fires that burned between plots (as indicated in the NPS atlas). Only twice did the same fires-scar year in separate plots result from individual small burns (1 and 5 ha, respectively), and in only one of those cases were the scarred plots adjacent to each other (it is possible also that the fire atlas map was incorrect and the fire did spread between plots). This is not an artifact of the suppression era because multiple, non-adjacent fire scars were equally rare in this dataset prior to 1900 and also with targeted samples (Baisan and Swetnam 1990). These results are consistent with Stephens et al. (2003), who found that widespread fire years scarred at the 25% filter level generally corresponded with large fire frequencies reconstructed from aerial photos during the same period in the Sierra San Pedro Mártir.

Based upon our observations and logic, we posit that there are at least five reasons why small fires at multiple sample locations in the same years are highly unlikely to result in an overestimation of large fire extent or frequency from fire-scar data. First, small fires would have to occur (and be detected) at many separate sample locations in a given year to result in a significant misclassification of area burned. In simulations with our dataset (not shown) we found that this would typically involve 10 to 25% or more of the sample locations recording separate small fires in a given year, or 6 to 15 plots. The occurrence of multiple small fires at just two or three plots in the same year (assuming they are recorded) would not appreciably influence estimation of cumulative area burned or resultant area-based summary statistics such as the NFR. Second, such high rates of small-fire synchrony at multiple plots would have to occur *repeatedly* over many years to result in any meaningful bias (i.e., only one or two years with numerous plots scarred by small fires would have relatively little influence statistically). Third, widespread fires are typically recorded by adjacent fire-scar samples and are clearly clustered spatially, making them easily distinguishable as spreading fires rather than multiple small fires. Fourth, we observed that the same groups and combinations of plots tended to record the widespread fire years repeatedly over time (and often the same, multiple-scarred trees within those plots). The probability that small, spatially discrete fires would (a) repeatedly burn in the same random/systematic plots *and* (b) form scars on the same trees is exceedingly small. Finally, because scale dependence is very strong for small fires but decreases significantly with increasing fire size, large fires are on average disproportionately more common at fine scales where scar formation actually occurs (Falk et al. 2007, Farris 2009 Appendix B). This ensures that filtering of cross-dated fire-scar year will effectively discriminate between isolated small fires and large burns.

Spatial Patterns of Fire Occurrence

There was very strong spatial agreement between fire frequency maps interpolated from fire-scar data and the NPS fire atlas. Relatively few fire history studies to date have used fire-scar data to quantify spatially explicit patterns of surface fire frequency (but see Everett et al. 2000, Heyerdahl et al. 2000, Niklasson and Granström 2000, Taylor and Skinner 2003, Jordon et al. 2005, Iniguez et al. 2008). The results of this study suggest that spatially explicit inferences from distributed fire-scar data may be more robust than recognized previously (Hessl et al. 2007). Unlike high severity fires that create distinct evidence of fire perimeters in tree or shrub size/age structures (Turner and Romme 1994, Johnson and Gutsell 1994, Minnich et al. 2000), discrete boundaries of low intensity surface fires are generally not discernable more than a few years after burning (a pattern we observed in the field repeatedly). Spatial patterns of low intensity surface fires may be impossible to reconstruct to annual resolution from aerial photos in contemporary landscapes because overlapping burns or adjacent short-interval burns often occur between aerial photo flights (Stephens et al. 2003). There were six major overlapping surface fires on Mica Mountain between available aerial photo sets that would have been missed using repeat aerial photo interpretation methods employed by Minnich et al. (2000). Given these considerations, we suggest fire-scar data not only are useful but are necessary to accurately characterize long-term spatial variation in frequent surface fire regimes.

We attribute the high corroboration between interpolated fire-scar maps and NPS fire atlas maps in this study to several factors. First, our sampling network was well-distributed spatially which improved the accuracy and precision of interpolated fire boundaries between burned and unburned plots (see Van Horne and Fulé 2006 and Farris et al. submitted for a comprehensive empirical analysis of the effects different spatial sampling strategies). Second, plot-level compositing reduced Type II error which increased the quality (completeness) of interpolation data points. Third, the high quality of the NPS fire atlas reduced potential mismatches between the datasets that may result from mapping errors in the "reference" data (Shapiro-Miller et al. 2007). The Saguaro National Park fire atlas may be relatively unique compared to many other atlases in terms of the long temporal consistency and high accuracy and completeness of intensive mapping efforts. Finally, there was a well-defined area of inference (study area boundary) that provided a clear interpolation border to reduce potential edge effects.

We found a much stronger correlation between interpolated fire-scar perimeters and mapped fires in our study than Collins and Stephens (2007), who reported that fire-scar data generally underestimated fire extent and area in their study area. This was likely because they used a more conservative interpolation procedure (convex hulls assume no fire spread beyond the outermost points), their fire-scar data were less densely and evenly distributed and consisted of individual tree sample units (many of their samples were based on stratification of mapped burn frequency), and possibly because of differences in the fire atlas quality (particularly for older fires), which is typical across multiple management units (Shapiro-Miller et al. 2007, Morgan et al. 2001).

A broad distribution of fire-scar samples (assuming they are present) combined with relatively simple nearest neighbor assumptions and interpolation rules such as Thiessen Polygons appear robust for reconstructing complex spatial burn patterns of fire frequency. The demonstrated efficacy of this fire perimeter interpolation approach is a reflection of strong spatial autocorrelation inherent in fire spread and the resultant formation of synchronous fire scars. More complex geostatistical procedures are available for interpolating point-based fire-scar data and may produce smoother surfaces (e.g., Jordan et al. 2005, Hessl et al. 2007), but they have not been tested empirically against independent reference data and it is unknown whether they result in a significant increase in accuracy, particularly given the relatively coarse resolution of most fire perimeter interpolations (as we discuss below in more detail). Moreover, most linear interpolation methods for binary data can be expected to perform similarly when sample size is high and/or area burned is dominated by relatively widespread fires (Burrough and McDonnel 1998).

Any spatial interpolation from point data is subject to a minimum interpretable mapping resolution, below which the actual spatial pattern is unknown or indistinguishable from noise or error. This resolution is largely a function of sample density and quality (i.e., completeness or reliability of the fire record at each data point). One useful measure of resolution is the minimum mapping unit (MMU), defined as the smallest map element that can be reasonably detected (Quattrochi and Goodchild 1997). A minimum estimate of the MMU for interpolated fire-scar maps in this study area would be twice the average density of samples because at least two adjacent plots were required to determine if a fire spread between them. Given an average sample density of 1 plot per 46 ha on Mica Mountain during the study period, a conservative estimate of interpolation MMU might therefore be approximately 92 ha (on average). As we have shown, this resolution is sufficient to detect distinct spatial patterns of fire frequency in our study area and is adequate to address most landscape-scale research and management applications.

It should be noted also that issues of resolution, data quality and uncertainty are inherent in all fire history data sets, including fire atlas maps (Morgan et al. 2001, Shapiro-Miller et al. 2007). Recent remote sensing approaches eventually may increase the spatial and attribute resolution of mapped fire history data, but obviously only for contemporary fire events where instrumental measurements are available (Key and Benson 2002, Miller and Thode 2007).

Fire Frequency Statistics: “Accuracy” and Implications

Given the strong spatial and temporal corroboration between fire scars and mapped fire perimeters in our study, it is not surprising that fire frequency summary statistics were so similar between the two data sources. Compared to the NPS fire atlas, the fire-scar NFR differed by less than 3 years and the fire-scar MFI estimates differed by 0 to 4 years depending on the level of filtering and methodology. This difference is not large enough to substantially affect ecological interpretations or management implications in the study area. These results show that fire-scar sampling networks can accurately represent a wide range of metrics to summarize distinctly different aspects of the fire frequency-area distribution.

Our results illustrate also how the value and interpretation of different fire frequency statistics can differ for the same set of known fire events. This has important implications because much of the debate and confusion about fire-scar based fire histories can be traced to incongruent statistical comparisons and interpretations of different summary statistics. It has been argued, for example, that fire-scar fire histories are "biased" because they give undue importance to small fires that are frequent but burn little cumulative area, but those conclusions have been based largely on inappropriate comparisons between the unfiltered composite MFI_{all} and NFR (see Minnich et al. 2000, Baker and Ehle 2001, 2003, Kou and Baker 2006). The MFI_{all} however is not designed to measure cumulative area burned like the NFR. Given the clear and contrasting definition of the two metrics (Romme 1980), we submit that differences between them do not demonstrate a fire-scar bias but an interpretation error (Stephens et al. 2003, Fulé et al. 2003, Parsons et al. 2007). The results of our empirical corroboration demonstrate clearly that (a) fire-scar data can produce accurate estimates of NFR and large fire frequency when that is the objective and (b) statistical influence of small fires on interval estimation can be effectively eliminated through filtering. Other empirical comparisons between fire-scar data and fire atlas maps have demonstrated in fact that fire-scar data often *under*estimate large fire extent and cumulative area burned (and resultant NFR calculation) due to unrecorded fires (see also Shapiro-Miller et al. 2007, Collins and Stephens 2007)..

The relationship between the MFI and NFR can be complex (Stephens et al. 2003, Kou and Baker 20006, Van Horne and Fulé 2006, Collins and Stephens 2007, Farris 2009 Appendix B) and neither measure is appropriate for all circumstances or objectives. Attempts to equate or convert directly between them may lead potentially to misleading conclusions about fire occurrence and management implications rather than clarification. For example, Baker and Ehle (2001, 2003) proposed correction factors to "convert" published values of the MFI_{all} closer to what they believed true NFRs for those stands might be (although empirical values were unknown). Based on that analysis they suggested pre-settlement NFRs in western ponderosa pine forests ranged from a median of 52 years at the low end to 170 years at the high end (overall range 22 to 308 years) and that prescribed burning at intervals shorter than 20 years lacked sound scientific basis (Baker and Ehle 2003). Our empirical corroboration does not support those conclusions. Even the 20th century, fire suppression era NFR of 27 years on Mica Mountain falls at the lowest range of "corrected" pre-settlement (<1900) era values proposed by Baker and Ehle (2001). Applying the same methodologies tested successfully in this study, Farris et al. (submitted) calculated a pre-settlement NFR of 9 to 11 years on Mica Mountain and two other study sites in the Southwest, which are less than half the value of the lowest "corrected" value by Baker and Ehle (2001) (and 5 times lower than the estimated lower median). These values not surprisingly are consistent with large fire intervals (i.e., ≥25% filter level) reported throughout the region: the median $MFI_{25\%}$ for 63 ponderosa pine and pine-dominated mixed conifer forests in the Southwest (including Mexico) was 12.7 years (Swetnam and Baisan 1996). Fires of this size are accurately and completely inventoried with fire-scar data and have the strongest influence on the NFR (see also Stephens and Skinner 2003, Van Horne and Fulé 2006, Collins and Stephens 2007). Moreover, Van Horne and Fulé (2003) and Farris et al. (submitted) found little difference between systematic, random or targeted pre-settlement intervals estimates of widespread fire (>25%) intervals in northern Arizona ponderosa pine. We conclude that direct conversions between different fire history statistics conflate their interpretation and may lead to erroneous conclusions (Stephens et al. 2003). A more prudent approach would be to reanalyze original data (if possible) or to restrict new inferences in a manner consistent with the limitations of the existing and intended definitions of fire history statistics (Romme 1980).

It was not our intent to argue that any single summary statistic (e.g., MFI or NFR) is best for all scales or applications. All summary statistics have advantages and disadvantages depending on the research objectives, available data, scale of analysis, and aspect of the fire frequency-area distribution one wishes to emphasize. Our purpose instead was to assess the relative "accuracy" of individual metrics reconstructed from fire scars by way of empirical corroboration with independently mapped fire perimeters. Given the strong empirical agreement between fire-scar data and mapped fires, we agree with Fulé et al. (2003) and Veblen (2003) that multiple statistics should be presented to provide the most complete picture and interpretation of fire occurrence at multiple scales and resolutions within a study area. In our study area, for example, one could determine from the various statistics in Table 4 that an area equivalent to the study area was burned approximately every 27 years on average. Fires that burned at least 10% of the sampled plots or study area occurred every 6.7 to 9.2 years on average respectively, and fires that burned at least 25% of the plots or study area occurred every 25.5 years. Although a fire occurred somewhere in the study area every year, the number of fires occurring within individual 1-ha sampling plots during the 64 year study period ranged from 0 to 9. When examined in tandem with mapped representations (Figure 6), distinctive spatial patterns of multi-decadal fire frequency become evident, such as highest fire frequencies at the summit of Mica Mountain, and lower frequencies at lower elevations (similar patterns can be detected from simpler analyses of scarred sample locations and/or master fire chronology charts). Examining multiple statistics in tandem should lead to a clearer and more traceable interpretation of fire frequency characteristics, including analytical assumptions and uncertainties.

<u>Fire Seasonality</u>

Interest in using fire-scar data to determine fire seasonality has increased in recent years as more research has focused on regional fire-climate variation and long-term influences of climate change on fire occurrence (Grissino-Mayer and Swetnam 2000, Grissino-Mayer et al. 2004, Swetnam and Anderson 2008). Our empirical results reaffirm the strong relationship between intra-annual ring position of fire scars and seasonal fire occurrence in the Southwest. Fulé et al (2003) found a similarly strong agreement between documentary fire years and empirical fire-scar ring positions in northern Arizona. Together, these studies demonstrate that long-term analyses of fire seasonality have an accurate basis in tree physiology. It should be noted however that the cambial phenology of ponderosa pine and a few other tree species has been relatively well studied in the Southwest (e.g. Fritts et al, 1976, Baisan and Swetnam 1994, Allen unpublished). Such detailed phenology data may be lacking in other regions and tree species. Given the increasing interest in broad-scale geographic variation in seasonal fire occurrence, similar comparisons between tree-growth and intra-annual scar positions in other regions would be very useful.

Additional Considerations

This study provided a rare opportunity to compare fire-scar data with independent, annually resolved fire maps in a frequently burned landscape. The Saguaro National Park fire atlas contains a relatively detailed and consistent record for the 64 year study period, but it cannot be considered to be the unconditional “truth.” All data types of significant temporal length and spatial coverage available to us contain varying levels of resolution and uncertainty. Hence, in some ways the comparison of fire-scar data with historical mapped fire perimeter data is also a test of the accuracy and precision of the fire atlas data. The strength of the spatial and temporal corroboration between fire-scar data and the NPS fire atlas suggests both datasets are relatively accurate representations of the 20th century fire history at the resolution and scale analyzed.

This research represents a single case study in one forest type – a circumstance that is true of all site-specific fire history research, and a great other many ecological studies. However, the climate, topography, forest and fire environment on Mica Mountain is qualitatively similar to many “Sky Island” pine forests throughout the Southwest borderlands. The similarity of pre-settlement ponderosa and mixed conifer fire regimes in these mountain ranges is supported by the broad similarity in fire history statistics (i.e., MFIs, filtered and unfiltered) from more than 30 sites of similar size and forest type in this region (Baisan and Swetnam 1990, Swetnam 2005, Iniguez et al. 2008).

Finally, from a fire history perspective we conclude the 20th century fire regime on Mica Mountain provides an especially rigorous test-bed for accuracy testing of fire-scar based estimates of fire frequency and spatial fire pattern. Our dataset indicates that prior to 1900 large fires were considerably more frequent and extensive than during the test period. The largest fire during the 20th century, for example, would have been only the ninth largest fire reconstructed during the 19th century (Farris et al. submitted). There is also strong evidence of more spatial clustering and variability in fire frequency during the 20th century than the 19th century, as evidenced by the fact that some areas burned nine times and others not at all. Had documentary fire maps of the typically larger 19th century fires been available for comparison, we believe that corroboration with the fire-scar record would be even stronger and more robust because widespread fires are inventoried more completely and accurately. We conclude that the analytical methods tested in this study are very appropriate for reconstructing historical fire occurrence during the pre-settlement era.

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References

Agee, J.K. 1993. Fire ecology of Pacific Northwest forests. Island Press, Washington, D.C.

Allen, C.D. Unpublished data. Tree growth monitoring in Bandelier National Monument, New Mexico.

Allen, C.D. 2002. Lots of lightning and plenty of people: An ecological history of fire in the upland southwest. *In* Western Wilderness: Fire, Native Peoples, and the Natural Landscape. Island Press, Covelo, CA. pp. 143-193.

Baker, W.L. and D. Ehle. 2001. Uncertainty in surface-fire history: the case of ponderosa pine forests in the western United States. Canadian Journal of Forest Research 31: 205-1226.

Baker, W.L. and D. Ehle. 2003. Uncertainty in fire history and restoration of ponderosa pine forests in the western United States. *In* Conference proceedings: fire, fuel treatments, and ecological restoration. *Edited by* P.N. Omi and L.A. Joyce. USDA Forest Service, RMRS-P-29. Fort Collins, CO. pp. 319-334.

Baisan, C.H. 1994. Dendromenter data for ponderosa pine in southern Arizona. Technical report on file, Laboratory of Tree-Ring Research, The University of Arizona, Tucson, AZ 85721.

Baisan, C.H. and T.W. Swetnam. 1990. Fire history on a desert mountain range: Rincon Mountain Wilderness, Arizona, U.S.A. Canadian Journal of Forest Research 20: 1559-1569.

Baisan, C.H. and T.W. Swetnam. 1994. Assessment of phonological growth patterns in four coniferous species, Rhyolite Canyon, Chiricahua National Monument. Technical report on file at the Laboratory of Tree-Ring Research, University of Arizona, Tucson.

Baisan, C. H., and T.W. Swetnam. 1995. Historical fire occurrence patterns in remote mountains of Southwestern New Mexico and northern Mexico. Pages 153-156 *in* J. K. Brown, R.W. Mutch, C.W. Spoon, and R.H. Wakimoto, editors. Proceedings: Symposium on Fire in Wilderness and Park Management. Missoula, MT, March 30-April 1, 1993. General Technical Report INT-GTR-320. USDA Forest Service, Intermountain Research Station.

Bowers, J. E. and S.P. McLaughlin. 1987. Flora and vegetation of the Rincon Mountains, Pima County, Arizona. Desert Plants 8(2): 50-94

Brown, P.M., M.W. Kaye, L.S. Huckaby, and C.H. Baisan, C.H. 2001. Fire history along environmental gradients in the Sacramento Mountains, New Mexico: Influences of local patterns and regional processes. Écoscience 8:115-126.

Brown, P.M. and R. Wu. 2006. Climate and disturbance forcing of episodic tree recruitment in a southwestern ponderosa pine landscape. Ecology 86(11): 3030-3038.

Burrough, P.A. and R.A. McDonnel. 1998. Principles of geographic information systems (2nd edition). Clarendon Press, Oxford, England.

Collins, B.M. and S.L. Stephens. 2007. Fire scarring patterns in Sierra Nevada wilderness areas burned by multiple wildland fire use fires. Fire Ecology 3(2):53-67.

Crimmins, M.A. and A.C. Comrie. 2004. Wildfire-Climate Interactions Across Southeast Arizona. International Journal of Wildland Fire 13:455-466.

Dieterich, J.H., 1980. The composite fire interval—a tool for more accurate interpretation of fire history. Pages 8-14 *in* M.A. Stokes and J.H. Dieterich., editors. Proceedings of the fire history workshop, USDA Forest Service. *In* Proceedings of the fire history workshop. General Technical Report RM-GTR-81. USDA Forest Service, Rocky Mountain Research Station.

Dieterich, J. H., and Swetnam, T.W. 1984. Dendrochronology of a fire scarred ponderosa pine. Forest Science 30(1):238-247.

Everett, R.L., R. Schellhaas, D. Keenum, D. Spurbeck, and P. Ohlson. 2000. Fire history in the ponderosa pine/Douglas-fir forests on the east slope of the Washington Cascades. Forest Ecology and Management 129:207-225.

Falk, D.A. 2004. Scaling rules for fire regimes. PhD. Dissertation. University of Arizona, Tucson.

Falk, D. A. and T.W. Swetnam. 2003. Scaling rules and probability models for surface fire regimes in ponderosa pine forests. Pages 301-318 *in* P.N. Omi and L.A. Joyce, editors. Conference proceedings: fire, fuel treatments, and ecological restoration. Proceedings RMRS-P-29. USDA Forest Service.

Falk, D.A., C. Miller, D. McKenzie, and A.E. Black. 2007. Cross-scale analysis of fire regimes. Ecosystems 10:809-823.

Farris, C.A. 2009. Spatial and temporal validation of fire-scar fire histories. PhD. Dissertation. University of Arizona, Tucson.

Farris, C.A., M.L. Van Horne, C.H. Baisan, D.A. Falk, P.Z. Fulé, and T.W. Swetnam. Submitted. Targeted fire-scar sampling can accurately and efficiently estimate past fire regime parameters in Southwestern ponderosa pine forests. Canadian Journal of Forest Research.

Fulé, P.Z., T.A. Henlein, W.W. Covington, and M.M. Moore. 2003. Assessing fire regimes on Grand Canyon landscapes with fire scar and fire record data. International journal of Wildland Fire 12(2):129-145.

Fulé, P. Z., J. Villanueva-Díaz, and M. M. Ramos-Gómez. 2005. Fire regime in a conservation reserve in Chihuahua, Mexico Canadian Journal of Forest Research 35 (2): 320-330.

Fritts, H. C. 1976. Tree Rings and Climate. Academic Press, London.

Grissino-Mayer, H. D. and T.W. Swetnam. 2000. Century scale changes in fire regimes and climate in the Southwest. The Holocene 10(2):207-214.

Grissino-Mayer, H.D., W.H. Romme, M.L. Floyd, and D.D. Hanna. 2004. Climatic and human influences on fire regimes of the southern San Juan Mountains, Colorado, USA. Ecology 85: 1708-1724.

Henry, M.C. and S.R. Yool. 2002. Characterizing fire-related spatial patterns in the Arizona sky islands using Landsat TM data. Photogrammetric Engineering and Remote Sensing 68 (10):1011-1019.

Hessl, A., J. Miller, J. Kernan, D. Keenum, and D. McKenzie. 2007. Mapping paleo-fire boundaries from binary point data: comparing interpolation methods. The Professional Geographer 59(1):87-104.

Heyerdahl, E.K. and E. Alvarado. 2003. Influence of climate and land use on historical surface fires in pine-oak forests, Sierra Madre Occidental, Mexico. *In* Fire and climatic change in temperate ecosystems of the western Americas. Springer-Verlag, New York, NY. pp.196-217.

Heyerdahl, E.K., L.B. Brubaker, and J.K. Agee. 2001. Spatial controls of historical fire regimes: a multiscale example from the Interior West, USA. Ecology 82:660-678.

Iniguez, J.M., T.W. Swetnam, and S.R. Yool. 2008. Topography affected landscape fire history patterns in southern Arizona, USA. Forest Ecology and Management 256:295-303.

Johnson, E.A. and S.L. Gutsell. 1994. Fire frequency models, methods and interpretations. Advances in Ecological Research 25:239-287.

Jordan, G.J., M-J. Fortin, and K.P. Lertzman. 2005. Assessing Spatial Uncertainty Associated with Forest Fire Boundary Delineation. Landscape Ecology 20(6):719-731.

Key, C.H. and N.C. Benson. 2002. Measuring and remote sensing of burn severity. In J.L. Coffelt and R.K. Livingston, U.S. Geological Survey Wildland Fire Workshop, Los Alamos, NM October 31-November 3, 2000. USGS Open-File Report 02-11. p 55.

Kou, X, and W.L. Baker. 2006. A landscape model quantifies error in reconstructing fire history from scars. Landscape Ecology 21(5):735-745.

Miller, J.D. and A.E. Thode. 2007. Quantifying burn severity in a heterogeneous landscape with a relative version of the delta Normalized Burn Ratio (dNBR). Remote Sensing of Environment 109(1): 66-80.

Minnich, R. A., M.G. Barbour, J.H. Burk, J. H., and J. Sosa-Ramírez. 2000. California mixed-conifer forests under unmanaged fire regimes in the Sierra San Pedro Mártir, Baja California, Mexico. Journal of Biogeography 27: 105-129

Morgan, P., C. Hardy, T.W. Swetnam, M.G. Rollins, and D.G. Long. 2001. Mapping fire regimes across time and space: Understanding coarse and fine-scale patterns. International Journal of Wildland Fire 10 (3-4): 329-342.

Morrison, P.H. and F.J. Swanson. 1990. Fire history and pattern in a Cascade landscape. Pacific Northwest Research Station, USDA Forest Service, PNW-GTR-254.

Niklasson, M. and A. Granström. 2000. Numbers and sizes of fires: Long-term spatially explicit fire history in a Swedish boreal landscape. Ecology 81:1484–99.

Parsons R.A., E.K. Heyerdahl, R.E. Keane, B. Dorner, and J. Fall. 2007. Assessing the accuracy of surface fire histories: Simulation modeling of point fire frequency across landscapes. Canadian Journal of Forest Research 37:1605-1614.

Quattrochi, D.A. and M. Goodchild. (eds.). 1997. Scale in remote sensing and GIS. CRC Press, Boca Raton, Fl.

Rollins, M.G, T.W. Swetnam, and P. Morgan. 2001. Evaluating a century of fire patterns in two Rocky Mountain wilderness areas using digital fire atlases. Canadian Journal of Forest Research 31(12): 2107-2123.

Romme, W.H. 1980. Fire history terminology: report to the ad hoc committee. *in* M.A. Stokes and J.H. Dieterich, J.H. Proceedings of the fire history workshop. General Technical Report RM-GTR-81. USDA Forest Service.

Saguaro National Park. Fire and resource management database. On File, 3693 South Old Spanish Trail, Tucson, Arizona 85730

Shapiro-Miller, L.B., E.K. Heyerdahl, and P. Morgan. 2007. Comparison of fire scars, fire atlases, and satellite data in the northwestern United States. Canadian Journal of Forest Research 37:1933-1943.

Sherriff, R.L. and T.T. Veblen. 2007. A spatially explicit reconstruction of historical fire occurrence in the ponderosa pine zone of the Colorado Front Range. Ecosystems 9:1342-1347.

Stephens, S.L., C.N. Skinner, and S.J. Gill. 2003. Dendrochronology-based fire history of Jeffrey pine-mixed conifer forests in the Sierra San Pedro Mártir, Mexico. Canadian Journal of Forest Research 33:1090-1101.

Stokes, M.A. and T.L. Smiley. 1968. An introduction to tree-ring dating. University of Chicago, Chicago.

Swantek, P. J., W.L. Halvorson, and C.R. Schwalbe. 1999a. Analysis of fire history in Saguaro National Park using geographic information systems. George Wright Society Biennial Proceedings 10:121-124.

Swantek, P. J., W.L. Halvorson, and C.R. Schwalbe. 1999b. GIS database development to analyze fire history in southern Arizona and beyond: an example from Saguaro National Park. U.S. Geological Survey, Cooperative Park Studies Unit, University of Arizona, Tucson. Tech. Report No. 61. 43 p.

Swetnam, T. W. 1993. Fire history and climate change in giant sequoia groves. Science 262:885-889.

Swetnam, T. W. 2005. Fire histories from pine-dominant forests. Rocky Mountain Research Station. Rocky Mountain Research Station. Pages 35-43 *in* G.L. Gottfried, B.S. Gebow, L.G. Eskew, and C.B. Edminster, editors. Proceedings of the Conference: Biodiversity and Management of the Madrean Archipelago II: Connecting Mountain Islands and Desert Seas, Tucson, AZ, May 11-15. General Technical Report RMRS-P-36. USDA Forest Service.

Swetnam, T. W. and C.H. Baisan. 1996a. Historical fire regime patterns in the Southwestern United States since AD 1700. Pages 11-32 *in* C.D. Allen, editor. Proceedings of the Second La Mesa Fire Symposium, Los Alamos, New Mexico, March 29-31. General Technical Report RM-GTR-286. USDA Forest Service.

Swetnam, T. W. and C.H. Baisan. 1996b. Fire histories of montane forests in the Madrean Borderlands. Rocky Mountain Research Station. Pages 15-36 *in* P.F. Ffolliott, L.F. DeBano, M.B. Maker, Jr., G.J. Gottfried, G. Solis-Garza, C.B. Edminster, D.G. Neary, L.S. Allen, editors. Effects of fire on Madrean Province Ecosystems, A symposium proceedings. General Technical Report RM-GTR-289. USDA Forest Service.

Swetnam, T.W. and R.S. Anderson. 2008. Fire climatology in the western United States: Introduction to special issue. International Journal of Wildland Fire 17:1-7.

Swetnam, T.W., C.D. Allen, and J.L. Betancourt. 1999. Applied Historical Ecology: Using the Past to Manage for the Future. Ecological Applications 9(4):1189-1206.

Taylor, A.H. and C.N. Skinner. 1998. Fire history and landscape dynamics in a late-successional reserve, Klamath Mountains, California. Forest Ecology and Management 111:285-301.

Taylor, A.H. and C.N. Skinner. 2003. Spatial patterns and controls on historical fire regimes and forest structure in the Klamath Mountains. Ecological Applications (13(3):704- 719.

Turner, M.G., R.H. Gardner, and R.V. O'Neill. 2001. Landscape Ecology in Theory and Practice. Springer-Verlag, New York, NY.

Turner, M.G. and W.H. Romme. 1994 Landscape dynamics in crown fire ecosystems. Landscape Ecology 9(1):59–77

Van Horne, M.L. and P.Z. Fulé. 2006. Comparing methods of reconstructing fire history using fire scars in a southwestern USA ponderosa pine forest. Canadian Journal of Forest Research 36(4):855-867

Veblen, T.T. 2003. Key issues in fire regime research for fuels management and ecological restoration. Pages 259-276 *in* P.N. Omni and L.A. Joyce, editors. Fire, fuel treatments, and ecological restoration; conference proceedings. General Technical Report RMRS-P-29. USDA Forest Service.

Zar, Jerrold H. 1999. Biostatistical Analysis. 4th Edition. Prentice-Hall, Inc., Upper Saddle River, NJ.

Table 1. Summary of documentary fire occurrence records for the 2780 ha Mica Mountain study area from 1937 to 2000 (based on the National Park Service Fire Atlas).

Total Number of Fire Years	64
Total Number of Individual Fires	414
Lightning	383
Human	25
Prescribed Burns	6
Total Area Burned (ha)	6,636
Lightning	5,697
Human	10
Prescribed Burns	929
Mapped Fire Perimeters >100 ha	21
Lightning Ignited Wildfires	16
Prescribed Burns	5

Table 2. Number of fire years documented in the National Park Service fire atlas that were detected by fire-scar plots.

Annual Area Burned Filter	Documentary Fire Years	Detected by Fire Scars: At Least One Plot	Detected by Fire Scars: At Least Two Plots
All fire years	64	27 (42%)	14 (22%)
Fires Years With ≥40 ha Burned	16	13 (81%)	12 (75%)
Fires Years With ≥100 ha Burned	12	12 (100%)	12 (100%)

Table 3. Proportion of plots where compositing was required to identify all extensive fire years within a plot. Extensive fires are defined as fires large enough to have spread across multiple plots.

Frequency of Extensive Fire-Scar Years in a Plot	Number of Plots	Compositing Required
2-3	31	26 (84%)
≥4	11	5 (45%)

Table 4. Comparison of composite scar-to-scar Mean Fire Return Intervals (MFI) filtered at different levels and Natural Fire Rotation (NFR) for the Mica Mountain study area estimated from the NPS Fire Atlas and fire-scar data.

		Area-Based Calculation [b]		Point-Based Calculation [c]
Fire Frequency Metric	Time Period [a]	NPS Atlas	Fire Scars	Fire Scars
Composite MFI (s.e.)				
MFI_{all}	1943-1998	1.0 (0.0)	2.2 (0.4)	2.2 (0.4)
$MFI_{10\%}$	1943-1998	11.0 (4.0)	9.2 (3.6)	6.9 (3.2)
$MFI_{25\%}$	1943-1994	25.5 (15)	25.5 (15)	25.5 (15)
Natural Fire Rotation (NFR)	1937-2000	26.8	29.6	23.9

[a] Time period between the first and last fire scar for MFI calculations.
[b] Filtered MFIs for fire atlas data were calculated based on the percentage of *area* burned. Filtered fire-scar MFIs and the NFR were calculated using area-based Thiessen Polygon interpolations for a standardized comparison.
[c] Filtered fire-scar MFIs and the NFR were calculated using the percentage of plots scarred

Figure 1. Location of the Mica Mountain study area and fire-scar plots in Saguaro National Park, southern Arizona.

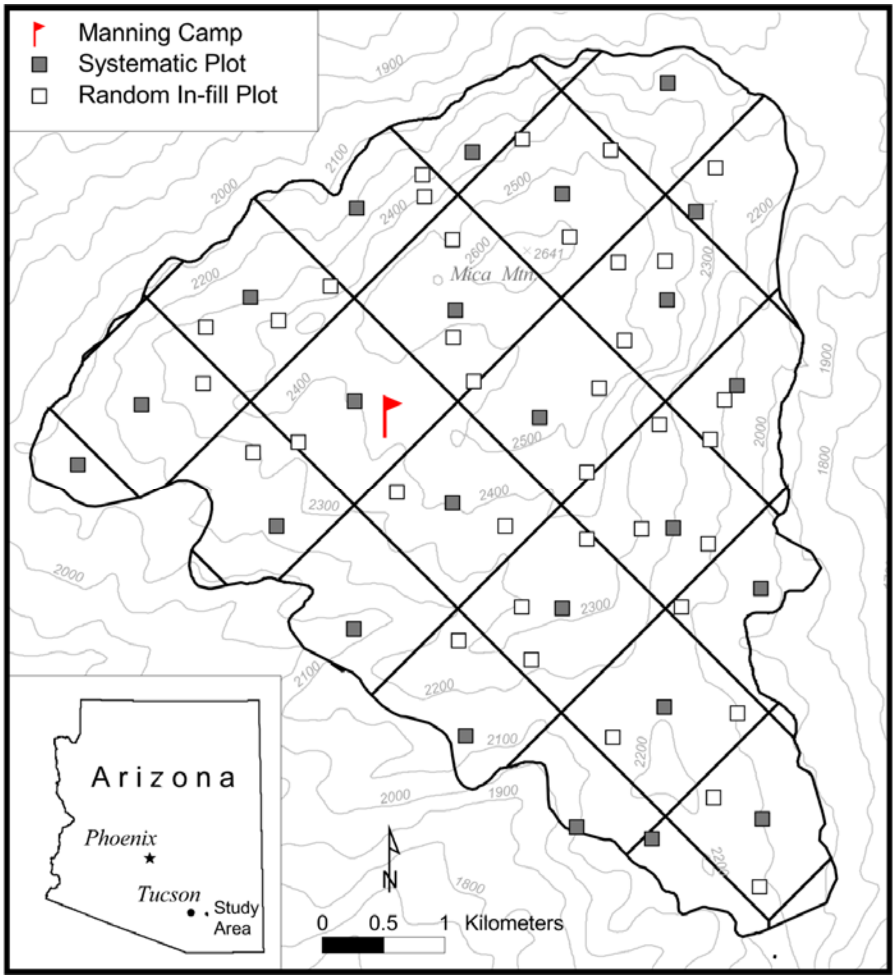


Figure 2. The percentage of fire scar-plots that recorded a fire year (black bars), and the total number of recording plots (black line) between 1937 and 2000. The dotted horizontal lines represent the 10% and 25% scarring levels.

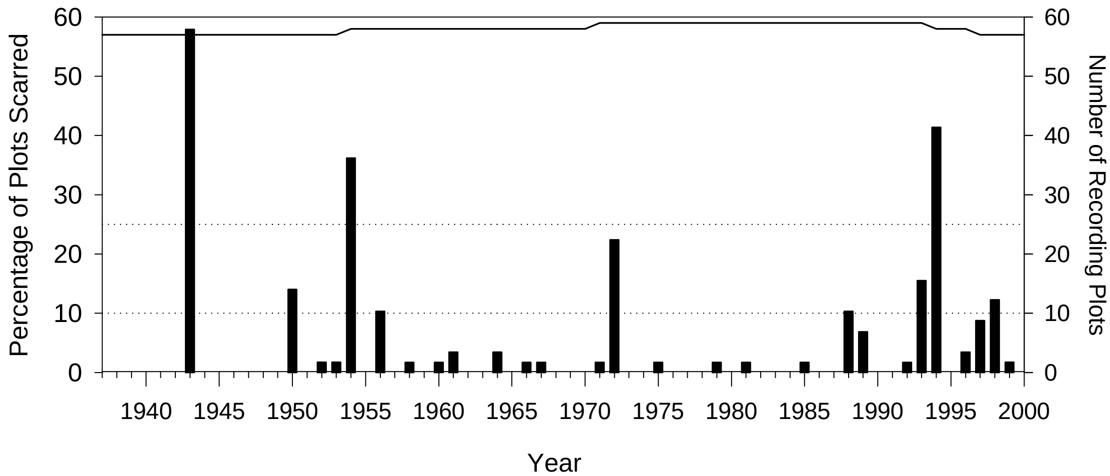
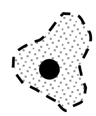
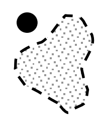
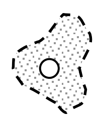
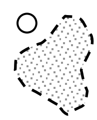


Figure 3. Error matrix showing the number of plots within mapped fire perimeters that recorded a fire-scar year. The conceptual diagrams graphically depict all four possible outcomes. Polygons represent a mapped fire perimeter, white circles represent a fire history plot that did not record a fire, and black circles represent fire history plots that recorded a fire.

	Plot Inside Mapped Perimeter	Plot Outside Mapped Perimeter
Fire Scar Present	132 	6 
Fire Scar Absent	27 	530 

Overall Agreement = 95% (662 correct outcomes out of 695)
Type II error: 17% (fire scar absent within a mapped perimeter)
Type I error: 1% (fire scar is present outside a mapped perimeter)

Figure 4. Relationship between (a) annual area burned and fire-scar synchrony ($y = 0.0003x + 0.0087$, $r^2 = 0.96$, $p << 0.001$), and (b) mean annual area burned and three categorical levels of fire-scar filtering.

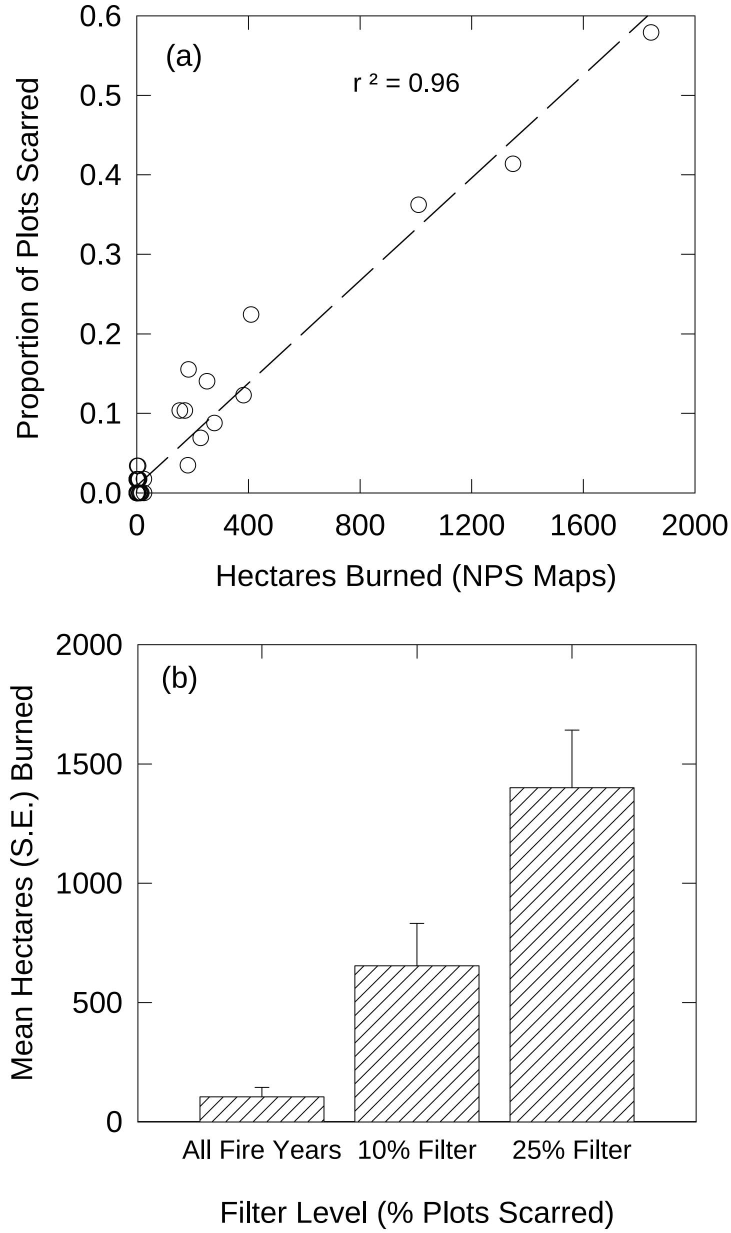


Figure 5. Partial cross-section from Mica Mountain showing corresponding fire maps for each fire-scar year. Fire years shown in yellow indicate extensive fires that burned multiple adjacent plots. Fire years shown in white indicate small fires that did not scar adjacent plots and have no corresponding perimeter map (arrows for the 1994 map indicate interior side of fire polygon).

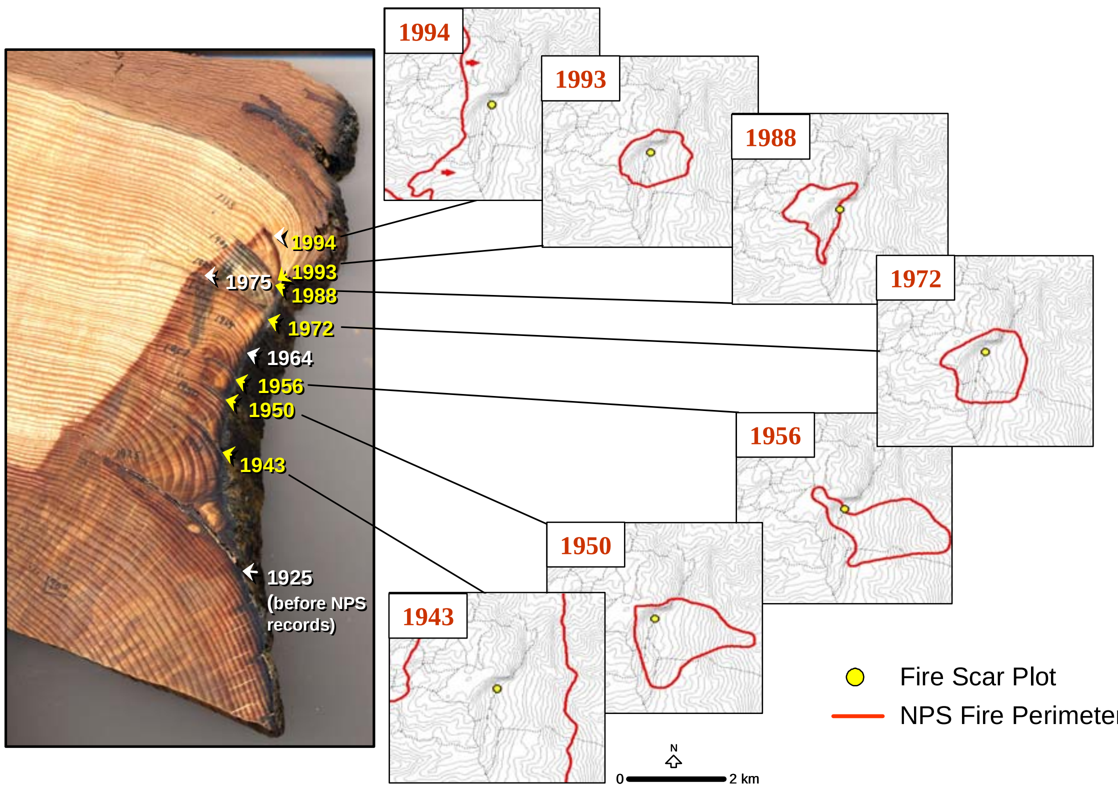


Figure 6. Spatial patterns of fire frequency from 1937 and 2000 calculated from (a) NPS Atlas maps and (b) fire-scar data interpolated with Thiessen Polygons. The proportion of the study area occupied by each fire frequency class in the two maps is shown in (c).

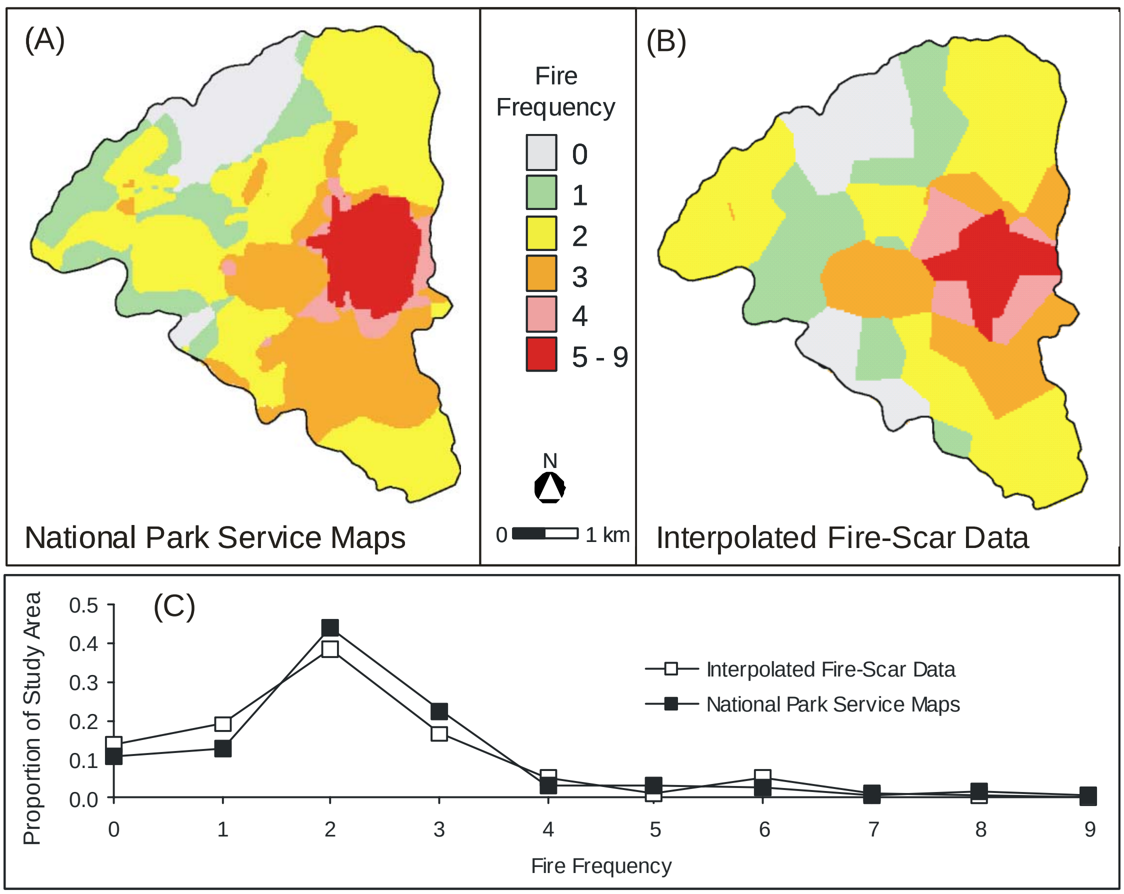


Figure 7. Relationship between annual area burned (hectares) calculated from NPS fire maps and reconstructed from fire-scar data. Fire-scar data were converted to hectares burned using area burned from fire-scar data: Thiessen Polygons ($y = 0.819x + 35.5$, $r^2 = 0.97$, $p < 0.001$) and fire-scar synchrony ratio ($y = 0.898x + 24.1$, $r^2 = 0.96$, $p < 0.001$). The diagonal dashed line represents a 1:1 relationship.

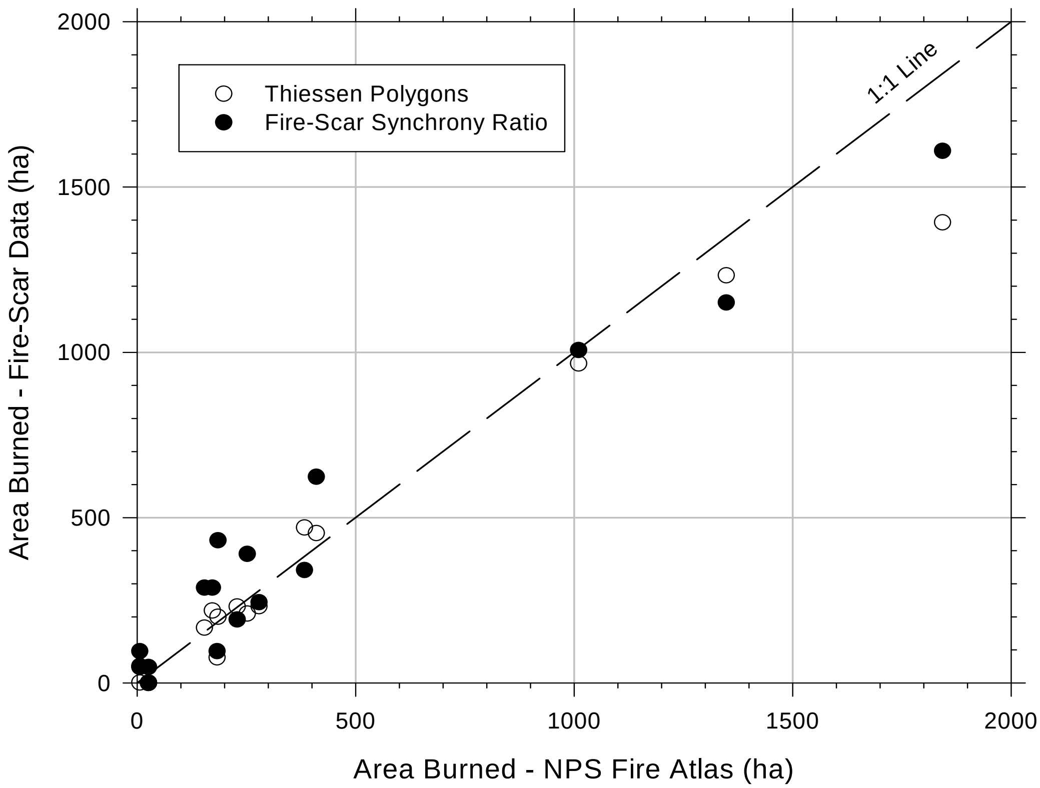
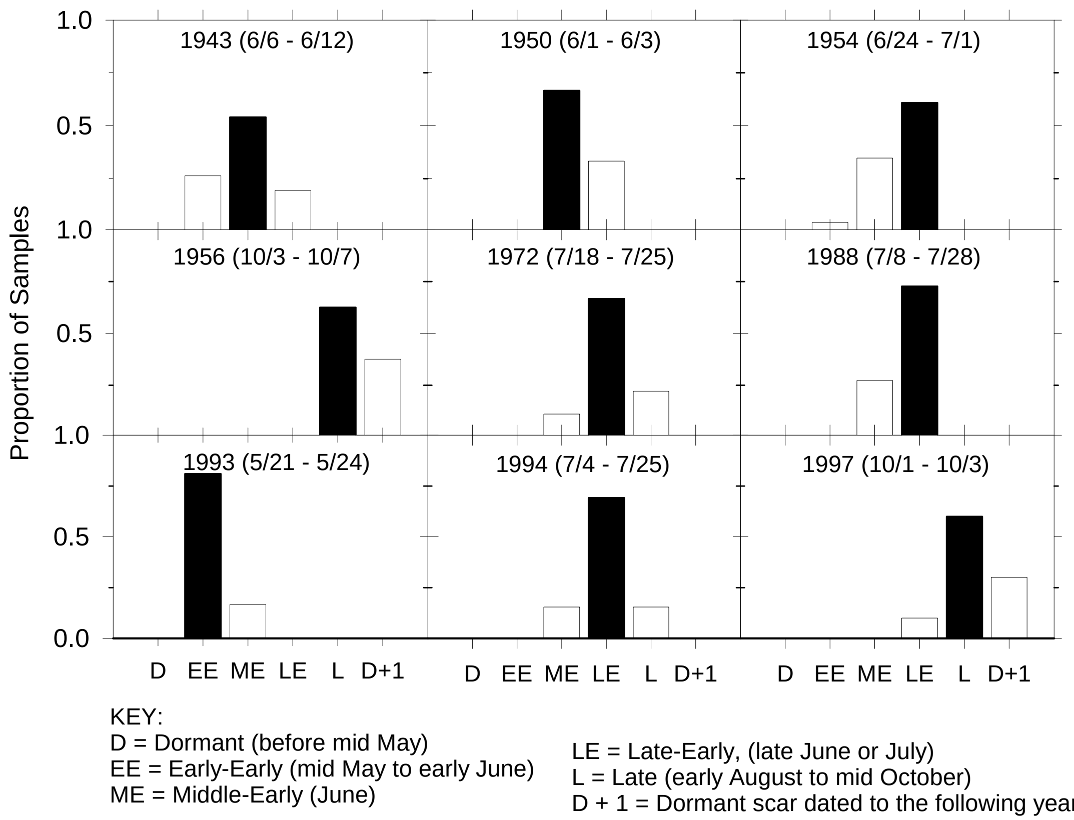


Figure 8. Percent frequency distribution of intra-annual fire-scar positions for six large fire dates. The black bars indicate the expected scar position based on the reported burn dates in the NPS fire atlas. The discovery date and control date for each fire are shown in parentheses.



APPENDIX B

EMPIRICAL CORROBORATION OF SCALE AND SAMPLE SIZE DEPENDENCE OF FIRE-SCAR DATA UNDER DIFFERENT FIRE REGIMES

CALVIN A. FARRIS

(Paper Not Submitted Yet)

Empirical corroboration of scale and sample size dependence of fire-scar data under different fire regimes

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Abstract

Sample size and scale dependence are inherent properties of point-based sample data used to infer continuous spatial processes. This study examined the sensitivity of point-based fire-scar reconstructions to variation in spatial scale (contiguous area of analysis), sample size, and underlying fire size distribution. We used documentary fire perimeter maps to quantify variation in fire-scar detection probabilities across a range of spatial scales, sample sizes, and area burned. We then compared fire-scar estimates of Mean Fire Return Interval (MFI) and Natural Fire Rotation (NFR) between the 20th century (fire exclusion era) and 19th century (pre-settlement era) to assess how the fire-scar dataset reflected the differing fire regimes. Our results showed that sample size and spatial scale dependence of fire-scar detection probabilities was strong for small fire years but consistently weak for larger fire years. Scale dependence of the fire-scar NFRs was relatively low: most of the variation was attributable to the actual scale dependence of documentary fire occurrence and the empirical underlying NFR. Overall variability in fire frequency statistics was significantly lower during the 19th century than the 20th century reflecting the prevalence of larger fires on the landscape prior to contemporary land-use and fire suppression. Fire frequency parameters were most similar within each century at fine spatial scales, reflecting the high relative proportion or large fires in small areas and the high probability they will be detected. These results suggest fire-scar data are robust for detecting major (widespread or extensive) fire years and fire frequency statistics based on area burned across a range of sampling and fire regime conditions.

They also support ecological interpretations and management implications from previous studies suggesting that widespread fires were a frequent occurrence prior the 20th century.

Introduction

Forest fires are distributed unevenly in time and space due to variation in weather, topography, fuels, ignition pattern, or chance (Agee 1993, Baisan and Swetnam 1995, Taylor and Skinner 1998, 2003, Turner et al. 2001, Falk et al. 2007, Iniguez et al. 2008). Proxy evidence of past fires in the form of fire scars are also distributed unevenly due to vagaries of fire-scar formation and retention (Swetnam and Baisan 1996, Fulé et al. 2003, Falk 2004, Van Horne and Fulé 2006, Collins and Stephens 2007). The degree to which fire-scar fire histories represent actual fire regimes depends on the correspondence between available fire-scar specimens and the underlying fire regime patterns across space and time. Analytical factors such as the types of assumptions used to infer fire occurrence between sample units can further compound uncertainties in fire history reconstructions (Baker and Ehle 2001, 2003, Van Horne and Fulé 2006, Farris 2009 Appendix C). An improved understanding of the ways in which fire regime variability interacts with sampling variability is needed to assess the robustness of fire-scar fire histories.

Two variable attributes of fire-scar sampling that can differ most widely between studies are the number of samples (sample size) and the size of the contiguous analysis area (spatial scale). The effect of sample size on fire-scar data has been well documented – the number of fire years detected increases with increasing sample size until eventually the rate of detection levels off when most fires have been detected (see Arno and Peterson 1986, Baker and Ehle 2001, Falk and Swetnam 2003, Stephens et al. 2003, Swetnam et al. 2003, Falk 2004, Hessl et al. 2004, Van Horne and Fulé 2006). The scaling properties of fire-scar data – and fire regimes in general – have been less well studied (Arno and Peterson 1986, Falk and Swetnam 2003, Falk 2004, Van Horne 2006, Falk et al. 2007). Using a theoretical framework based on species-area curves in ecology, Falk (2004) showed how the detection of fire-scar years increases mathematically with increasing scale (analogous to the detection of new species with scale) (see also Falk and Swetnam 2003, Falk et al. 2007). There is some evidence, however, that strength of sample size and scale dependence varies strongly as a function of fire size and relative extent (Stephens et al. 2003, Swetnam et al. 2003, Hessl et al. 2004, Van Horne and Fulé 2006, Falk et al. 2007).

An inherent limitation of existing fire-scar studies of scale and sample size dependence of historical fires is they lack independent fire regime data to serve as a baseline reference (i.e., a best estimation of the "truth"). Empirical comparisons of fire-scar data with independently mapped fire perimeters offer the best available option for assessing the relative "accuracy" of fire-scar fire histories (Farris 2009 Appendix A, Collins and Stephens 2007, 2003, Fulé et al. 2003). Knowledge of the actual frequency-area distribution of fires is necessary to determine the extent to which sample size or scale dependence reflects variation in fire occurrence or analytical/detection biases. For example, variability in certain fire frequency parameters across different scales may track actual underlying spatial patterns of fire occurrence or may be an artifact of differential detection probabilities of certain fires (or a combination of both) (Falk 2004). Sample size dependence may result in a biased estimate of fire histories if certain types of fires are more (or less) likely to be detected than others, but this cannot be determined definitively unless the actual number and location of fires of differing size are known. Modeling experiments can provide insight into theoretical relationships between these parameters (Falk et al. 2007, Kou and Baker 2006, Parsons et al. 2007, Li 2002), but as yet they do not adequately simulate real-world variability of fire-scar formation or retention processes which is an inherently important (but poorly understood) factor driving the sample selection process.

In a companion study we compared documentary fire perimeter data with independently collected fire-scar reconstructions on Mica Mountain in southern Arizona (Farris 2009 Appendix A). We found a strong correspondence between key spatial and temporal fire frequency parameters reconstructed from each dataset, thereby corroborating (*sensu* Turner et al. 2001) the analytical techniques used to reconstruct fire frequency. However, our analyses were conducted at a single spatial scale (the entire 2,780 hectare study area), using the complete sample size of fire-scar data (n = 60 plots), and for a single temporal period and fire-frequency regime (1937 to 2000). In this research we expand on that study to (a) quantify the relative interactions of spatial scale, sample size and fire-size distribution on empirical fire-scar detection probabilities and (b) examine how these factors influence the estimation of fire frequency statistics in differing fire frequency regimes (as typified by pre- and post-settlement eras).

To address these questions we integrated two case studies in this research. We first utilized 20th century documentary maps (NPS fire atlas) to determine fire-scar detection probabilities for fire years of varying size (annual area burned) across a range of sample size and scale. For sample size we held area constant (study area) and randomly varied the number of samples (Falk 2004). For spatial scale we held sample density constant and varied the size of contiguous areas of interest (Falk 2004). We secondly compared fire frequency summary statistics estimated using multiple sample sizes and spatial scales between the pre-settlement era (pre-20th century) and contemporary fire suppression era (20th century) in the study area. These two periods differ in the relative extent and frequency of burning: total area burned during the 20th century on Mica Mountain was dominated by spatially clustered fires of moderate size ($\leq$50% of the study area), whereas total area burned during the 19th century was dominated by very widespread burns unimpeded by fire suppression or land use (Baisan and Swetnam 1990). These periods therefore represent different fire regime conditions in terms of the underlying frequency-area distribution and spatial heterogeneity.

These multiple comparisons enabled us to examine scale and sample size dependence concurrently within the same landscape but with different underlying fire frequency-area distributions. We sought answers to the following questions: (1) How does sample size and scale dependence influence fire-scar detection probabilities along a gradient of annual area burned?; (2) How closely does scale dependence of fire frequency estimated from fire-scar data track the scale dependence of the fire regime?; (3) How does sample size dependence, scale dependence, and fire size distribution interact to influence estimation of fire frequency summary statistics?; (4) What are the implications of these interactions for sampling and interpreting fire history data?

Methods

Study Area

The study area is located in the Rincon Mountains in Saguaro National Park Wilderness Area near Tucson, AZ, USA (Fig. 1). The Rincon Mountains are a Sonoran Desert "Sky Island," rising from the desert floor at an elevation of 940 m to the forested summit of Mica Mountain at 2,641 m. Mica Mountain harbors extensive coniferous forests at the high elevations (Bowers and McLaughlin, 1987). The study area polygon consists of 2,780 ha and marks the extent of the coniferous forest belt on Mica Mountain. The polygon was delineated prior to field sampling using aerial photography to map the lower forest ecotone. Ponderosa pine (*Pinus ponderosa* P.& C. Lawson) or Arizona pine (*Pinus ponderosa* var. arizonica) is the dominant tree species above 2,100 m. Gambel oak (*Quercus gambelii* Nutt.) occurs as isolated individuals or small groups, or occasionally in thickets on cooler aspects, throughout this zone. Southwestern white pine (*Pinus strobiformis* Engelm.) is a ubiquitous co-dominant above 2,200 m. White fir (*Abies concolor* (Gord. & Glend.) Lindl. ex Hildebr) and Douglas-fir (*Pseudotsuga menziesii* (Mirbel) Franco) form isolated mixed conifer stands with ponderosa and Southwestern white pine on north aspects in the northern part of the study area. Ponderosa pine decreases in dominance at lower elevations and becomes locally absent near the lower forest boundary. Alligator juniper (*Juniperus deppeana* Steud.), border pinyon (*Pinus discolor* D.K. Bailey & Hawksworth), Arizona white oak (*Quercus arizonica* Sarg.), and silverleaf oak (*Quercus hypoleucoides* A. Camus) are common at the lower elevations near the lower forest ecotone (below 2,200 m).

Average annual precipitation varies strongly with elevation, ranging from approximately 33 cm at the base of the mountain (800 m elevation) to approximately 89 cm at Manning Camp (2,438 m elevation). The seasonal distribution of precipitation is bimodal. About 58% falls as rain between May and September, peaking in July and August during the wet summer monsoon season. The remainder falls as rain or snow between October and March, peaking in December and January.

Reference Data – NPS Fire Atlas

The National Park Service has maintained detailed records and maps of fires on Mica Mountain since 1937, referred to hereafter as NPS fire atlas (Swantek 1999a 1999b, Saguaro National Park 2002). For the 64-year period between 1937 and 2000, 414 fires were documented in the study area for a total of 6,636 hectares (ha). Twenty-one large (>100ha) fires resulted in numerous overlapping burn polygons with frequencies up to 9 fires. At least some fires burned every year, but 12 large fire years (>100 ha) accounted for 97% of the total area burned during the 64-year period (see Farris 2009 Appendix A for a more detailed description).

Fire season typically occurs between April and September. Maximum area burned peaks during June, whereas the maximum number of ignitions is in early July, coincident with the monsoon and peak lightning occurrence season (Baisan and Swetnam 1990, Crimmins and Comrie 2004). Ninety-three per cent of 20th century fires in the study area were ignited by lightning (Baisan and Swetnam 1990). Lightning ignitions are common during the monsoon season in July and August but they rarely become widespread before being extinguished by rain.

Fire-scar data

We sampled fire-scar data from sixty 1-ha plots using a two-phase systematic and random sampling approach (Fig .1). The purpose was to provide a uniform distribution of sample plots with variable densities completely independent of the fire atlas. An initial plot was established randomly within the study area. From this plot, a 1.2 km grid was generated with a 45 degree orientation to maximize the number of grid cells within the study area. During the first phase, 23 plots were generated systematically within the center of each 1.2 km grid (Fig. 1). During the second phase, 37 additional plots were located randomly between initial grid points to increase the sampling density and create greater variation in lag distances between points. When systematic or random plots were located on rock outcrops or barren ground, these plots were moved to the nearest forest stand. Some low elevation grid cells had a lower plot density because coniferous cover was sparse near the ecotone.

Within each plot, we collected 3 to 14 (average 6) fire-scarred cross sections from living trees and remnant wood (i.e., logs, stumps, snags). We sampled 405 fire-scarred cross sections, 202 of which had tree-ring records encompassing part or all of the corroboration period (1937 to 2000). In most cases we collected all of the fire-scarred material that was present within each 1-ha plot. Where there was an abundance of material, we sampled trees with well-preserved fire scars that provided the best combination of records from both young and old specimens to maximize the length and completeness of the temporal record. All cross sections were prepared and cross-dated in the laboratory using standard dendrochronology techniques (Stokes and Smiley 1968). All fire scars were assigned a calendar date, and where possible, an intra-annual ring position to determine the approximate seasonal timing of fires (Dieterich and Swetnam 1984, Baisan and Swetnam 1990).

Because trees may not record (or preserve) all fires that burned the bole, all fire years within individual plots were combined to form a single composite chronology for each plot (*sensu* Dieterich 1980). Vegetation and topography were typically homogeneous within the plots, therefore the composite plot chronologies are reasonably assumed to be relatively complete inventories of fire events within the 1-ha sampling areas during the time spans encompassed by the tree-ring specimens. The composite fire records from each plot were analyzed collectively as 1-ha "points", and we made no inference about within-plot spatial or temporal heterogeneity. A master fire chronology (*sensu* Dieterich 1980) was developed for the study area based on the composite chronologies from the 60 plots.

Data Analysis

Corroboration of Sample Size Dependence

We constructed collector's curves (Magurran 2004) to plot fire-scar detection probabilities as a function of samples size (see also Morino 1996, Swetnam and Baisan 2003, Stephens et al. 2003, Falk 2004). Sample sizes of n = 1, 3, 5, 10, 15, 20, 30, 40, 50 and 60 (full dataset) plots were analyzed for this study. For each sample size, a bootstrapping procedure without replacement (*sensu* Krebs 1998) was used to select 200 independent combinations of *n* plots randomly without replacement from the full dataset. The proportion of NPS fire atlas dates detected by each combination of *n* plots was calculated and the overall mean and standard deviation of all 200 permutations for each sample size were plotted. Separate curves were constructed for four different subsets of fire years based on annual area burned: all fire years (n = 63), and fire years in which at least 20 ha (n = 15), 200 ha (n = 8), or 400 ha (n = 4) burned respectively.

Corroboration of Scale Dependence

Scale is defined in this study as a spatially *contiguous* area (or "window") that defines the extent of sampling and statistical inference. We calculated scale dependence of fire-scar detection probabilities using event-area curves (*sensu* Falk 2004). In contrast to collector's curves where area is held constant and sample density varies, event-area curves hold sample density constant and systematically vary spatial scale (i.e., sampling and inference extent). Sample density (plots/ha) was relatively constant across different scales in our study because plots were distributed uniformly, although larger windows inherently contain more total samples than smaller windows.

We calculated detection probabilities for 17 different spatial scales ranging from 100 ha to 2,700 ha at 100 to 200 ha intervals. We used a moving window analysis (Burrough and McDonnel1998) to calculate the number of fire-scar dates detected within any given circular area of *n* hectares throughout the study area. Potential edge effects can result from boundary windows that partially extend outside the study area where there are no plots (Burrough and McDonnel 1998). To account for this we developed an algorithm to inhibit window growth at study area boundaries and subsequently expand circularly into the interior until the specified size was achieved. The proportion of total fire years in the study area detected by fire scars was calculated for each window that had a unique combination of plots. We repeated this process for three different subsets of fire years: all fire years (n = 63 dates); fire years in which at least 200 ha burned (n = 8); and fire years in which at least 400 ha (n = 4) burned.

Corroboration of Fire-Scar Synchrony and Area Burned

Fire-scar synchrony, defined as the proportion of sample units recording a fire year, has been shown to be correlated closely with the amount of area burned (Farris 2009, Appendix A). We evaluated the sample size dependence of this relationship by regressing annual area burned of NPS fire atlas maps against the proportion of fire-scar plots that recorded the fire year for different sample sizes. Sample sizes of n = 10, 20, 30, 40, 50, and 60 plots were analyzed. For each sample size, bootstrapping without replacement (*sensu* Krebs 1998) was used to estimate the mean proportion of plots scarred for 200 permutations of random plot combinations.

Comparative Analysis between the 20th and 19th Century

We restricted our pre-fire exclusion analysis to the 19th century (and not earlier) to maintain similar temporal length and sample depth as 20th century data.

Fire Frequency Summary Statistics

Two widely reported fire frequency summary statistics in the literature are the composite Mean Fire Return Interval (MFI) and the Natural Fire Rotation (NFR). The MFI is the average number of years between any fires within a specified area and time period (Romme 1980). Because individual fire scars are incomplete recorders of fires, fire years from multiple samples are composited to ensure a complete record of fires for the area of interest (Dieterich 1980, Farris 2009 Appendix A). The NFR is the average number of years required to burn an area equivalent to the size of the study area (2,780 ha for this study) (Romme 1980, Agee 1993).

Sample Size and Scale Dependence of Fire Frequency Statistics

We compared collector's curves for fire frequency statistics for each century using the same sample size intervals and bootstrapping procedure described previously. Fire historians typically report the MFI separately for fire years of differing size. For pre-documentary periods, differentiating between large and small fire years is typically done in a relative manner using "filtering" (Swetnam and Baisan 1996), wherein minimum percent-scarring thresholds are used to identify relatively widespread fire years and intervals between them. We thus constructed separate collector's curves for all fire years (no filter applied) and for fire years in which $\geq$10% and $\geq$25% of the selected plots recorded a scar. We used the notation MFI_{all}, $MFI_{10\%}$, and $MFI_{25\%}$ to refer to each level of filtering.

The NFR was calculated as:

(1) $NFR = T \div P$

Where *T* is the number of years (1937 to 2000 in this case) and *P* is the cumulative proportion of the study area burned (which can be greater than 100%). Area burned was estimated based on fire-scar synchrony whereby the proportion of plots scarred was assumed to be equivalent to the proportion of the study area burned (Morrison and Swanson 1990, Farris 2009 Appendix A). This method is appropriate in our study area because (a) samples are well-distributed, (b) sample size is large, and (c) large fires that contribute most to the NFR are widely recorded (Farris 2009 Appendix A). Most fire years detected by a single plot likely burned very small areas. To eliminate any potential cumulative influence of numerous small fires, we also estimated area burned using a 2-plot filter in which at least two adjacent plots had to record the fire year to be counted in the calculation.

Scale dependence of fire frequency summary statistics was assessed using the same moving window analysis and event-area curves described previously. Fire occurrence and annual area burned within individual sample windows was calculated. The average fire frequency, MFI, and NFR for all moving window permutations were plotted as a function of scale to quantify variability of fire frequency summary statistics with increasing sampling extent. We also computed scale-dependence of NPS fire atlas fires to determine how scale dependence of the fire-scar reconstruction tracked that of the underlying documentary record.

Ratios – Spatial Scale/Sample Size Dependence

Successive levels of fire-scar filtering are cumulative by nature because fire years with $\geq$25% of samples scarred have $\geq$10% of samples scarred also. The ratio of MFI values filtered at different levels can therefore provide useful insights about cumulative fire size distributions (i.e., proportion of small to large fires) (Fulé et al. 2003). To assess how sample size and spatial scale influences the relationships between filtered and unfiltered MFIs, we calculated the ratio of the $MFI_{25\%}$ to the MFI_{all} ($MFI_{25\%}$:MFI_{all}) and the $MFI_{25\%}$ to $MFI_{10\%}$ ($MFI_{25\%}$:$MFI_{10\%}$) across the full range of sample sizes and scales described in previous sections.

Results

<u>Corroboration of Sample Size Dependence</u>

The proportion of documentary fire years detected by fire scars increased with increasing sample size, but fewer samples were required to detect greater proportions of large fire years than small fire years (Fig. 2). Collector's curves for unfiltered fire years never reached an asymptote and the maximum proportion of fires detected was only 42.9% with the entire dataset. In contrast, an average of only 30 plots were required to detect all fire years $\geq$ 200 ha and an average of only 15 plots were required to detect all fire years ≥ 400 ha. These results indicate that sample size dependence of fire-scar data is primarily due to small fires.

Corroboration of Spatial Scale Dependence

Scale dependence of documentary fire years decreased with increasing area burned (Fig. 3). Scale dependence of fire-scar detection probabilities tracked the documentary record poorly (Fig. 3a), but when small fires were filtered-out the relationship was strong (Fig. 3b and 3c). Proportions of documentary fire years increased from 0.2 in 100 ha windows to 1.0 in 2800 ha windows (Fig 3a), but <0.5 of those were ultimately detected by fire-scar data. For fire years with ≥400 ha burned (Fig. 3c), conversely, the average proportion of documentary years ranged from 0.7 in 100 ha windows to 1.0 in windows ≥1,200 ha and the corresponding proportion detected by fire scars ranged from 0.55 to 1.0 respectively.

Corroboration of Fire-Scar Synchrony and Area Burned

The average relationship between area burned and fire-scar synchrony was consistent across all sample sizes (Fig. 4). Variability in the percentage of randomly drawn plot combinations that recorded a given fire year increased as sample size decreased, but the overall mean and slope coefficient remained little changed. Scarring percentages of 0 for some documentary fire years >100 ha (i.e., failure to detect) occurred when sample size was <20 plots, but there were only two cases (out of hundreds possible) in which fire-scar data failed to record a fire that burned ≥20% of the study area.

Comparison Between the 20th and 19th Century

The frequency of fire-scar dates for 19th and 20th century fires is shown in Table 1. These data confirm the assumption that large fire years (i.e., 25%-filter) were more common during the 19th century prior to fire suppression, consistent with findings of Baisan and Swetnam (1990).

Sample Size Dependence of Fire Frequency Summary Statistics

Sample size dependence was generally strong for the MFI_{all} but weak for the $MFI_{10\%}$ and $MFI_{25\%}$ (Fig. 5). The mean 20th century MFI_{all} varied by about 11 years (range 2.3 to 13.5) across the range of sample sizes analyzed, compared to an average of about 7 years (range 2.2 to 9.4) during the 19th century. The $MFI_{10\%}$ and $MFI_{25\%}$ in contrast varied by less than 4 years during the 20th century (6.9 to 9.4, and 21.3 to 25 respectively) and by less than 1 year during the 19th century across all sample sizes analyzed.

Sample size dependence of the NFR was relatively weak overall, especially during the 19th century (Fig. 6). The average 19th century NFR varied by less than 1.5 years across the full range of sample sizes analyzed, regardless of filtering method (10.7 to 12.4 years for the 2-plot filter and 10.4 to 10.8 years for unfiltered estimate). Sample size dependence of the 20th century NFR varied by less than 1 year for the unfiltered estimate (23.2 to 24.2) and by about 5 years for the two-plot filter estimate. The 20th century fire-scar NFR was consistently within 3 years of the NPS fire atlas estimates across all sample sizes. The biggest deviation occurred for the smallest sample size (n = 10) when a two-plot filter was used. Large fires that control the NFR were so widespread during the 19th century that all were detected by multiple samples even when sample size was small. In contrast, only one 20th century fire burned $\geq$50% of the study area and there were many examples of detection at a single plot for small sample sizes (leading to the underestimation of area burned).

Spatial Scale of Fire Frequency Summary Statistics

The MFI_{all} decreased steadily with increasing scale but the $MFI_{10\%}$ and $MFI_{25\%}$ were remarkably stable across all spatial scales during both centuries (Fig 7). Scale dependence of MFI_{all} was much weaker overall during the 19th century however. For spatial scales ranging from 200 ha to 2,700 ha, the MFI_{all} ranged from an average of 13.1 to 2.2 years during the 20th century but only 5.0 to 2.1 years during the 19th century. Variability of filtered MFIs was even lower during the 19th century: the $MFI_{10\%}$ and $MFI_{25\%}$ varied by an average of <1 year across the full range of scales. The filtered 20th century MFIs were slightly more variable, ranging from an average of 6.3 to 15.3 years for the $MFI_{10\%}$ and 18.4 to 26 years for the $MFI_{25\%}$.

The average NFR of documentary fires in the NPS fire atlas ranged from about 52 years at 200 ha to about 27 years for the full study area, but scale dependence was weak beyond 1,000 ha (Fig. 8). The fire-scar NFR tracked the documentary NFR very closely across all scales, but the unfiltered fire-scar estimated corresponded more closely overall than the two-plot filter which showed a bias toward a longer NFRs at smaller scales.

Scale dependence during the 19th century was virtually absent: the average unfiltered fire-scar NFR was approximately 10 years across all scales and the two-plot filter estimate ranged 14.3 years at 200 ha to 10.8 years at 2700 ha (although there was no variation at scales beyond 200 ha). These results indicate that scale dependence of fire-scar NFRs reflect primarily the spatial variability of the underlying fire regime (i.e., NPS fire atlas).

Ratios between Fire History Statistics

The $MFI_{25\%}$:MFI_{all} varied strongly as a function of sample size and scale during both centuries, but this was driven primarily by variation in the MFI_{all} (i.e., small fires). The $MFI_{25\%}$:$MFI_{10\%}$ was relatively stable, especially during the 19th century (Fig. 9). The mean $MFI_{25\%}$:$MFI_{10\%}$ approached 1.0 across all sample sizes and spatial scales during the 19th century, indicating that nearly all pre-settlement era fires that grew to the $\geq$10% filtering level also grew to the $\geq$25% level.

Discussion

This study provides insight into how spatial and temporal variation in fire frequency and sampling characteristics affect fire-scar reconstructions. Fire-scar fire history reconstructions may reflect the underlying frequency-area distribution of fires in a landscape and/or differential detection probabilities of fires across that distribution. Statistical corroboration between fire-scar data and the NPS fire atlas for large fire parameters was strong but varied widely for small fires. Nineteenth century fire frequency summary statistics were less variable across all scales and sample sizes than during the 20th century, reflecting the greater prevalence of widespread fire years. Different fire frequency metrics were most similar at small scales (i.e., plots and stands) which contained mostly large fires.

<u>Multi-scale and Multi-sample Corroboration</u>

Sample size and scale dependence are inherent properties of spatial inferences made from point-data (Magurran 2004). For fire-scar data, the relative strength of these dependencies is due largely to differential detection probabilities of fire years. Our results indicate that scale and sample size dependence is primarily a function of small, poorly detected fires, but that few samples collected from relatively small areas are required (on average) to characterize widespread burns. This is consistent with other ecological inventory studies showing that point detection probabilities are highest for species with more even spatial distributions (Magurran 2004). The result is that fire-scar derived fire frequency parameters based on area burned, such as the $MFI_{25\%}$ or NFR, will generally be more "accurate" and stable across a wide range of sample sizes and scales (see also Van Horn and Fulé 2006). Fire-scar estimation error will be greatest when attempting capture small fire events (relative to the study area) over large areas because small fires are proportionately under-detected.

These results are consistent with theoretical expectations of scale dependence of fire regimes (Arno and Peterson 1983, Falk 2004, Falk et al. 2007). However, the scale dependence of fire-scar data appears to differ in important ways from actual patterns of fire occurrence (i.e., NPS fire atlas). Small fires are detected at much lower rates than they occur and this discrepancy increases with increasing scale. Scale dependence of large fires conversely decreases with increasing scale until most or all are detected. This has important implications for interpreting fire-scar records. When all fire years are analyzed, such as in calculation of the MFI_{all}, overall agreement between fire-scar data and mapped fires will be highest at relatively small spatial scales where small fires occur less frequently (see next paragraph). Fire-scar data underestimate overall fire occurrence for larger scales. When large-fire years are emphasized, such as in the calculation of the NFR or $MFI_{25\%}$, scale dependence will generally track empirical fire occurrence closely.

One explanation for these results is that the frequency-area distribution of fires changes predictably with scale in most landscapes. Although total numbers of fires increase with increasing scale, not all fire size classes increase proportionately. Small fires are proportionately less common in very small areas and increase more rapidly relative to large fires with increasing scale. This is due to the fact that (a) very small areas ('windows') *on average* are more likely to have a fire spread into them than a fire ignite in them, (b) fewer "new" fires are intersected as window size increases, and (c) small fires generally outnumber large fires in most landscapes. For example, the average number of documentary and fire-scar fire years were virtually identical at the scale of individual sampling units (1 ha) in our study because the largest fire years accounted for fully half of the fires detected within each plot on average.

Kou and Baker (2006) suggested from modeling experiments that the MFI will be similar to the NFR when samples are collected from scales of 1 ha with large sample sizes of >20 trees, but very rarely will that many scarred trees be available in such a small area. Only one 1-ha plot on MIC had as many as 13 scarred specimens, and many of those were not datable due to decay or were single-scarred specimens formed by the most recent burn. Our empirical data show that far fewer trees are necessary to obtain complete and representative inventories of documentary fires at small scales. We suggest that initial assessments of spatial and temporal synchrony of watersheds or other small landscapes can be obtained with relatively few dispersed samples. Large sample sizes may be still required for other reasons such as increasing the resolution of spatial pattern inferences and reducing variance of estimated fire frequency statistics.

Multi-Century Fire Frequency Statistics

Consistent with our empirical detection probability findings, sample size and scale dependence of fire frequency statistics during the 19th century were considerably lower than for the 20th century. Even the MFI_{all} which should be most sensitive to scale and sample size varied by less than 5 years during the 19th century. Such small differences of absolute values are unlikely to change significantly any general interpretation of the fire regime. Fire-scar datasets appear therefore to be robust for reconstructing large-fire frequency parameters across a range of scale, sample size, and fire size in these systems. These results are similar to Van Horne and Fulé (2006) who also found relatively little scale and sample size dependence of $MFI_{10\%}$ and $MFI_{25\%}$ in a pre-settlement ponderosa pine forest in northern Arizona (calculated using a full census of 648 available samples).

In contrast to the 19th century fire regime, the 20th fire regime on Mica Mountain showed relatively strong scale dependence of the NFR for scales <500 ha. Large 20th century fires that most directly influence the NFR were smaller and more spatially clustered than during the 19th century (some areas burned 9 times and others burned 0 times). There was relatively higher variability of total area burned on average at scales <500 ha across the landscape in the 20th century but this variability was tracked accurately by fire-scar data. Scale and sample size dependence of NFR were absent for the 19th century fire regime where total area burned and spatial extent were greater and less variable spatially. Although the NFR is an area-adjusted (normalized) metric, there may be inherent differences between study areas of differing size. Fire -scar data should track these differences well, however, even in relatively heterogeneous fire regimes.

It is worth noting that the MFI_{all} and $MFI_{10\%}$ were very similar between the 20th and 19th century but the $MFI_{25\%}$.and NFR were much shorter during the 119th century. This suggests that the overall frequency – and/or detection – of fires has not changed during the 20th century fire exclusion/suppression era; what has changed primarily is the ultimate size and extent of large fire years. Suppression actions occurred at some point on every fire in the NPS fire atlas during the 20th century study period, and indirect influences such as grazing in the low elevation grasslands adjacent to the park may have hindered offsite ignitions from spreading into the study area. We posit that if some of the mid-sized 20th century fires were not suppressed we would have observed similar $MFI_{25\%}$ and NFR values between centuries. This would suggest that lightning ignitions within (and adjacent to) the study area are sufficient to produce the pre-settlement fire frequencies observed in the historical fire-scar record. Prescribed burns do not explain this pattern. Only one year did prescribed burns contribute to scarring >10% but <25% of plots; the other three years with prescribed burns either did not scar 10% of plots or occurred during a year when a wildfire scarred >10% but <25% of plots.

Ratios –Relationship to Other Studies

There were major differences in cumulative fire growth between centuries. During the 19th century, the probability of fire years scarring ≥ 10% of plots was only 15%, but once fire years scarred ≥10% of plots they had a 73% chance of scarring ≥25% of the plots (and often much more –six fire years burned ≥75% of plots during the 19th century). This suggests there is considerable inertia of initial fire growth in natural fire regimes due to variation in weather and local fuels (see Neuenschwander and Sampson 2000), but once suitable conditions for burning occur most fires are relatively unconstrained. This is consistent with broad-scale geographic patterns of fire-scar synchrony (across multiple watersheds and mountain ranges) that coincide with synoptic climate conditions favorable for burning (Swetnam and Betancourt 1998). All but two of the major 19th century fire years in the study area corresponded to regional fire years identified by Swetnam and Betancourt (1998). During the 20th century, the probability that fire years scarring ≥10% of plots would grow to scar ≥25% of plots was 34% despite active fire suppression, suggesting that favorable burning conditions were still important.

This property appears to be widespread in pre-settlement fire regimes in the Southwest and has implications for fire-scar interpretation. Of the 63 Southwestern ponderosa pine and mixed conifer fire histories summarized by Swetnam and Baisan (1996), the median $MFI_{25\%}$:MFI_{all} was 2.0 and the median $MFI_{25\%}$:$MFI_{10\%}$ was 1.1 (Fig. 10). This compares to 3.6 and 1.2 respectively for Mica Mountain. The high $MFI_{25\%}$:MFI_{all} on Mica Mountain relative to the greater Southwestern dataset is because (a) it is one of the largest study areas in the Southwest for a single composite MFI_{all}, and (b) it contains one of the largest number of plots/fire scarred trees sampled per study area. Hence, more small fire years in the study area were detected resulting in a very low MFI_{all}, whereas this was not achieved in most other studies. The fact that the $MFI_{25\%}$:MFI_{all} on MIC falls squarely within the narrow range of values for the greater Southwestern dataset is due to the fact that filtered MFIs are relatively insensitive to scale and sample size, and thus likely reflect regional synchrony of widespread burning. This was true even for the 20th century fire regime where fires were smaller and more clustered. These results suggest that there may be similarity among all studies in this parameter, despite different sampling densities, study area sizes, and location, and implies robustness of the overall dataset.

These data highlight the need for careful interpretation and comparison of fire history data. Outlier values may represent real differences in fire regimes between studies or an artifact of sampling. Three $MFI_{25\%}$:MFI_{all} outliers in Fig. 10 are from study areas that have highly dissected topography and vegetation and contain fewer widespread fire years (Baisan and Swetnam 1996). It is important therefore to examine other ancillary information such as FHX2 fire-scar chronology charts (Grissino-Mayer 2001), maps, sample characteristics, vegetation patterns, etc., rather than just one or two summary statistics to provide greater context (Swetnam and Baisan 1996, 2003, Veblen 2003). Collectively this information provides a more complete picture of the fire frequency regime (Farris, Appendix A).

<u>Other Considerations</u>

Several sampling parameters that undoubtedly influence fire-scar reconstructions were not considered explicitly or were controlled for in this study. We composited multiple trees within each stand so each data "point" (plot) contained a relatively complete record of the documented fires that passed through it (Farris 2009 Appendix A). Individual-tree sampling strategies will result in points with considerably more variability due to missing scars, although this may be offset by an increase in sample space (Van Horne and Fulé 2006, Hessl et al. 2007). Sample attrition can result in artificially long fire intervals as fewer scars are detected by small sample sizes, but that was not a factor in this study because sample size was consistently high for the 20th and 19th centuries. This study is based on an initial baseline of systematic and random plots rather than the more commonly used method of targeted sampling. We have analyzed the relative accuracy and robustness of targeted sampling in a companion study (Farris 2009 Appendix C) and found no significant difference in study area fire frequency estimation. Finally, we restricted our methods to those previously corroborated by Farris (2009 Appendix A) so methodology was not a source of variation (as it can be when studies with different analytical techniques are compared).

Sampling Implications

No single sampling approach is appropriate for all fire history research objectives. Due to the labor and time involved in data collection and preparation, and the patchy availability of fire-scar records in many managed landscapes, it will rarely be practical for researchers to conduct intensive systematic sampling across landscapes as large as we analyzed in the first study. A balance must be struck between intensive and extensive sampling to meet objectives in an efficient manner. A few general approaches can be tailored for fire history applications based on how fire-scar networks capture fire years. We suggest that fire history objectives can be divided broadly into three general categories: broad-scale fire-climate relationships, fire frequency estimation of representative vegetation or landscapes, and spatially explicit reconstructions. A description of possible sampling goals and some general recommendations for these categories are summarized in Table 2. Relatively few plots are required in most cases to obtain a general picture of large fire synchrony and extent, so pilot sampling or adaptive sampling of large landscapes may be a useful initial strategy.

In many cases, researchers or managers will have to depend on existing fire-scar datasets that may have been collected for other purposes and/or which may exhibit variability in sampling and scale parameters. This will continue to be the case as the finite fire-scar record disappears over time (particularly the ancient record). An improved understanding of the variable spatial and sampling parameters analyzed in this study provides important context for interpreting from different studies and sampling schemes. Our results suggest that differential fire-scar detection probabilities have a consistent and predictable influence on the estimation of fire frequency parameters: fire frequency summary statistics that are based on area burned, such as filtered MFI and NFR, appear to be estimated robustly across a relatively wide range of scale, sample size, and fire size. These factors should be considered individually for each dataset rather than relying on broad generalizations about accuracy or bias (Baker and Ehle 2001). Every fire-scar dataset moreover has minimum interpretable resolutions and limitations depending on quality and density of data; attempts to over-interpret existing data to scales too fine or too large could lead to erroneous conclusions (see Farris 2009 Appendix A).

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References

Agee, J.K. 1993. Fire ecology of Pacific Northwest forests. Island Press, Washington, D.C.

Agee, J.K. 1998. The landscape ecology of western fire regimes. Northwest Science 72:24-34.

Arno, S.F. and Peterson T.D. 1983. Variation in estimates of fire return intervals: a closer look at fire history on the Bitterroot National Forest. USDA Forest Service Research Paper GTR INT-301.

Baker, W.L. and Ehle, D. 2001. Uncertainty in surface-fire history: the case of ponderosa pine forests in the western United States. Canadian Journal of Forest Research 31: 1205-1226.

Baker, W.L. and Ehle, D. 2003. Uncertainty in fire history and restoration of ponderosa pine forests in the western United States. Rocky Mountain Research Station. USDA Forest Service. RMRS-P-29. 319-334. Fort Collins, Colorado. Fire, fuel treatments, and ecological restoration: Conference proceedings. Omi, P.N. and Joyce, L.A. (tech. eds.)

Baisan, C.H. and Swetnam, T.W. 1990. Fire history on a desert mountain range: Rincon Mountain Wilderness, Arizona, U.S.A. Canadian Journal of Forest Research 20: 1559-1569.

Baisan, C. H., and Swetnam, T. W. 1995. Historical fire occurrence patterns in remote mountains of Southwestern New Mexico and northern Mexico. In: J. K. Brown, R. W. Mutch, C. W. Spoon, and R. H. Wakimoto, tech. coords., Proceedings:

Symposium on Fire in Wilderness and Park Management, Missoula, MT, March 30-April 1, 1993,. USDA Forest Service General Technical Report INT-320:153-156.

Bowers, J. E. and McLaughlin, S.P. 1987. Flora and vegetation of the Rincon Mountains, Pima County, Arizona. Desert Plants. 8(2): 50-94

Burrough, P.A. and McDonnel, R.A. 1998. Principles of geographic information systems (2nd edition). Clarendon Press, Oxford, England.

Collins, B.M. and Stephens, S.L. 2007. Fire scarring patterns in Sierra Nevada wilderness areas burned by multiple wildland fire use fires. Fire Ecology. 3(2):53-67.

Crimmins, M.A. and Comrie, A.C., 2004. Wildfire-climate interactions across southeast Arizona. International Journal of Wildland Fire. 13: 455-466.

Dieterich, J.H., 1980. The composite fire interval—a tool for more accurate interpretation of fire history. Rocky Mountain Research Station, USDA Forest Service. RM-GTR-81, 8-14. Proceedings of the Fire History, Workshop. Stokes, M.A., Dieterich, J.H. (Tech. Coords.)

Dieterich, J. H., and Swetnam, T.W. 1984. Dendrochronology of a fire scarred ponderosa pine. Forest Science 30(1):238-247.

Falk, D.A. 2004. Scaling rules for fire regimes. PhD. Dissertation. University of Arizona, Tucson.

Falk, D. A. and Swetnam, T.W. 2003. Scaling rules and probability models for surface fire regimes in ponderosa pine forests. Rocky Mountain Research Station. USDA Forest Service Proceedings RMRS-P-29, 301-318. Fire, fuel treatments, and ecological restoration: conference proceedings. Omi, P.N. and Joyce, L.A. (tech. eds.)

Falk, D.A., Miller, C., McKenzie, D., and Black, A.E. 2007. Cross-scale analysis of fire regimes. Ecosystems 10:809-823.

Farris, C.A. 2009. Spatial and temporal validation of fire-scar fire histories. PhD. Dissertation. University of Arizona, Tucson.

Fulé, P.Z., Henlein, T.A., Covington, W.W., and Moore, M.M. 2003. Assessing fire regimes on Grand Canyon landscapes with fire scar and fire record data. International journal of Wildland Fire 12(2):129-145.

Grissino-Mayer, H.D. 2001. FHX2 – software for analyzing temporal and spatial patterns in fire regimes from tree rings. Tree-Ring Research 57(1):113-122.

Hessl, A. E., McKenzie, D., and Everett, R. 2004. Drought and Pacific Decadal Oscillation linked to fire occurrence in the inland Pacific Northwest. Ecological Applications 14(2):425-442.

Iniguez, J.M., Swetnam, T.W., and Yool, S.R. In Press (2008). Topography affected landscape fire history patterns in southern Arizona, USA. Forest Ecology and Management. 256:295-303.

Li, C. 2002. Estimation of fire frequency and fire cycle: a computational perspective. Ecological Modeling 154:103-120.

Kitzberger, T., P. M. Brown, E. K. Heyerdahl, T. W. Swetnam, and T. T. Veblen. 2007. Contingent Pacific-Atlantic ocean influence on multi-century wildfire synchrony over western North America. Proceedings of the National Academy of Sciences 104(2):543-548

Kou, X, and Baker, W.L. 2006. A landscape model quantifies error in reconstructing fire history from scars. Landscape Ecology 21(5):735-745.

Krebs, C.J. 1998. Ecological Methodology. Benjamin-Cummings (2nd ed.). 576 pp.

Magurran, A.E. 2004. Measuring biological diversity. Blackwell Publishing, Malden, MA. 256 pp.

McKenzie, D., D.L. Peterson, and J.K. Agee. 2000. Fire frequency in the Columbia River Basin: building regional models from fire history data. Ecological Applications 10:1497-1516.

McKenzie, D., Hessl, A.E., Kellogg, L.B., and Morgan-Martinez, A.M. 2006. Using neutral models to identify constraints on low-severity fire regimes. Landscape Ecology 21:139-152.

Morino, K. A. 1996. Reconstruction and interpretation of historical patterns of fire occurrence in the Organ Mountains, New Mexico. M.S. Thesis, The University of Arizona, Tucson, AZ. 144 p.

Morrison, P.H. and Swanson F.J. 1990. Fire history and pattern in a Cascade landscape. Pacific Northwest Research Station, USDA Forest Service, PNW-GTR-254.

Neuenschwander, L.F. and Samson, R.N. 2000. A wildfire and emissions policy model for the Boise National Forest. Journal of Sustainable Forestry 11(1/2):289-309.

Parsons RA, Heyerdahl E.K., Keane RE, Dorner B, and Fall J. 2007. Assessing the accuracy of surface fire histories: Simulation modeling of point fire frequency across landscapes. Canadian Journal of Forest Research. 37:1605-1614.

Romme, W.H. 1980. Fire history terminology: report to the ad hoc committee. Rocky Mountain Research Station, USDA Forest Service. RM-GTR-81. Proceedings of the Fire History, Workshop. Stokes, M.A., Dieterich, J.H. (Tech. Coords.)

Saguaro National Park. Fire and resource management database. On File, 3693 South Old Spanish Trail, Tucson, Arizona 85730

Stephens, S.L., Skinner, C.N., and Gill, S.J., 2003. Dendrochronology-based fire history of Jeffrey pine-mixed conifer forests in the Sierra San Pedro Mártir, Mexico. Canadian Journal of Forest Research 33:1090-1101.

Stokes, M.A. and Smiley, T.L. 1968. An introduction to tree-ring dating. University of Chicago, Chicago.

Swantek, P. J., Halvorson, W. L., and Schwalbe, C. R. 1999a. Analysis of fire history in Saguaro National Park using geographic information systems. George Wright Society Biennial Proceedings: 10:121-124.

Swantek, P. J., Halvorson, W. L., and Schwalbe, C. R. 1999b. GIS database development to analyze fire history in southern Arizona and beyond: an example from Saguaro National Park. U.S. Geological Survey, Cooperative Park Studies Unit, University of Arizona, Tucson. Tech. Report No. 61. 43 p.

Swetnam, T. W. and Baisan, C. H. 2003. Tree-ring reconstructions of fire and climate history in the Sierra Nevada and Southwestern United States. *In* Fire and climatic change in temperate ecosystems of the western Americas. Ecological Studies Vol. 160. Springer, New York, pp. 158-195.

Swetnam, T. W. and Baisan, C.H. 1996. Historical fire regime patterns in the Southwestern United States since AD 1700. Rocky Mountain Research Station. USDA Forest Service General Technical Report RM-GTR-286:11-32. Proceedings of the Second La Mesa Fire Symposium, Los Alamos, New Mexico, March 29-31. Allen, C.D.

Swetnam, T.W. and Betancourt, J.L. 1998. Mesoscale disturbance and ecological response to decadal climatic variability in the American Southwest. Journal of Climate 11:3128-3147

Taylor, A.H., and Skinner, C.N. 1998. Fire history and landscape dynamics in a late-successional reserve, Klamath Mountains, California. Forest Ecology and Management 111:285-301.

Taylor, A.H., and Skinner, C.N. 2003. Spatial patterns and controls on historical fire regimes and forest structure in the Klamath Mountains. Ecological Applications (13(3):704- 719.

Turner, M.G. and R.H. Gardner, O'Neill, R.V. 2001. Landscape Ecology in Theory and Practice. Springer-Verlag, New York, NY.

Van Horne, M.L., and Fulé P.Z. 2006. Comparing methods of reconstructing fire history using fire scars in a southwestern USA ponderosa pine forest. Canadian Journal of Forest Research 36(4):855-867

Veblen, T.T. 2003. Key issues in fire regime research for fuels management and ecological restoration. USDA Forest Service General Technical Report RMRS-P-29: 259-276. Fire, fuel treatments, and ecological restoration; conference proceedings. P. N. Omni et al. tech. coords.

Table 1. Fire frequency, mean fire interval (MFI), and natural fire rotation (NFR) in the Mica Mountain study area (2,780 hectares) for the 20th and 19th centuries calculated from the full fire-scar dataset.

	20th century [a]	19th century
Frequency (fires/century) [a]		
All fires	42	48
10% fires	14	15
25% fires	4.7	11
Composite MFI (years)		
All fires	2.2	2.2
10% filter	6.9	6.7
25% filter	25.5	8.0
NFR by Source Data (years)		
Fire atlas maps	26.4	not available
Fire scars (no filter)	23.4	9.2

[a] Twentieth century data are from1937 to 2000; normalized to a 100 year period

Table 2. Sampling considerations for different fire history objectives using fire-scar records in ponderosa pine landscapes (or other surface fire dominated fire regimes).

Fire History Objective	*Goal*	*Sampling Approaches*
Quantify Climate-Fire Relationships	- Identify major fire years - Obtain long temporal record - Efficient and extensive sampling - Non-spatial (or spatially implicit with networks)	- Target multiple scarred and old records - Categorical filtering to identify 'major' fire years - Composite old samples at stand level - Obtain multiple, widely dispersed sample networks
Representative Estimation of Fire Frequency Parameters	- Determine fire frequency parameters for a given area and/or or vegetation types - Spatially implicit to broadly explicit - Differentiate between small and large fires relativistically - Identify broad-scale variation in fire frequency within and between study areas	- Dispersed, representative sampling units (targeting OK if sample size/distribution adequate) - Individual tree or dispersed cluster sampling - Composite at small cluster or stratified study unit scale - Filtering for relative fire size - Use synchrony or polygons to estimate burned area
Spatially Explicit Fire Frequency Surface (continuous)	- Determine spatially explicit variation in fire frequency - Predict fine-scale variation between sample units - Input into landscape simulation models or other landscape ecology applications	- Intensive sampling (depends on desired spatial resolution). - Uniform spatial coverage desirable (and/or stratified sampling) - Spatially explicit interpolation of fire size and perimeters - Composite stands to capture widespread fires at 'points'

Figure 1. Location of the Mica Mountain study area and fire scar sampling plots in Saguaro National Park, southern Arizona.

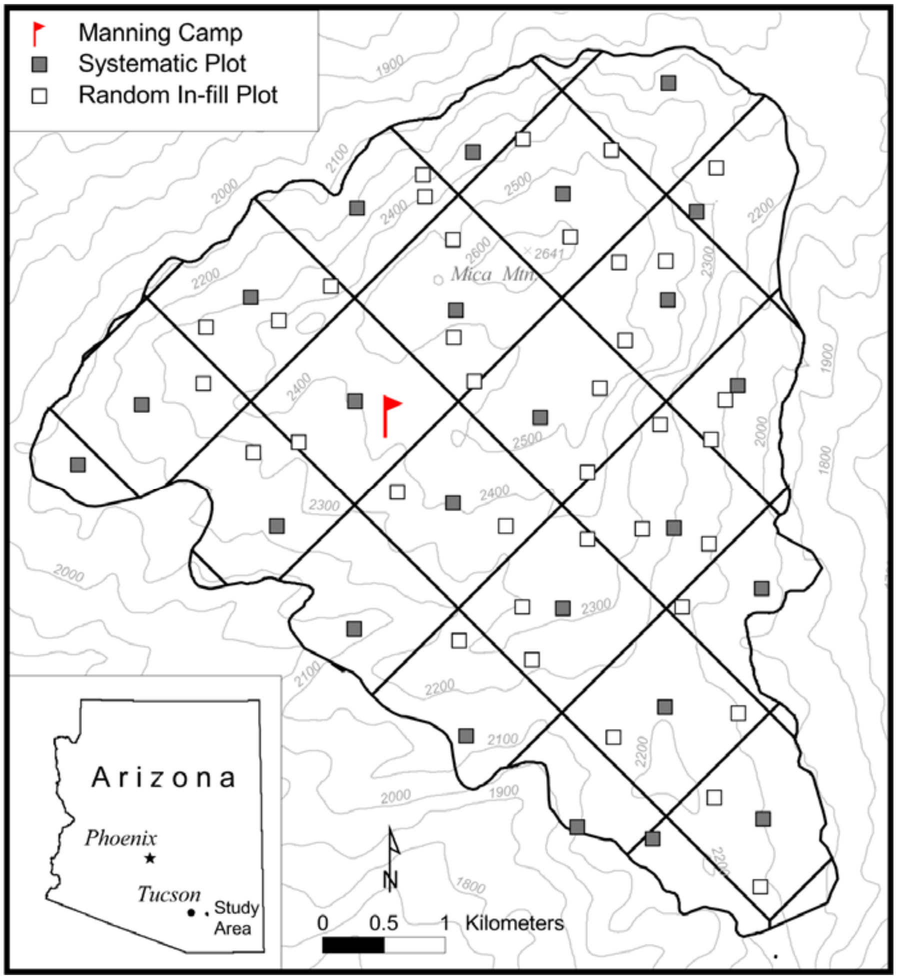


Figure 2. Proportion of mapped fire years detected by fire scars from 1937 to 2000 for different sample sizes (plots) and area burned filters. Area burned was derived from NPS fire atlas data. The "All Fire years" filter includes any fire year regardless of area burned (n = 63). The filtered fire years include only fire years in which more than 20 ha (n = 15), 200 ha (n = 8), and 400 ha (n = 4) burned respectively. For each sample size, the mean of 200 random combinations of *n* plots is shown.

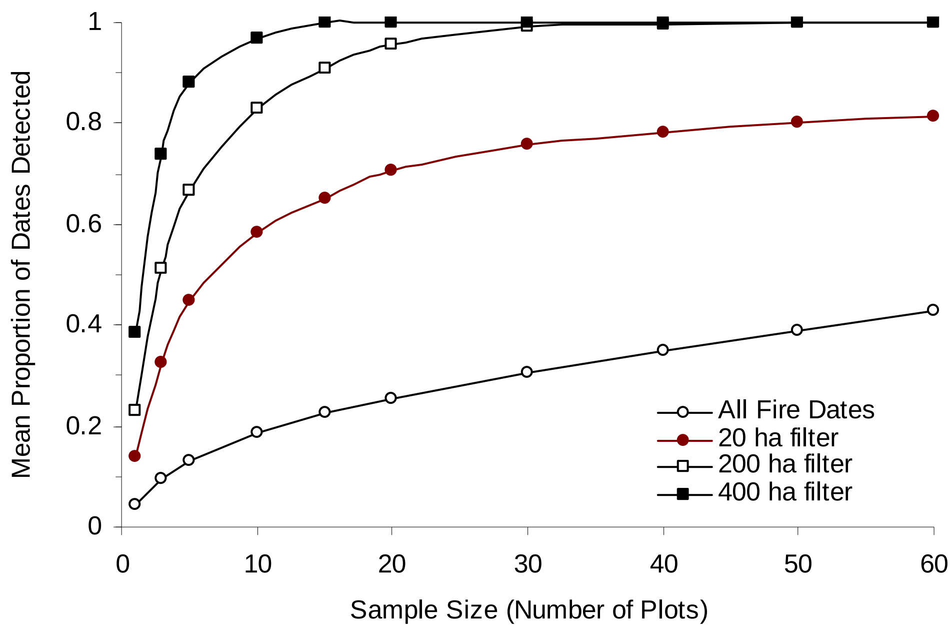


Figure 3. Influence of scale (sampling extent) and annual area burned on the detection of fire years during the 20th century. The solid line shows the mean proportion of total NPS fire atlas dates at different scales. The symbols show the mean proportion of NPS fire atlas dates detected by fire-scar data at each scale.

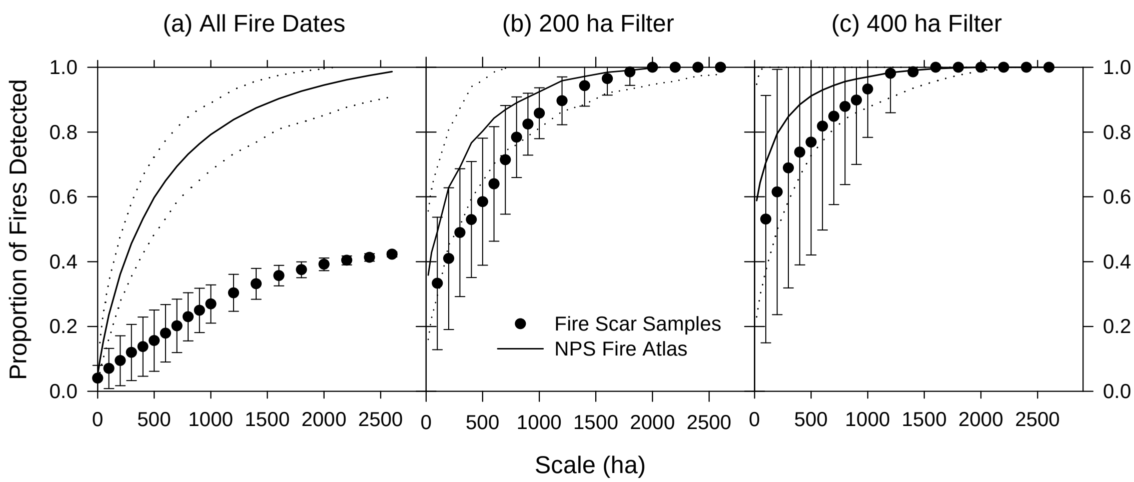


Figure 4. Influence of sample size (number of plots) on the relationship between fire-scar synchrony and area burned between 1937 and 2000. Data are plotted for the 14 years in which two or more plots recorded a fire. The proportion of the 2,780 ha study area that burned was obtained from the NPS fire atlas. For each sample size, the results of 200 combinations plots randomly drawn from the full dataset are plotted. Dashed lines show the 95% prediction interval.

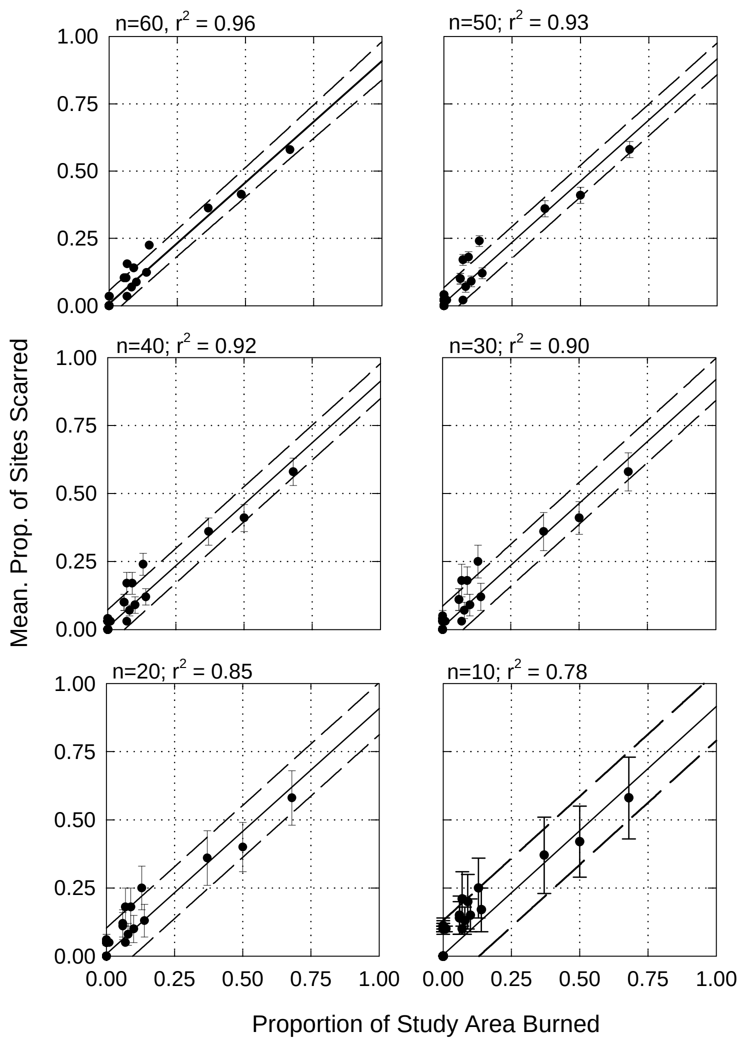


Figure 5. Influence of sample size (number of plots) and filtering on fire frequency and the Mean Fire Return Interval (MFI) for the 20th and 19th centuries. For each sample size, the mean (symbols) and standard deviation (brackets) of 200 combinations of *n* plots randomly drawn from the full dataset are shown.

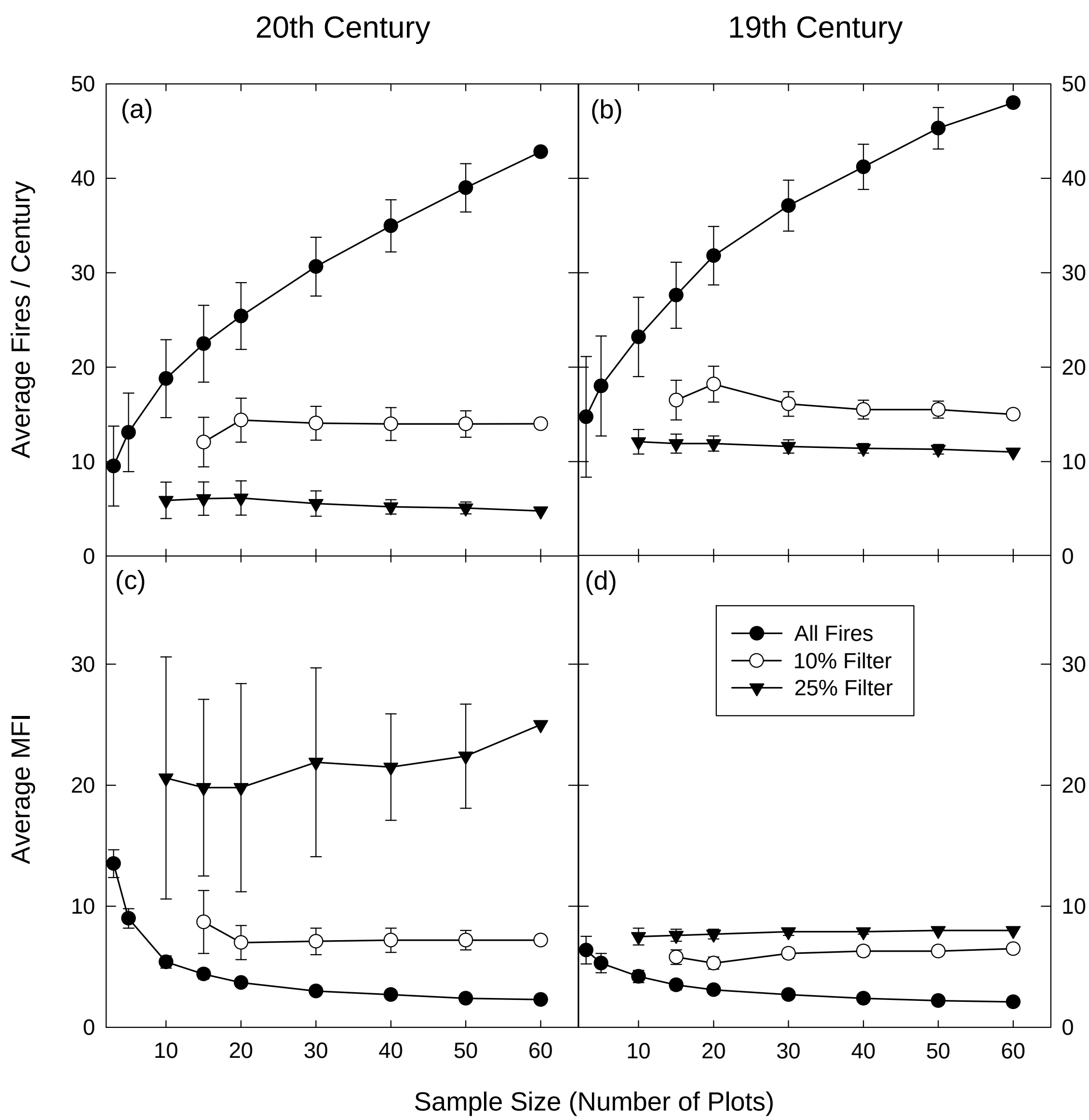


Figure 6. Influence of sample size (number of plots) on the Natural Fire Rotation (NFR) estimated from fire-scar data. For the 2-plot filter, only fire years are used in which 2 or more plots recorded a fire. The mean (symbol) and standard deviation (bracket) are shown for 200 randomly drawn combinations of plots for each sample size.

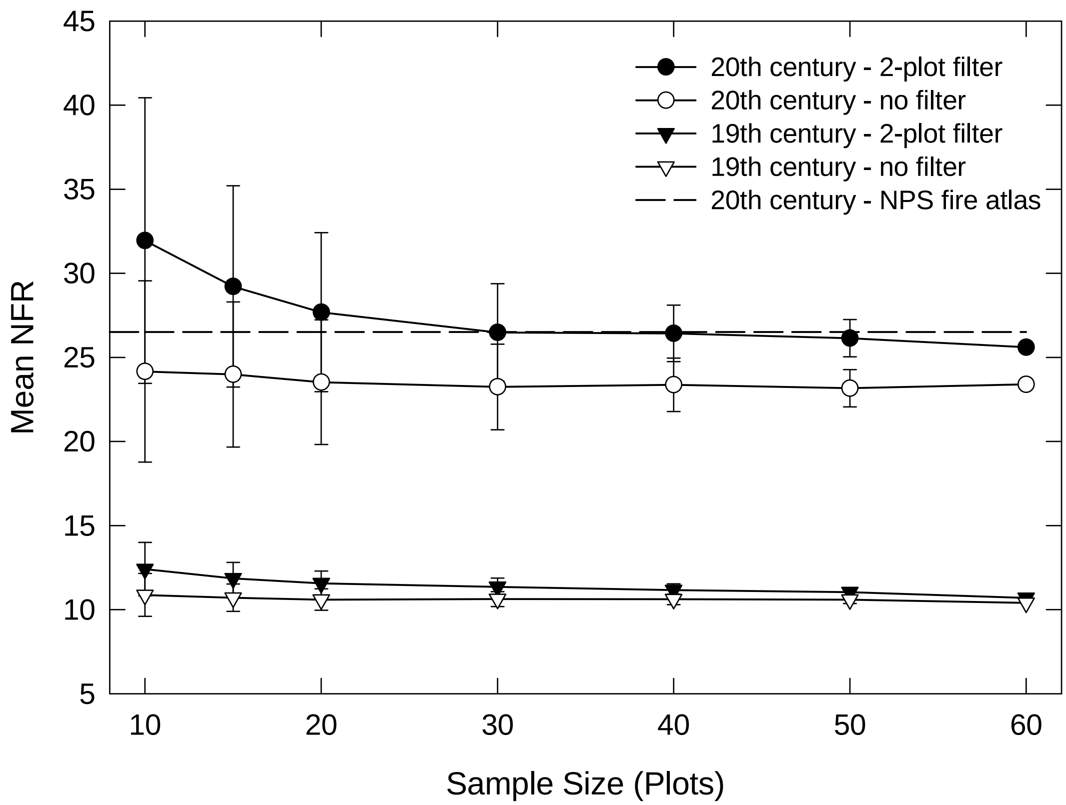


Figure 7. Influence of scale and filtering on fire frequency and Mean Fire Return Interval (MFI) for the 19th and 20th centuries. For each contiguous sampling extent (ha) on the x-axis, the mean (symbols) and standard deviation (brackets) of fires and MFIs are shown.

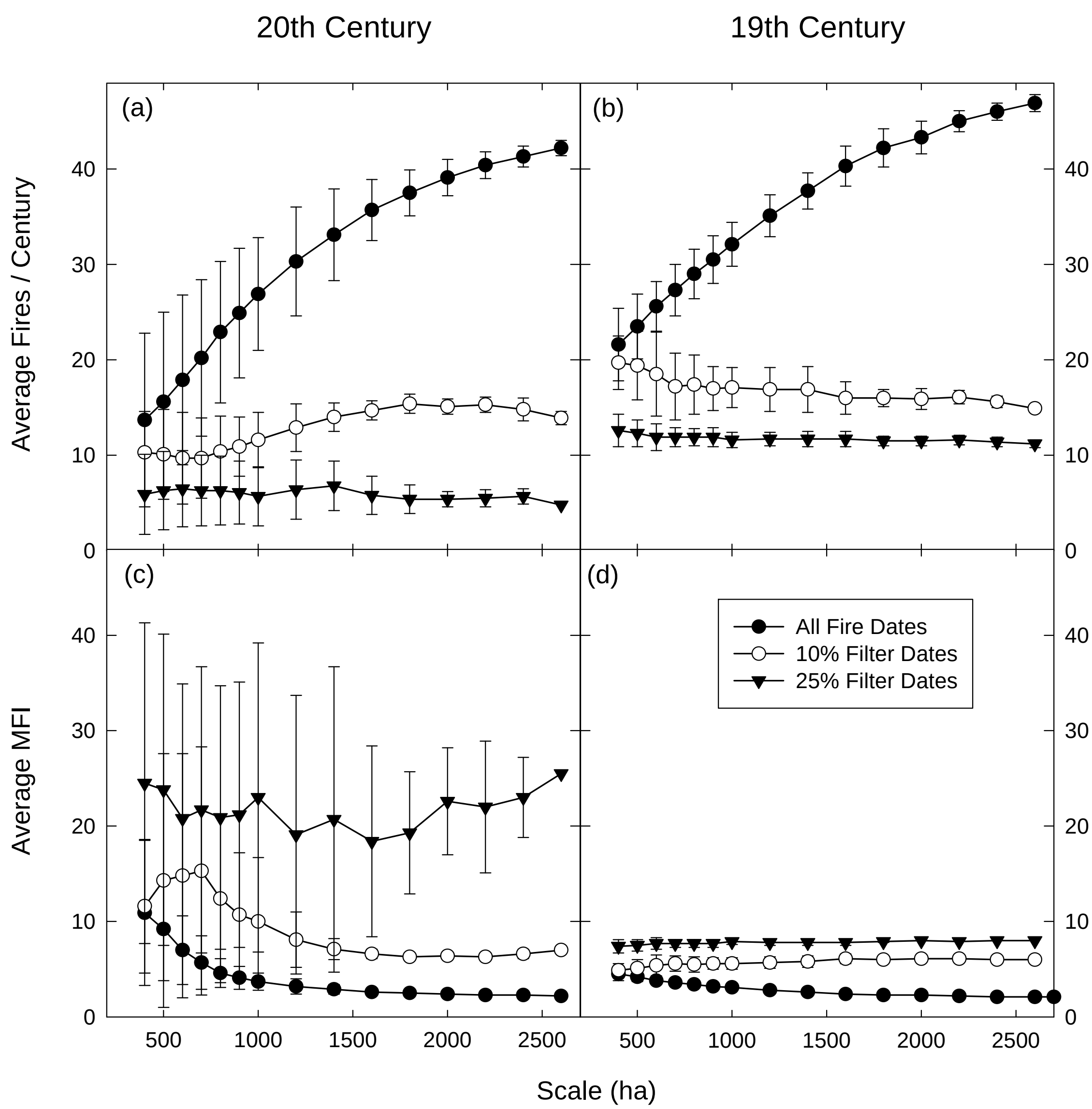


Figure 8. Relationship between scale and Natural Fire Rotation (NFR) for the 20th and 19th centuries. The mean (symbols) and standard error (brackets) of possible sample extents are shown. Fire scar estimates were done using all data and a 2-plot filter. The NPS fire atlas NFR was derived using the 414 mapped fire locations.

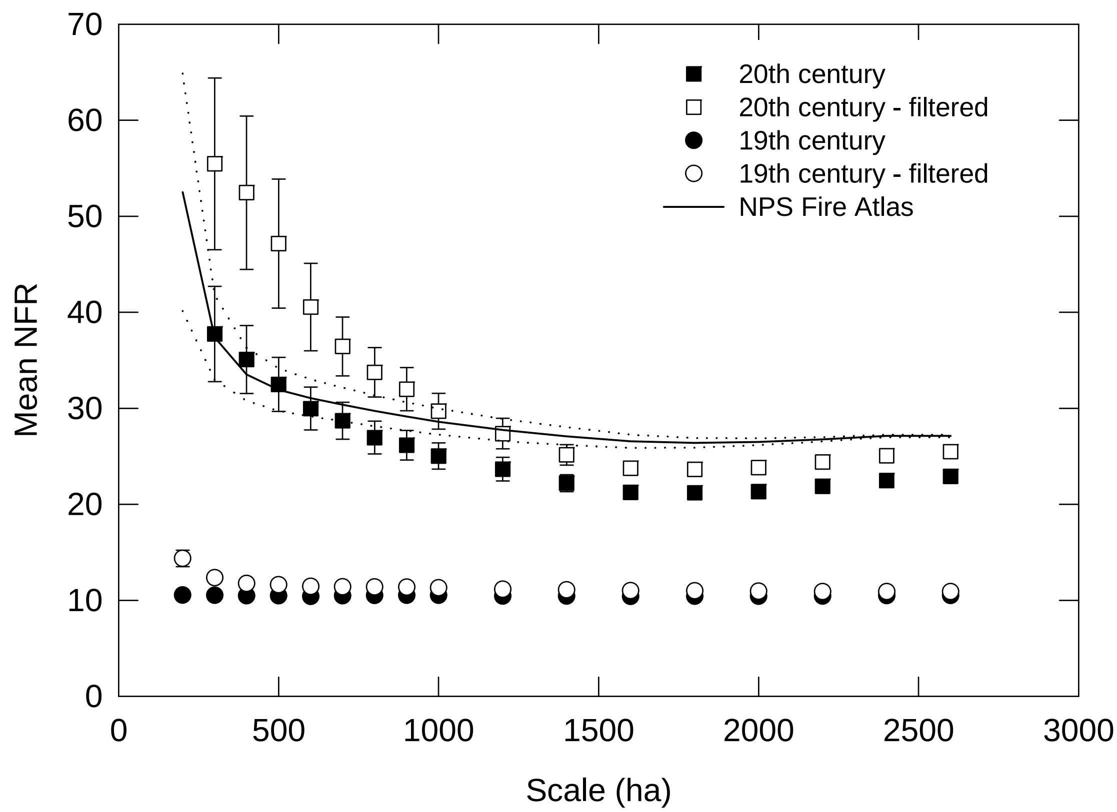


Figure 9. Influence of sample size and scale on the ratio between filtered and unfiltered Mean Fire Return Intervals (MFI) for the 20th and 19th centuries.

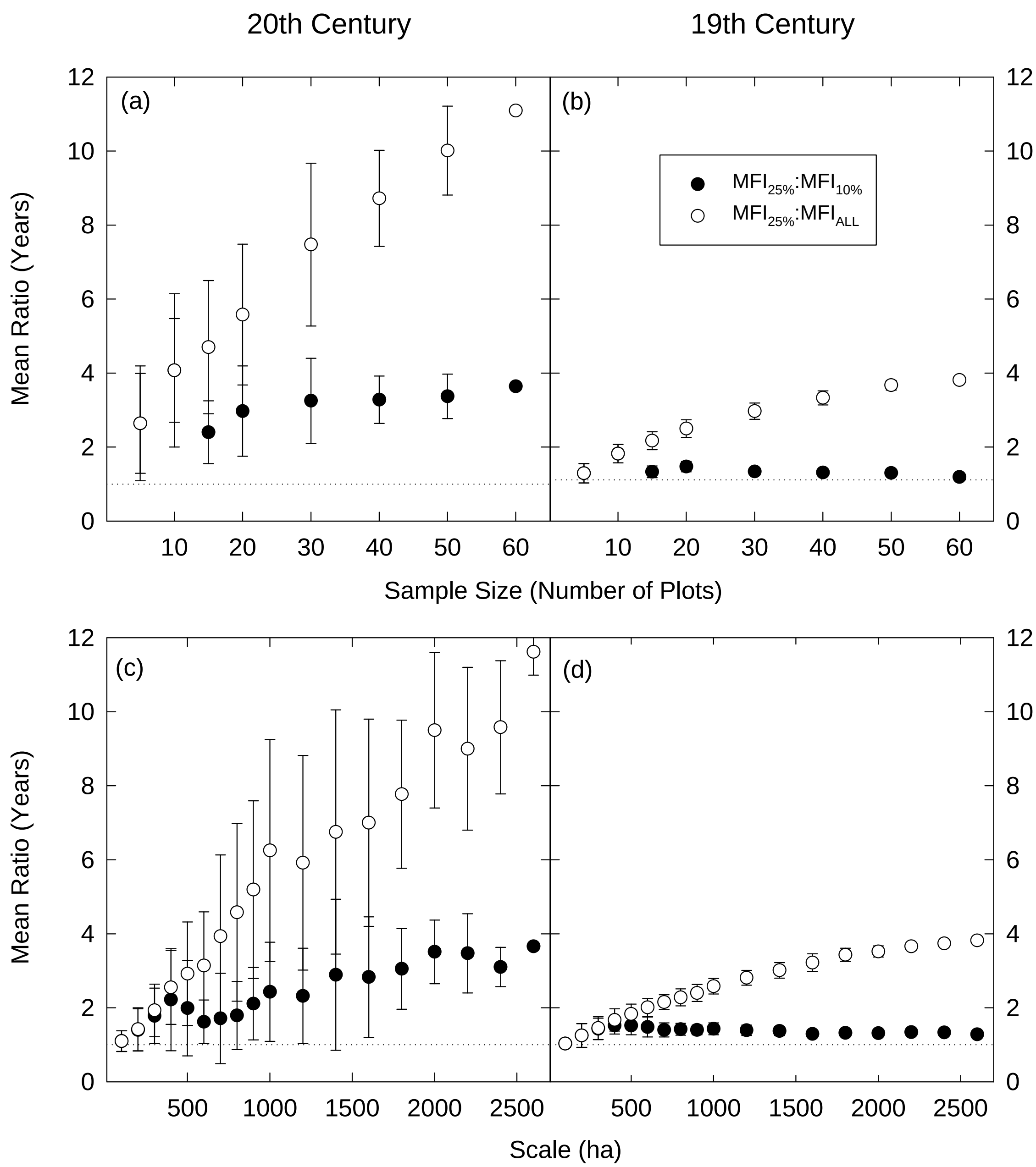
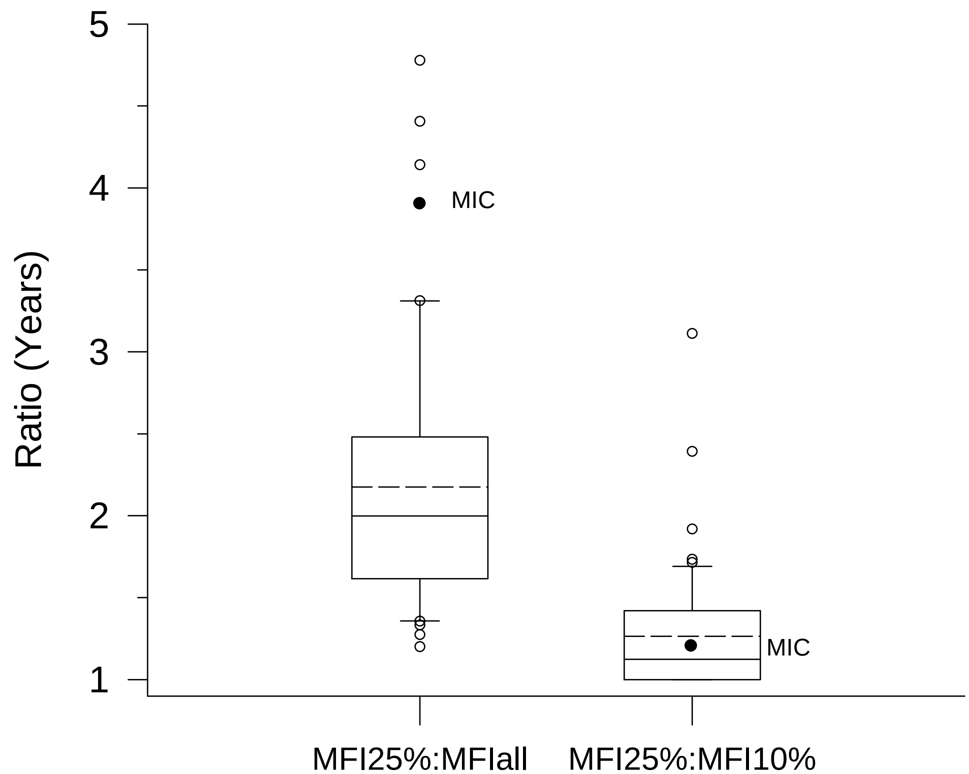


Figure 10. Ratio of the $MFI_{25\%}$:$MFI_{10\%}$ and $MFI_{25\%}$:MFI_{all} for 54 pre-settlement (pre-20th century) ponderosa pine fire histories across the Southwest (Swetnam and Baisan 1996). The ratios for the full dataset from this study on Mica Mountain (MIC) are shown with a black circle for comparison. The dashed horizontal bar is the mean and the solid horizontal line is the median.



APPENDIX C

TARGETED FIRE-SCAR SAMPLING CAN ACCURATELY AND EFFICIENTLY ESTIMATE PAST FIRE REGIME PATTERNS IN SOUTHWESTERN PONDEROSA PINE FORESTS

CALVIN A. FARRIS

(Paper in Peer Review, Canadian Journal of Forest Research)

Targeted fire-scar sampling can accurately and efficiently estimate past fire regime patterns in Southwestern ponderosa pine forests

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Abstract

Fire historians typically employ various forms of search-based sampling to “target” specimens containing visible evidence of well-preserved fire scars. Targeted sampling is thought to be the most efficient way to increase the completeness and length of the fire-scar record, but the extent of error and bias of targeting for the estimation of fire history parameters is poorly understood. We compared key temporal and spatial fire occurrence parameters reconstructed from targeted and probabilistic (i.e., “non-targeted”) fire-scar sampling techniques to identify sources of potential sample bias. Data were analyzed in a meta-analysis of three separate case studies spanning a broad geographic range of ponderosa pine ecosystems across the Southwest and multiple spatial scales: Centennial Forest in northern Arizona (100 ha), Monument Canyon Research Natural Area (RNA) in central New Mexico (256 ha), and Mica Mountain in southern Arizona (2,780 ha). Our results showed that targeted and non-targeted fire-scar samples recorded fire years in nearly equal proportions at all three study areas, which is strong evidence against an inherent bias in targeted sampling. Commonly reported fire frequency summary statistics – including the Mean Fire Return Interval (MFI) and Natural Fire Rotation (NFR) – varied by a maximum of 3.7 years between targeted and non-targeted data at all three study areas. Consistent with theoretical expectations, targeted fire-scar data provided clear advantages in terms of overall sample depth and efficiency. These results demonstrate that targeted sampling can produce accurate estimates of temporal and spatial fire history parameters similar to those derived from intensive non-targeted sampling. Our results also reaffirm conclusions from previous fire history research in

Southwestern ponderosa pine forests that relatively widespread fires occurred frequently (<15 years on average) prior to 20th century fire exclusion.

Introduction

Fire scars on living and dead trees are the primary source of proxy evidence used to estimate frequency and extent of historical fires in forests dominated by low severity surface fires. Accurate fire history data are needed to understand long-term impacts of fire and climate on ecosystem dynamics and to help guide fire and resource management decisions. A major challenge for fire historians is to efficiently sample the fire-scar record to reconstruct fire regime parameters that are both temporally long and spatially representative. Like other paleoecological data, individual fire-scarred specimens provide only a partial record of past fire events for a given point location and time period. Many fires that burn around the base of trees do not form a fire scar, and many scars are destroyed by subsequent fires, decay, weathering and tree mortality (Lachmund 1921, Weaver 1951, Dieterich and Swetnam 1984, Swetnam and Baisan 1996a, Falk 2004, Van Horne and Fulé 2006, Collins and Stephens 2007). Thus, while the presence of a scar is positive evidence of the presence of a fire, the absence of fire-scarred specimens or individual scars does not affirmatively prove the absence of fire (Van Horne and Fulé 2006, Farris et al. submitted). Spatial and temporal variation in scar formation and retention can result in a highly variable fire-scar record across the landscape (Swetnam and Baisan 1996a, Falk 2004), and the quality of the record declines with increasing time before present (i.e., “the fading record” problem in paleo-studies, Swetnam et al. 1999).

Given the heterogeneous spatial and temporal distribution of fire scars in most landscapes, random or systematic sampling (i.e., probabilistic) of trees is not always be practical or efficient for obtaining complete and lengthy records of past fires (Swetnam and Baisan 1996a, Allen et al. 2002, Fulé et al. 2003a). Fire historians have instead traditionally employed various forms of search-based sampling to “target” samples containing well preserved, ancient, and spatially distributed fire scars (Swetnam and Baisan 1996a, 1996b, Fulé et al. 2003a, Baker and Ehle 2001). The purported advantage of targeted sampling is that experienced researchers can locate high quality specimens, which thereby increase the likelihood of obtaining more complete inventories of fire events and lengthy records, especially of widespread events that tend to constitute the majority of area burned (Swetnam and Baisan 1996a, Van Horne and Fulé 2006). Targeted sampling is defined most simply by what it is not: purely unbiased or probabilistic sampling. In practice targeted sampling may be highly variable among studies and researchers because it involves expert knowledge used to evaluate site and specimen conditions, and it often incorporates elements of traditional sampling strategies such as landscape stratification or spatial partitioning of searches. The characteristics of trees with high quality fire scars can also vary considerably, and researchers may target a variety of characteristics to achieve multiple objectives. Study areas and sampling locations, moreover, are often determined largely by the information needs or restrictions of land management units (e.g., National Parks or Forests) funding or authorizing the fire history project.

Despite the practical efficiency and widespread use of targeted sampling in fire history research, the validity of the approach for obtaining unbiased estimates of fire history parameters has been challenged on theoretical grounds (Johnson and Gutsell 1994, Minnich et al. 2000, Baker and Ehle 2001, 2003). Baker and Ehle (2001) hypothesized that targeting may produce biased estimates of large fire intervals and cumulative area burned. They argued that sites containing multiple-scarred specimens are likely to have experienced more frequent fires than sites with fewer scars, resulting in artificial inflation of estimated average fire extent. Baker and Ehle (2003) suggested that targeting multiple-scarred trees may actually result in an incomplete detection of important fire years (particularly ancient fires) that may be recorded on single-scarred specimens. Practitioners of targeting methods argue that purely probabilistic sampling (hereafter referred to as "non-targeted" sampling) is unlikely to result in a long, complete record of past fires unless (a) the fire-scar record is preserved evenly across the study area and/or (b) large sample sizes (perhaps hundreds of trees) are obtained at great expense to increase the chances of acquiring old, rare and irregularly distributed fire scars (Swetnam and Baisan 1996, Fulé et al. 2003a). Although random spatial sampling makes it possible to statistically estimate area-relevant parameter errors *a priori* (Johnson and Gutsell 1994), statistical inference in the context of the paleo fire-scar record may be misleading by implying greater confidence than is warranted about the absence of fire events (years).

To resolve these questions, empirical studies comparing statistical properties of targeted versus random and/or systematically derived fire histories are needed. This is especially important because most published fire histories in the Southwest (and elsewhere) have been based on some variation of targeting (Baisan and Swetnam 1996a, 1996b, Baker and Ehle 2001, Fulé et al. 2003a, Swetnam and Baisan 2003). Suitable datasets for such comparisons require the co-occurrence of spatially overlapping, independently collected targeted and "non-targeted" fire-scar data. Targeted sampling should occur either before non-targeted sampling or by independent field researchers to prevent unconscious, unintended bias of the search process. Non-targeted datasets must contain a sufficiently high density and distribution of samples to ensure a complete and representative baseline "statistical reference" for the targeted data. Given the great effort and expense required to sample fire scars, such comparative datasets are very rare and there are rarely incentives, other than scientific testing (as in this paper), to re-sample the same area with a different approach.

In the only rigorous study meeting these criteria published to date, Van Horne and Fulé (2006) conducted a complete census of 1,246 fire-scarred specimens (n = 648 cross-dated) following an independent targeted sampling effort (n = 36) in a 100 ha ponderosa pine forest in northern Arizona. They found composite mean fire return intervals (MFI) calculated from targeted data differed by less than one year from the census MFI and from randomly and systematically selected specimens (for the time period 1682 to 1881). However, their analyses did not explicitly compare key area-based fire frequency summary statistics (such as the Natural Fire Rotation) or fire year inventories, and it represents a single case study. Collins and Stephens (2007) found that "opportunistically" sampled fire-scar specimens underestimated total area-burned compared to fire perimeter maps (i.e., documentary sources), but no comparisons were made with non-targeted sampling. Similarly, Shapiro et al. (2007) found that systematically sampled fire-scar data correlated well with remotely sensed fire maps but no similar comparison was conducted with non-targeted sampling.

We present in this paper the first multi-site, multi-scale comparison of fire history parameters estimated from empirically targeted and non-targeted sampling approaches. Our comparison is based on a meta-analysis of three study areas: Mica Mountain in the Rincon Mountains of southern Arizona, Monument Canyon Research Natural Area in north-central New Mexico, and Centennial Forest of Northern Arizona University near Flagstaff, Arizona (the latter is an expanded analysis of Van Horne and Fulé 2006). These case studies, which collectively contain more than 1,300 cross-dated specimens and span three different spatial scales (100, 256, and 2,780 ha), are among the most comprehensive Southwestern examples of non-targeted fire-scar sampling. The analytical methods in this study have furthermore been empirically corroborated against independent 20th fire perimeter maps at Mica Mountain (Farris et al. submitted)

We address the following research questions. (1) Did targeted fire-scar data record fire years with the same relative proportion of samples as non-targeted data? (2) How similar were fire year inventories obtained from targeted and non-targeted data? (3) Did targeted sampling result in a systematic bias of frequency-based or area-based fire frequency summary statistics? (4) Were targeted fire-scar data more efficient than non-targeted sampling in terms of the length of the recovered fire history and the rate of fire-scar detection?

Fire History Case Studies

Centennial Forest, AZ (CEN)

The 100 ha Northern Arizona University Centennial Forest (CEN) study area is located near Flagstaff (Fig 1.). Van Horne and Fulé (2006) reconstructed independent fire histories for CEN using a targeted sampling approach first, followed by a complete "census" of all available fire-scarred material. For the targeted sampling, they searched representative stands in the study area and selected 36 distributed samples containing old, well-preserved records with multiple fire scars (Fig 1A, Tables 1-2). This targeted approach was designed to be consistent with previously published fire history research by Fulé and colleagues in Arizona and Mexico (see Fulé et. al. 1997, 2003, 2003b, 2005, Heinlein et al. 2005) and by others elsewhere (Swetnam and Baisan 1996a).

The non-targeted dataset consisted of a complete census of all remaining 1,246 trees/logs/stumps in the study area that had external fire scars visible, of which 612 were datable. The reference non-targeted data for the purpose of this analysis consists of the entire potential dataset of fire-scarred specimens that were not subjectively selected by targeted sampling. The targeted and non-targeted samples were collected to characterize the exact same area of inference (the CEN forest boundary) and overlapped spatially. Both datasets consist of distributed individual trees not constrained by plot boundaries.

Monument Canyon (MCN)

The 256 ha Monument Canyon (MCN) Research Natural Area study (RNA) area in northern New Mexico was established in 1932 on the Santa Fe National Forest as an example of unlogged ponderosa pine forest (Fig. 1). Touchan et al. (1995) conducted a targeted fire history of the RNA to quantify changes in fire return intervals during the pre-settlement and settlement eras. They searched for old specimens with the maximum number of visible fire scars in the northern portion of the RNA where road access was best. They collected 30 specimens (Fig 1B, Table 1 and 2). Fifteen additional samples not cross-dated at the time of publication (Touchan et al. 1995) were included in this analysis. The original area sampled was determined to be sufficiently representative of most of the RNA forest cover and landform, which is primarily ponderosa pine on a relatively level mesa top.

Falk (2004) conducted an independent fire history study for MCN using an intensive 200 m systematic grid to locate 50 1-ha fire-scar plots throughout the RNA. Within each plot they collected available fire-scarred specimens (an average of 4 dated samples per plot, totaling 198 dated specimens) and developed composite fire chronologies (*sensu* Dieterich 1980) for grid-point and the study area. Both datasets were collected to characterize the same area of inference (MCN RNA boundary), but the targeted data consisted of individual trees and the non-targeted data consisted of systematic plots containing groups of trees.

Mica Mountain (MIC)

The 2,780 ha Mica Mountain (MIC) study area is located in the Saguaro National Park Wilderness in southern Arizona (Fig. 1). The irregular study area boundary traces the lower coniferous forest ecotone of the Rincon Mountains (Fig. 1C). Baisan and Swetnam (1990) characterized pre-20th century fire history for the coniferous forest zone on MIC using targeted sampling of remnant wood. They surveyed the forest zone on foot along the trail system and selected subjectively 12 spatially distributed stands deemed to be representative of the prevailing forest cover and which contained visibly well-preserved and apparently old fire-scarred material (Fig 1C, Tables 1-2). Within each stand they collected fire-scarred specimens from a 1 to 2.5 ha area (total of 52 specimens) and developed composite stand level and study area fire-scar chronologies.

Farris (2009) conducted an independent, non-targeted fire history for MIC. Twenty-four systematic 1-ha fire-scar plots were established from a randomly initiated 1.2 km grid, followed by 36 random plots between the grid points (Fig. 1C, Tables 1-2). Within each plot an average of 6 fire-scarred cross sections were selected from living trees and remnant wood (i.e., logs, stumps, snags). Where there was an abundance of material, trees with visible well-preserved fire scars were selected from both old and young specimens to maximize the length and completeness of the temporal record. Both datasets thus consisted of a series of small plots (termed "clusters" in Baisan and Swetnam 1990) selected either subjectively or systematically/randomly. Both studies were conducted to characterize fire history for the visibly distinct coniferous forest zone on MIC.

Methods

Study Area Descriptions

The CEN study area consists mostly of climax ponderosa pine (*Pinus ponderosa* P. & C. Lawson) forests with occasional Gambel oak (*Quercus gambelii* Nutt.) in the understory. Elevation ranges from about 2100 to 2200 m with no major prominent topographic features. Fuels are continuous with no significant natural barrier to fire spread. Average annual precipitation in Flagstaff is approximately 54 cm with most of the precipitation falling in late winter (Jan – Mar) and late summer (Jul – Aug). Heavy livestock grazing occurred in the 1880's resulting in the cessation of widespread fires. Some high-grade logging also occurred in the late 1800's. Fire suppression has prevented major fires in CEN during the twentieth century.

The MCN study area consists mostly (about 80%) of nearly pure ponderosa pine forests on relatively level mesa tops between 2,500 and 2,550 m elevation. The remaining 20% of the study area is dissected by north-northeast ravines dropping to as low as 2,350 m that support a component of Douglas-fir (*Pseudotsuga menziesii* (Mirbel) Franco), white fir (*Abies concolor* (Gord. & Glend.) Lindl. ex Hildebr) and southwestern white pine (*Pinus strobiformis* Engelm.). Average annual precipitation at Jemez Springs (3.5 km away but 200 m lower in elevation) is 46.5 cm with about half falling in late summer (Jul-Aug) and half in winter (Oct-Mar) (Falk 2004). Heavy livestock grazing resulted in cessation of widespread burning around 1900, slightly later than more accessible areas in the region (Touchan et al. 1995, Falk 2004). No major fires have occurred since the early 20th century and the area is not grazed or logged.

The MIC study area is dominated by ponderosa pine with southwestern white pine subdominant at higher elevations and evergreen oak species at lower elevations. Small stands of isolated mixed conifer, dominated by ponderosa pine, Douglas-fir, white fir, southwestern white pine and Gambel oak are limited to small ravines on the north slope of Mica Mountain. Elevation ranges from 2000 m to 2641 m. Terrain ranges from gentle slopes near top of the mountain to steep dissected canyons at the mid to lower elevations. Average annual precipitation at Manning Camp Ranger Station (2438 m) is 89 cm with most falling in late summer (Jul-Aug) and winter (Oct-Mar). MIC has been managed by the National Park Service since 1933 and is not logged or grazed.

Study Duration and Sampling Units Considerations

Variation in non-targeted sampling strategies and sample size at each study area required us to use different analysis units and time periods for each comparison. At MIC the common sample size unit for targeted and non-targeted data was the composite plot (targeted n = 12 plots; non-targeted n = 60 plots) and at CEN it was the individual tree (targeted n = 36 trees; non-targeted n = 612 trees). At MCN, where targeted data were collected as individual trees and non-targeted data were collected as composite plots (targeted = 45 trees; non-targeted = 50 plots/197 trees), we used the individual tree as the common sample unit for re-sampling analyses that utilized partial subsets of the full datasets.

We restricted our analyses to the time period from 1700 to 1900 for MCN and CEN and 1800 to 1900 for MIC. These time periods contain the maximum sample size overlap between datasets and represent the pre-settlement era that targeted sampling is typically used to characterize in the Southwestern region (Swetnam and Baisan 1996a, Swetnam et al. 1999). At MIC the targeted sample size consisted of n = 12 plots so we could analyze data only back to 1800 in order to maintain at least 10 recording non-targeted plots, which was required for consistency when comparing filtered and re-sampled fire history summary statistics (described later).

Van Horne and Fulé (2006) included the 36 targeted trees at CEN as part of the full census in their original study, which by definition would include every tree. For the purpose of this study, we treated targeted and non-targeted trees independently as separate sample sets. This was appropriate because (a) our goal was to compare the statistical properties of subjectively targeted samples with those that were not targeted and (b) the probability that two or more of the 36 targeted trees would have been randomly selected from the 1,282 total scarred trees is very low (<0.001).

Data Analysis

Empirical Validation of Fire-Scar Reconstruction Methods

The MIC study area is relatively rare among ponderosa pine forests in the United States because it has experienced numerous large, overlapping fires during the 20th century (up to 9 between 1937 and 2000 in some stands). Detailed records of these fires, derived mostly from ground-based mapping maintained by the National Park Service since 1936 (NPS fire atlas), were used in a companion analysis (Farris et al. submitted) to validate the relative accuracy of fire-scar reconstruction methods used in this current study. There was very strong spatial and temporal agreement between fire-scar reconstructions and the NPS fire atlas data for all fire history parameters used in this current study (see Farris et al. submitted for more detail). Given that (a) the same fire-scar reconstruction methods field tested at MIC were applied at MCN and CEN, (b) the non-targeted sample density at MCN and CEN were considerably higher than MIC, and (c) the study areas are all broadly similar ecologically in terms of dominant vegetation and climate, it can be reasonably assumed that the non-targeted fire histories in this study are accurate and serve as suitable reference data.

Fire-Scar Synchrony

The proportion of fire-scar samples recording a given fire year (i.e., fire-scar synchrony) is correlated strongly with annual area burned for well distributed, non-targeted fire-scar data (Farris et al. submitted). To test whether fire-scar synchrony differed significantly between sampling methods, we plotted the proportion of non-targeted samples (x-axis) that recorded a given fire year against the proportion of targeted samples (y-axis) that recorded the same fire year. Only fire years detected by at least one sample in either dataset were plotted (i.e., double-zeros, years in which neither dataset recorded a fire were not plotted). If targeted and non-targeted data recorded fire synchrony in exactly the same proportion (i.e., rate of detection), we would expect a 1:1 line with a slope of 1.0. We used a two-sample Student's *t* statistic to test whether the regression coefficient for each study area (β) differed significantly from 1.0 (H_o: $\beta = 1.0$; $\alpha = 0.05$) (Zar 1999). We used a 1-sample Student's *t* statistic to test the hypothesis that targeted data are biased toward more frequently burned sites, as suggested by Baker and Ehle (2001), which would be reflected by regression slopes >1.0 (i.e., skewed toward higher targeted scarring percentages for each year; H_o: $\beta > 1.0$; $\alpha = 0.05$) (Zar 1999).

Study Area Fire Frequency Summary Statistics

The two most commonly reported summary statistics to characterize fire occurrence are the composite Mean Fire Return Interval (MFI) and the Natural Fire Rotation (NFR). The composite MFI is defined as the mean interval (years) between fires of any size, that occurred anywhere within a specified area and time period (Dieterich 1980, Romme 1980). With point-based fire-scar data, fire frequencies are often sorted or "filtered" by the percentage of samples scarred to provide a relative estimate of fire sizes. For example, $MFI_{25\%}$ would indicate the mean interval between fire years that scarred $\geq$25% of the recording samples, which may be inferred to be fires that were relatively more extensive than those recorded by a smaller percentage of samples. It is important to note that composite MFI does not necessarily equate to the average interval between fires at every single point on the landscape (i.e., the "population MFI", *sensu* Baker and Ehle 2001). Relatively stringent percentage filters ($\geq$25%) may approach this equivalence, as we have shown in 20th century documentary and fire-scar network comparisons for MIC (Farris 2009 et al. submitted), and as we show here in a later section.

The Natural Fire Rotation (NFR) is defined as the time (years) required to burn an area equal to the size of study area (Romme 1980, Agee 1993). It is calculated as,

(1) $$NFR = T \div P$$

where T is the time period being considered and *P* is the cumulative proportion of the study area burned during that period. Because *P* can be >1.0 and include the same acre more than once, in practice the NFR represents the average period of time required for an area equivalent to the study area to burn. The NFR does not necessarily indicate that the entire study area burned over at the same rate during a given time period; some areas may burn multiple times whereas others parts may burn less frequently or not at all.

We compared the MFI_{all} (i.e., all fire years), $MFI_{10\%}$, $MFI_{25\%}$, and NFR for each study area calculated from targeted and non-targeted datasets. These widely reported statistics represent a range of emphasis along the fire frequency-area continuum: the MFI_{all} is based on the frequency of fires (regardless of size), the NFR is based on cumulative rate of area burned, and the $MFI_{10\%}$ and $MFI_{25\%}$ are intermediate because they have both frequency and relative area burned components. Only scar-to-scar intervals were included in the MFI calculations because of ambiguity in interpretation of the period before the first scar (Van Horne and Fulé 2006). Annual area burned for NFR calculations was estimated from the relationship between fire-scar synchrony and fire size as,

(2) $A_i = (SA)(P_i)$

where A_i is the area burned in the i^{th} year, SA is the study area size (ha), and P_i is the proportion of recording samples in the i^{th} year that detected a fire scar (Taylor and Skinner 1988, Morrison and Swanson 1990, Farris et al. submitted). This approach for estimating the NFR has been shown empirically to be accurate when samples are broadly distributed and sample size is high (as is the case for all three non-targeted datasets examined here) (Farris et al. submitted). It is also robust for smaller sample sizes if fires are large relative to the study area (Farris 2009 Appendix B).

To account for the large differences in sample size between the targeted and non-targeted datasets, we also calculated each fire interval statistic by correcting for sample size using a bootstrapping procedure (Krebs 1988). At each study area, three-hundred combinations of *n* non-targeted samples were randomly selected from the full dataset, where *n* was the sample size of the corresponding targeted dataset (Table 1). At MCN we calculated non-targeted values using both individual trees and composite plots to account for potential sample unit differences. A two-tailed Mann Whitney U Test (Zar 1999) was used to determine if there were significant differences between targeted and non-targeted metrics ($\alpha = 0.5$).

We constructed frequency histograms to analyze variability around the mean of the study area MFI and NFR. The MFI is the mean of a distribution of individual fire free intervals (Falk 2004). We used the mean number of bootstrapped intervals to account for large sample size differences. The NFR consists of a frequency distribution of individual rotation intervals when $P > 1.0$ (equation 1). Each individual rotation interval is the time required to burn an area equivalent to the study area once. We tested for differences in the distribution of composite fire intervals and rotation intervals between targeted and non-targeted data using a two-sample Kolmogorov-Smirnov Test (Zar1999).

Stand Level Fire Frequency Distribution

The previously described analyses examine fire history summary statistics for the entire study area. To determine whether individual stands selected subjectively by targeted sampling burned more frequently than non-targeted stands, we compared the frequency distribution of stand-level MFI values for composite plots at MIC. This analysis could not be performed at MCN or CEN without major assumptions because the targeted sample unit consisted of dispersed individual trees that were not restricted to distinct stands or spatially discrete areas (i.e., plot clusters). Individual trees are imperfect recorders so individual comparisons between trees could represent differences in scar formation and preservation rather than actual fire occurrence, and for an undefined area beyond the bole (Dieterich 1980, Farris et al submitted).

Inventory of Categorical Fire Years

Categorical groupings of fire years sorted (or filtered) by relative size are used for some types of analyses, such as determining the relationship between climate and "major" fire years (e.g., Swetnam and Betancourt 1998). For each calendar year, we compared agreement between filtered and unfiltered fire-scar years classified from targeted and non-targeted sampling using matched 2x2 contingency tables (Zar 1999). One of four possible outcomes was tallied for each year: 1) a fire year was detected by both datasets, 2) a fire year was detected by only the targeted dataset, 3) a fire year was detected by only the non-targeted dataset, and 4) no fire scar was recorded by either dataset. Tables were constructed for all fire years, fire years recorded by $\geq$10% of samples, and fire years recorded by ≥25% of samples to assess how agreement varied with relative area burned.

Sampling Efficiency and Depth

Sample efficiency was assessed using three broad measures. We first analyzed sample size efficiency for small and large fire years using rarefaction curves to quantify proportion of total fire years detected as a function of sample size (Morino 1996, Stephens et al. 2003, Swetnam and Baisan 2003, Falk 2004, Magurran 2004). For a given sample size (*n*), bootstrapping (Krebs 1998) was used to estimate the mean number of years detected from 200 random combinations of *n* samples from the full dataset. These values were plotted as a function of sample size for all fire years and for fire years that scarred ≥25% of samples (i.e., larger fires).

A second measure of efficiency tested was average fire-scar density, or number of scars per sample for a given time period of interest. A Mann-Whitney U test (Zar 1999) was used to determine if average fire-scar density differed significantly between targeted and non-targeted samples.

Because fire intervals are generally defined as the time between successive fire scars, trees are considered to be potential "recorders" of fire between the first scar and outer ring date (*sensu* Romme 1980). Sample depth refers to how many samples in a given dataset are potential recorders of fires during any given year. If targeted samples contain longer and more complete records of fire years, sample depth should be proportionately higher for a longer period than for non-targeted samples. We compared proportional sample depths between targeted and non-targeted data by plotting the proportion of total samples capable of recording fire intervals over time.

Results

Fire Scar Synchrony

There was a strong linear relationship between the proportion of targeted and non-targeted samples that recorded fire-scar years at all study sites (Fig. 2). Slope coefficients (β) approached 1.0 at all three study sites indicating that targeted and non-targeted samples detected fire years in nearly equal proportion (CEN $\beta = 0.87$, $r^2 = 0.73$; MCN $\beta = 0.86$, $r^2 = 0.91$; MIC $\beta = 1.05$, $r^2 = 0.84$.). The two-tailed test of the null hypothesis of $\beta = 1.0$ was not rejected at CEN ($p = 0.16$) and MIC ($p = 0.84$) but was rejected at MCN ($p = 0.02$). The two-tailed test of the null hypothesis of $\beta > 1.0$ was rejected for all study areas ($p < 0.001$), indicating that targeted data were not biased toward higher rates of detection relative to non-targeted data.

Fire Frequency Summary Statistics

All fire frequency summary statistics calculated from targeted and non-targeted data were very similar for each study area (Table 3): At CEN and MIC, no summary statistic differed by more than 1.6 years, regardless of whether sample size corrections using bootstrapping were applied. At MCN the maximum difference between summary statistics was slightly larger, 3.4 years. Of the 30 row comparisons in Table 3 (counting both individual tree and plot comparisons at MCN), the only statistically significant difference was the MFI_{all} at MCN using uncorrected sample sizes ($p = 0.03$). The absolute difference between those two statistics, however, was just 1.8 years.

The frequency distributions of individual MFI and NFR intervals were also similar between targeted and non-targeted data (Fig. 3 and 4): Sample size corrected composite fire intervals did not differ significantly for analyses based on all fire years (CEN $p = 0.85$; MCN $p = 0.75$; MIC $p = 1.0$) or 25%-filtered fire years (CEN $p = 1.0$; MCN $p = 0.94$; MIC $p = 1.0$). A small number of non-targeted large fire (25%-filter) intervals were slightly longer than maximum intervals observed for targeted data (Fig. 3), but these accounted for <1% of the 3,342 bootstrap estimates. The probability of bootstrapped intervals at the 25%-filter level being >20 years was <0.5% at CEN (max 40 yrs.) and MCN (max 25 yrs.), and 0% for MIC. Fire rotation intervals for targeted trees were skewed slightly toward longer intervals than targeted trees at MCN, but the difference was not statistically significant (CEN, $p = 0.96$; MCN, $p = 0.29$; MIC, $p = 1.00$).

Stand Level Fire Frequency

The frequency distribution of stand level composite MFI values for individual plots at MIC did not differ significantly ($p = 0.89$) between targeted (mean = 9.1) and non-targeted data (mean = 9.6) (Fig. 5). This indicates that stands within MIC selected subjectively for targeting did not burn more frequently on average than stands selected systematically or randomly. Minimum and maximum plot MFI differed by only one and three years respectively between datasets.

Fire Year Inventory

Categorical classification of fire-scar years between targeted and non-targeted datasets (without sample size correction) varied depending on relative fire size and study area size (Table 4). There were fewer classification discrepancies for large fire (filtered) years than unfiltered fire years at all study areas: overall matrix agreement for 25%-filtered fire years was 99% at MIC, 97% at MCN, and 93% at CEN. Classification agreement for large fire years increased with increasing scale (study area size) but the opposite was true for "all" fire years. This is due in part to differences sampling and scale. Individual tree data at CEN and MCN are more variable than composite plots and MIC, and a 25%-filtered year in CEN could be as small as 25 ha whereas at MIC they were typically several hundred to thousands of hectares. The small number of fire years detected exclusively by targeted data is evidence against a targeted sampling bias.

Sample Size Efficiency and Sample Depth

The number of unfiltered fire-scar years increased sharply as a function of sample size, whereas the number of 25%-filtered fire-scar years was insensitive to sample size (Fig. 6). These results were consistent across all study areas. Targeted fire-scar data at CEN and MIC detected unfiltered fires at a slightly higher rate on average than non-targeted samples at small sample sizes. Rarefaction curves for 25%-filtered fire years were flat for all study areas, indicating no sample size dependence.

Targeted fire-scar data contained significantly more fire scars per sample unit than non-targeted data at all three study areas (CEN p = <<0.001; MCN p = <<0.001; MIC p = 0.03) (Fig. 7), consistent with the selection process of targeting, aimed at obtaining samples with well-preserved scars.

The overall length of the fire-scar record was similar between datasets at all three study areas despite the fact there were 4.4 to 17 times more non-targeted samples than targeted samples (Fig. 8). However, a consistently higher proportion of targeted samples were active recorders over that time period than non-targeted samples (Fig. 8). Targeted sampling thus produced equal or longer temporal records and with proportionately greater sample depth over time than non-targeted sampling.

Discussion

This research represents the most comprehensive comparison of empirically targeted and non-targeted fire-scar sampling across multiple study sites. Fire-scar synchrony and fire frequency statistics were very similar between targeted and non-targeted fire-scar data. Although targeted fire-scar data contained greater numbers of fire scars per sample, collectively they did not overestimate numbers or extents of widespread fire years relative to non-targeted data. Targeted samples instead contained more complete inventories of total fire years on average for the time periods analyzed. Consistent with theoretical expectations, targeted sampling resulted in proportionally greater sample depth and comparable temporal records despite significantly lower sample sizes than available for non-targeted data. These findings indicate that targeted fire-scar sampling can be a highly efficient and accurate approach for obtaining long-term fire histories.

Our findings are particularly robust for evaluating accuracy and potential biases of targeted sampling for reconstructing fire occurrence, for multiple reasons: (a) targeted fire-scar data were collected empirically rather than being modeled (Li 2002, Kou and Baker 2006, Parsons et al. 2007) or hypothetically constructed by re-sampling non-targeted data (e.g., Baker and Ehle 2001, 20003); (b) overlapping targeted and non-targeted sampling was conducted with complete independence; (c) the study areas were defined clearly by administrative and/or natural boundaries, thereby removing any uncertainty about intended sample and inference space when comparing datasets; (d) analytical techniques for estimating fire history parameters used in this meta-analysis were field-validated against ground-mapped 20th century fires at MIC (Farris et al. submitted); (e) a range of fire frequency summary statistics were compared, ranging from MFI_{all} to NFR; (f) we analyzed multiple case studies representing a wide geographic range of ponderosa pine-dominated ecosystems in the Southwest; (g) the study areas collectively spanned an order of magnitude difference in study area size and fire-scar sample numbers/area sampled; and (g) the non-targeted datasets represent some of the best available “reference” datasets in the Southwest (i.e., most intensive non-targeted sampling). Thus, if systematic biases were inherent in targeted sampling we would have detected them with these datasets. The targeted fire histories in this study have been published and cited widely and no original conclusions about fire occurrence would change in light of these new analyses.

Relationships Between Targeted and Non-targeted Fire-Scar Data

If targeted sampling resulted in a fundamental detection bias relative to non-targeted sampling, we would have expected to see major differences in the rate and magnitude at which fire-scar years were detected. Our results showed instead that fire years at each study area were detected by nearly identical proportions of targeted and non-targeted fire-scar samples, despite large differences in sample size. Regression slopes of targeted and non-targeted synchrony were close to 1.0 at all study sites and there was no statistical evidence that targeted data detected fires in greater proportions at any study area. This has important implications because fire-scar synchrony forms the basis for nearly every interpretation and analysis of fire size or relative extent (Morrison and Swanson 1990, Swetnam and Baisan 1996a, Taylor 1998, Brown et al. 1999, Norman and Taylor 2003, Iniguez et al. 2008). Well distributed non-targeted fire-scar networks have been shown empirically to be strongly correlated with annual area burned (Farris et al. submitted). The fact then that targeted fire-scar synchrony correlated so closely with non-targeted data at all three study areas is strong evidence that targeted data accurately represented landscape-scale fire occurrence and extent.

One likely factor that contributed to the strong similarity between datasets is that targeted samples were relatively well-distributed across two of the study areas. Targeted samples were more clustered relative to the study area boundary at MCN than in CEN or MIC, which resulted in fire-scar synchrony being slightly underestimated relative to the systematic grid-based estimates (Falk 2004). Yet even at MCN regression slopes approached 1.0 (β = 0.87) and absolute differences in fire interval statistics were too small to alter fire history or ecological interpretations (relative to the non-targeted grid). Another likely factor contributing to similarity in fire history estimates is that pre-settlement fire regimes in these study areas (and typical of Southwestern ponderosa pine forests in general) were characterized by frequent, widespread fires that burned large portions of the study areas. Large fires increase the likelihood that fire scars will be detected across multiple sample locations, thus reducing the chances of disproportionate detection rates (Falk et al. 2007). Twentieth century documentary (fire atlas) data at MIC confirm that widespread burns are accurately and completely inventoried by fire scars across a range of spatial scales and sample sizes, but most small burns go undetected (Farris 2009 Appendix B).

Consistent with the strong correlation in fire-scar synchrony, all fire frequency summary statistics estimated from targeted data differed by less than 4 years from the full non-targeted fire-scar datasets at each study area regardless of sample units used (trees or plots). Moreover, there were no significant differences in the frequency distribution of individual fire return and rotation intervals at each study area. These distributions characterize temporal variability of fire occurrence and relative extent and would be skewed toward shorter (or longer) intervals relative to the non-targeted data if there was a targeted sampling bias. The consistency of these findings across all three study areas is compelling evidence against a systematic sample bias in targeted fire-scar data. Contrary to suggestions that targeted sampling leads to an overestimation of fire occurrence and/or extent, we found that targeted data may in fact underestimate area burned if plots are not distributed extensively enough across the area of inference to detect the full extent of large fires (e.g., MCN). Collins and Stephens (2007) also found that targeted sampling resulted in underestimation of burned area compared to mapped fire perimeters in the Sierra Nevada, supposedly due to undetected fires.

Baker and Ehle (2001) and Minnich et al. (2000) argued that targeting would have a higher tendency to detect small, insignificant fire years which might be recorded in multiple-scarred trees. We found that both targeted and non-targeted samples detected many small fire years, reflecting the fact that small fires were very common across these landscapes and were not restricted only to targeted fire-scar data. Documentary data indicate that 414 fires occurred in MIC from 1937 to 2000. The detection of small fire years appears to be more a function of sample size and scale rather than the sampling method (Falk, 2004, Farris 2009 Appendix B, Farris et al. submitted).

Sampling Efficiency and Sample Depth

Our results confirm that targeted sampling provides clear and consistent advantages in terms of efficiency and sample depth compared to non-targeted data. These advantages have been noted widely (see Swetnam and Baisan 1996a) but had not previously been demonstrated empirically relative to intensive random/systematic data. These results support one of the primary goals of targeted sampling, which is to produce the longest and most complete records of fire events for an area. In addition to producing long temporal records, high sample depth has important implications for ensuring temporal consistency and reliability of older fire intervals over time: as sample depth decreases it becomes less obvious whether very long intervals are real or an artifact of poor detection due to low sample size (Falk 2004). High sample depth provides clear advantages moreover for the analysis of spatial patterns in landscapes because interpolation error is reduced (Hessl et al. 2007, Farris et al. submitted). These results confirm that searching and field screening of fire-scarred specimens by experienced researchers is effective for identifying old samples and complete records of fire years in Southwestern ponderosa pine forests. We hypothesize that this protocol would hold elsewhere in forests with surface fire regimes and fire-scar susceptible trees.

Defining Bias in Relation to Other Studies

Bias can occur at any point in the fire history reconstruction process from field sampling to data analysis to interpretation. The primary concern with respect to targeted fire-scar sampling is *sample bias* (Morrison et al. 2001), which in this case would be the likelihood that certain fire years in a population are more likely to be detected or undetected *and* result in significant deviation in the estimation and interpretation of statistical fire occurrence parameters. In the absence of independent record of pre-20th century fire regimes (i.e., maps and other documentary records), we assessed potential sample bias of targeted data in this study through direct comparisons with the best non-targeted reference data we could obtain, i.e., via intensive random and systematic sampling and census data. This type of corroborative comparison (*sensu* Turner et. 2001) is meaningful because the non-targeted reference data in this study represent the best available means of reconstructing historical fire occurrence and extent that can feasibly be collected in most field studies. The census at CEN is the best reference theoretically possible for an area that size; the systematic sampling at MCN is the most intensive grid-based composite plot network (1 plot / 5 ha) in the Southwest; and the landscape-scale non-targeted sampling at MIC contains one of the largest sample size in the Southwest (next to CEN), and has been independently field validated with excellent results (Farris et al. submitted).

Our results do not support claims by Baker and Ehle (2001) that targeted sampling contributes to biased estimation of the NFR, namely, that area burned is overstated resulting in artificially lower NFRs. They argued that multiple-scarred samples that tend to be targeted by researchers may occur on sites that burn more frequently than the surrounding landscape. We showed that this is unlikely to be the case in our study areas, for several reasons. First, the NFR is a function of total area burned rather than total number of fire-scar years. What matters therefore in terms of sample bias is not whether targeted samples contain more fire scars, but whether they result in an incorrect classification of *widespread* fires (i.e., widely synchronous fire-scar years) that would significantly inflate area burned estimation. Such a bias would occur only if (a) fire-scar years were detected disproportionately by targeted samples (skewed synchrony) or (b) if targeted samples were scarred synchronously by numerous small fires occurring separately in the same year rather than large spreading fires. We found no evidence of either of these scenarios in this study. A total of only 21 fire-scar years were detected exclusively by targeted samples across all three study areas (out of 249 total fire-scar years), and of those only 2 scarred more than 10% of targeted samples (one at CEN and one at MIC). Farris et al. (submitted) demonstrated that fire-scar synchrony at MIC was primarily a function of widespread fires rather than the simultaneous detection of multiple small fires. We conclude that fires large enough to significantly influence the NFR are extremely unlikely to be restricted exclusively to targeted sample locations, and/or be recorded disproportionately by targeted samples.

Second, the assertion that sites (or points/trees) with multiple fire scars or higher fire-scar densities burned more frequently than the broader landscape is based on a questionable implicit assumption, *viz.* that the absence of a fire scar indicates the absence of fire. The absence of fire scars is ambiguous evidence and could be explained in several ways: (a) no fire occurred adjacent to the base of the tree; (b) fire burned around the base of the tree but failed to scar the tree (because of thick bark and/or insufficient fire intensity); (c) a scar was formed but was later destroyed by subsequent fires, decay, or other disturbances; or (d) a scar was formed but was completely healed over by growth processes, and so was not detected or sampled (Fall 1998). There are currently insufficient data to determine the relative importance of each of these factors on available fire scars in any given landscape, but it can be stated that the lack of a fire scar does not positively indicate a lack of fire.

We have observed numerous specimens that show indications that fire scars were probably present at one time (i.e., combinations of: characteristic curled ring overgrowth, traumatic resin canals within rings, sudden ring growth changes, ring separations, and other indicators), but were subsequently burned, or broken off or decayed. Van Horne and Fulé (2006) showed examples of fire-scarred trees (and years) located within meters of neighboring trees that lack corresponding fire-scar years recorded on the adjacent trees. We also have observed this phenomenon commonly throughout the region during our field studies (e.g., Fig. 9). Fire-scar years are often observed on one side of a fire-scarred tree cross section, but not on the other side, or scars may be present low on a stem but not at higher locations, or vice versa (Dieterich and Swetnam 1984). The formation and retention of fire scars on individual trees is a function of numerous deterministic and stochastic factors (Dieterich and Swetnam 1984, Falk 2004, Collins and Stephens 2007) and these factors may vary in different sites (Swetnam and Baisan 1996a, Falk et al. 2007). Consequently, we usually cannot know for certain whether the frequency of fire scars (or fire scars per tree) in a given area reflect tree or site specific vagaries of scar dynamics, specimen quality, real differences in fire frequency or extent, or some combination of all these factors. We concur with Baker and Ehle (2001) that a better understanding of the relationship between fire occurrence and scarring is needed.

Characterizing Targeted Sampling

Targeted sampling by experienced fire historians is usually more sophisticated than has been assumed previously in hypothetical assessments (e.g., Baker and Ehle 2001, 2003). Rather than simply identifying specimens with the most fire scars, targeted specimens in practice usually contain varying numbers of fire scars collected from both remnant wood (stumps, logs, and snags) and living trees. Trees with relatively few visible scars or relatively young fire-scarred trees are often included to provide temporal overlap in gaps and to cover the modern period. For example, the number of scars per targeted tree ranged from 2 to 38 at CEN and 1 to 23 at MCN. The goal is usually to compile long and complete temporal records utilizing combinations of well-preserved samples that exhibit multiple specimen characteristics, including broad spatial distribution throughout study areas. Finding and identifying trees of different ages with well-preserved scars requires knowledge of the appearance and characteristics of highest quality specimens. Such experience and skill develops both from extensive field sampling, and preparing and analyzing specimens in the laboratory. Effective sampling also requires skilled sawyers who understand the peculiarities of fire-scarred trees, and the necessity of careful sampling in optimal locations on the fire-scarred stem to recover the most complete, well-preserved records.

Targeted sampling moreover often includes additional layers of complexity in how an area is searched, including elements of non-targeted sampling such as stratification and guided searches. For example, targeting at CEN utilized informal "systematic" search paths to guide the search for high quality samples, thereby ensuring broad spatial representation. This approach is consistent with other targeted fire histories in the Southwest and elsewhere (Fulé and Covington 1994, Swetnam and Baisan 1996a, 1996b, Fulé and Covington 1997, Taylor 2000, Fulé et al. 2003b, Heinlein et al. 2005). At MCN targeted sampling by Touchan et al. (1995) was more opportunistic taking advantage of roads, but intentionally selecting multiple stands deemed to be representative of the general vegetation and topography of the Monument Canyon RNA (see also Stephens and Collins 2004, Stephens and Fry 2005, Fry and Stephens 2006). At MIC Baisan and Swetnam (1990) stratified the landscape informally to ensure sampling in the major vegetation and topographic facets (north-south slopes) and broad ecological and spatial representation.

Similar multi-faceted "hybrid" targeting approaches are used routinely by fire historians in most areas depending upon objectives, landscape characteristics, logistics and feasibility. Taylor and Skinner (1998, 2003), for example used broadly distributed clear-cuts in the Klamath Mountains to obtain samples from stump tops, which is a form of opportunistic targeting. Others have had to rely on remnant wood and logged stumps scattered about study areas to obtain pre-settlement data (Swetnam 1993, Taylor and Beaty 2005) or because of sampling constraints on live trees (Baisan and Swetnam 1990). Targeting often occurs in association with formal topographic and/or vegetative stratification in landscapes (Everett et al. 2000, Beaty and Taylor 2001, Stephens 2001, Stephens et al. 2003, Hessl et al. 2004), or with stratified points distributed for purposes such as vegetation sampling (Fulé and Covington 1994, 1997, Brown and Wu 2006, Collins and Stephens 2007). Targeting has also been employed to obtain representative fire inventories along a range of ecological gradients, linear ecotones, or broad geographic extent (Caprio and Swetnam 1995, Swetnam and Betancourt 1998, Brown et al. 2001, Grissino-Mayer et al. 2004, Fulé et al. 2005, Heyerdahl et al. 2006, Moody et al. 2006). In some cases fire-scar sampling is necessarily restricted to targeting non-random locations where trees that record fire scars grow (or are preserved), such as in patches or stringers of forest within non-forest communities (Arno and Gruell 1986, Kaib 1998, Miller and Rose 1999, Grissino-Mayer 2000, Norman and Taylor 2003, Heyerdahl et al. 2006, Miller and Heyerdahl 2008), or in non-random features of interest such as fireinduced vegetation patches identified from aerial photos (Gonzalez et al. 2005, Johnson and Gutsell 1994). In very large landscapes, targeting may be necessary if only certain areas are accessible due to ownership or administrative constraints (Veblen et al. 2000, Sherriff and Veblen 2007). Collectively these factors make validation studies of targeted sampling difficult to perform or model without the benefit of empirical data and independent reference data.

Implications

Based on the results of this study and other recent fire-scar methodology research (Fulé et al. 2003, Baker and Ehle 2003, Fulé et al. 2006, Van Horne and Fulé 2006, Collins and Stephens 2007, Shapiro-Miller et al. 2007, Farris et al. submitted), we conclude that targeted sampling is a practical and accurate strategy for achieving many fire history objectives. Factors such as sample size and spatial distribution appear to be more important than the method by which samples are selected. Practical measures such as clearly defining the inference space, selecting a variety of sample characteristics, or spatial stratification can help ensure complete and representative fire histories. Targeted fire-scar datasets should be evaluated carefully to ensure they are appropriate and adequate for addressing a given objective. We suggest such scrutiny be applied to *all* fire history data sources, including non-targeted fire-scar data, documentary fire atlas maps, and age-structure based fire histories (Morgan et al. 2001, Rollins et al. 2001, Shapiro-Miller et al. 2007). It is apparent for example, that non-random sampling of trees for age structure analysis is not uncommon in fire history studies in stand replacing fire regimes (e.g., Johnson and Gutsell 1994).

Our findings also reaffirm conclusions from previously published fire histories that widespread fires occurred at frequent intervals of 10 to 15 years prior to the 20th century in Southwestern ponderosa pine and mixed conifer forests (see summaries by Swetnam and Baisan 1996a, 1996b, Swetnam et. al. 2003). NFRs estimated from all non-targeted datasets were <15 years in this study regardless of study area, sampling technique or sample size. These values are significantly lower than the hypothetical range of "corrected" NFRs (*sic* population mean fire intervals) proposed by Baker and Ehle (2001), which range from a median of 52 years on the low end to 170 years on the high end (total range 22 to 308). The median $MFI_{25\%}$ of sixty-three Southwestern histories summarized by Swetnam and Baisan (1996a) was 12.7 years respectively (range 4 to 36), which is consistent with the range of 5 to 10.5 years in this study. The $MFI_{25\%}$ and NFR are closely coupled metrics because they reflect the same sets of widespread fire events and are accurately characterized by fire-scar data (Farris et al. submitted).

Although innovative non-targeted sampling techniques offer much potential for addressing fine-scale, spatially explicit variability in fire regime parameters (see Heyerdahl et al. 2001, Falk et al. 2007, Iniguez et al. 2008), there are several reasons that targeted sampling likely will continue to play a critical role in fire history research. First, a significant body of existing fire history research has been collected using some form of targeting. Second, targeted sampling is important for collecting increasingly rare and ancient paleo-fire scars, especially as older pre-settlement era specimens continue to be lost permanently to natural and anthropogenic-induced attrition. Finally, many important contemporary research objectives are suited ideally for targeted sampling, such as broad-scale fire-climate research that relies on lengthy and complete inventories of major fire years, requiring maximally efficient sampling over enormous areas (e.g., Kitzberger et al. 2007). Studies that improve our understanding of the statistical properties of targeted fire-scar data will continue to be valuable for interpreting existing and future fire histories.

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References

Agee, J.K. 1993. Fire ecology of Pacific Northwest forests. Island Press, Washington, D.C.

Allen, C.D., Savage M., Falk, D.A., Suckling, K.F., Swetnam, T.W., Schulke, T. Stacey, P.B., Morgan, P., Hoffman, M., and Klingel, J.T. 2002. Ecological restoration of Southwestern ponderosa pine ecosystems: a broad perspective. Ecological Applications 12(5):1418-1433.

Arno, S. F., and Gruell, G. E. 1986. Douglas-fir encroachment into mountain grasslands in southwestern Montana. Journal of Range Management 39:272–275.

Baisan, C.H. and Swetnam, T.W. 1990. Fire history on a desert mountain range: Rincon Mountain Wilderness, Arizona, U.S.A. Canadian Journal of Forest Research 20: 1559-1569.

Baisan, C. H., and Swetnam, T. W. 1995. Historical fire occurrence patterns in remote mountains of Southwestern New Mexico and northern Mexico. *In* Proceedings: Symposium on Fire in Wilderness and Park Management, Missoula, MT, March 30-April 1, 1993. *Edited by* James. K. Brown, Robert. W. Mutch, Charles. W. Spoon, and Ronald. H. Wakimoto (technical coordinators). USDA Forest Service General Technical Report INT-320. pp. 153-156.

Baker, W.L. 2006. Fire history in ponderosa pine landscapes of Grand Canyon National Park: is it reliable enough for management and restoration? International Journal of Wildland Fire 15: 433-437.

Baker, W.L. and Ehle, D. 2001. Uncertainty in surface-fire history: the case of ponderosa pine forests in the western United States. Canadian Journal of Forest Research 31: 1205-1226.

Baker, W.L. and Ehle, D. 2003. Uncertainty in fire history and restoration of ponderosa pine forests in the western United States. *In* Conference proceedings: fire, fuel treatments, and ecological restoration. *Edited by* P.N. Omi and L.A. Joyce. USDA Forest Service, RMRS-P-29. Fort Collins, CO. pp. 319-334.

Beaty, R.M. and Taylor, A.H. 2001. Spatial and temporal variation of fire regimes in a mixed conifer forest landscape, Southern Cascades, California, USA. Journal of Biogeography 28: 955-966.

Boots, B.N. and A. Getis. 1988. Point pattern analysis. SAGE Publications. Newbury Park, N.J.

Beers, T.W., Dress, P.E., and Wensel, L.C. 1966. Aspect transformation in site productivity research. J. For. 64:691.

Brown, P.M. and R. Wu. 2006. Climate and disturbance forcing of episodic tree recruitment in a southwestern ponderosa pine landscape. Ecology 86 (11): 3030-3038.

Brown, P.M., Kaufmann, M.R., and Shepperd, W.D. 1999. Long-term, landscape patterns of past fire events in montane ponderosa pine forest of central Colorado. Landscape Ecology 14:513-532.

Brown, P.M., Kaye, M.W., Huckaby, L.S., and Baisan, C.H. 2001. Fire history along environmental gradients in the Sacramento Mountains, New Mexico: Influences of local patterns and regional processes. Écoscience 8:115-126.

Caprio, A.C, and Swetnam, T.W. 1995. Historic fire regimes along an elevational gradient on the west slope of the Sierra Nevada, California. *In* Proceedings: symposium on fire in wilderness and park management. *Edited by* J. Brown, R.W. Mutch, C.W. Spoon, and R.H. USDA Forest Service General Technical Report INT-GTR-320. pp. 173-179.

Collins, B.M. and Stephens, S.L. 2007. Fire scarring patterns in Sierra Nevada wilderness areas burned by multiple wildland fire use fires. Fire Ecology. 3(2):53-67.

Dieterich, J.H., 1980. The composite fire interval—a tool for more accurate interpretation of fire history. Rocky Mountain Research Station, USDA Forest Service. *In* Proceedings of the fire history workshop. *Edited by* M.A. Stokes and J.H. Dieterich, J.H. USDA Forest Service, General Technical Report RM-GTR-81. pp. 8-14.

Dieterich, J. H., and T. W. Swetnam. 1984. Dendrochronology of a fire scarred ponderosa pine. Forest Science 30(1):238-247.

Everett, R.L., Schellhaas, R., Keenum, D., Spurbeck, D., and Ohlson, D. 2000. Fire history in the ponderosa pine/Douglas-fir forests on the east slope of the Washington Cascades. Forest Ecology and Management 129:207-225.

Falk, D.A. 2004. Scaling rules for fire regimes. PhD. Dissertation. University of Arizona, Tucson.

Falk, D.A., McKenzie, D., Miller, C., and Black, A.E. 2007. Cross-scale analysis of fire regimes. Ecosystems. 10(5):809-823.

Fall, J.G. 1998. Reconstructing the historical frequency of fire: a modeling approach to developing and testing methods. M.S. Thesis, Simon Fraser University, Burnaby, British Columbia.

Farris, C.A. 2009. Spatial and temporal validation of fire-scar fire histories. PhD. Dissertation. University of Arizona, Tucson.

Farris, C.A., C.H. Baisan, D.A. Falk, S.R. Yool, and T.W. Swetnam. Submitted. Spatial and temporal corroboration of fire-scar based fire history reconstructions in a frequently burned ponderosa pine forest in southern Arizona. Canadian Journal of Forest Research.

Fry, D.L. and Stephens, S.L. 2005. Influence of humans and climate on the fire history of a ponderosa pine-mixed conifer forest in the southeastern Klamath Mountains, California. Forest Ecology and Management 223:428-438.

Fulé, P.Z., and Covington, W.W. 1994. Fire regime disruption and pine-oak forest structure in the Sierra Madre Occidental, Durango, Mexico. Restoration Ecology 2(4):261-272.

Fulé, P.Z. and Covington, W.W. 1997. Fire regimes and forest structure in the Sierra Madre Occidental, Durango, Mexico. Acta Botanica Mexicana 41:43-79.

Fulé, P.Z., Henlein, T.A., Covington, W.W., and Moore, M.M. 2003a. Assessing fire regimes on Grand Canyon landscapes with fire scar and fire record data. International journal of Wildland Fire 12(2):129-145.

Fulé, P.Z., J.E. Crouse, Heinlein, T.A., Moore, M.M., Covington, W.W., and Verkamp, G. 2003b. Mixed-Severity Fire Regime in a High-Elevation Forest: Grand Canyon, Arizona. Landscape Ecology 18:465-486.

Fulé, P. Z., J. Villanueva-Diaz and M. Ramos-Gomez. 2005. Fire regime in a conservation reserve in Chihuahua, Mexico. Canadian Journal of Forest Research 35 (2): 320-330.

Fulé, P.Z., Henlein, T.A., and Covington, W.W. 2006. Fire histories in ponderosa pine forests of Grand Canyon are well supported: reply to Baker. International journal of Wildland Fire 15:439-445.

Gonzalez, M.E., T. T. Veblen, and J.S. Sibold (2005). Fire history in *Araucaria-Nothofagus* forests in Villarrica National Park, Chile. Journal of Biogeography 32:1187-1202.

Grissino-Mayer, H.D., Romme, W.H., Floyd, L.M. and Hanna, D.D. 2004. Climatic and human influences on fire regimes of the southern San Juan Mountains, Colorado, USA. Ecology 85(6):1708-1724.

Grissino-Mayer, H.D. and Swetnam, T.W. 2000. Century-scale climate forcing of fire regimes in the American Southwest. The Holocene. 10(2):213-220.

Heinlein, T.A., M.M. Moore, P.Z. Fulé, and W.W. Covington. 2005. Fire history of two ponderosa pine—mixed conifer sites: San Francisco Peaks, Arizona, USA. International Journal of Wildland Fire 14:307-320.

Hessl, A. E., D. McKenzie, and R. Schellhaas. 2004. Drought and Pacific Decadal Oscillation linked to fire occurrence in the inland Pacific Northwest. Ecological Applications 14(2):425-442.

Hessl, A., Miller, J., Kernan, J., D. Keenum, and D. McKenzie. 2007. Mapping paleo-fire boundaries from binary point data: comparing interpolation methods. The Professional Geographer 59(1):87-104.

Heyerdahl, E.K., L.B. Brubaker, and J.K. Agee. 2001. Spatial controls of historical fire regimes: a multiscale example from the Interior West, USA. Ecology. 82:660-678.

Heyerdahl, E.K., R.F. Miller, and R.A. Parsons. 2006. History of fire and Douglas-fir establishment in a savanna and sagebrush-grassland mosaic, southwestern Montana, USA. Forest Ecology and Management. 230:107-118.

Iniguez, J.M., Swetnam, T.W., and Yool, S.R. 2008. Topography affected landscape fire history patterns in southern Arizona, USA. Forest Ecology and Management. 256:295-303.

Johnson, E.A. and Gutsell, S.L. 1994. Fire frequency models, methods and interpretations. Advances in Ecological Research 25:239-287.

Kaib, M. 1998. Fire history in riparian canyon pine-oak forests and the intervening desert grasslands of the Southwest borderlands: A dendroecological, historical, and cultural inquiry. M.S. thesis, The University of Arizona, Tucson. 234 pp.

Kitzberger, T., P. M. Brown, E. K. Heyerdahl, T. W. Swetnam, and T. T. Veblen. 2007. Contingent Pacific-Atlantic ocean influence on multi-century wildfire synchrony over western North America. Proceedings of the National Academy of Sciences 104(2):543-548.

Kou, X, and Baker, W.L. 2006. A landscape model quantifies error in reconstructing fire history from scars. Landscape Ecology 21(5):735-745.

Krebs, C.J. 1998. Ecological Methodology. Benjamin-Cummings (2nd ed.). 576 pp.

Lachmund, H.G. 1921. Some phases in the formation of fire scars. Journal of Forestry 19(6):638-640.

Li, C. 2002. Estimation of fire frequency and fire cycle: a computational perspective. Ecological Modeling 154:103-120.

Miller, R.F. and Rose, J.A. 1999. Fire history and western juniper encroachment in sagebrush steppe. Journal of Range Management 52:550-559.

Miller, R.F. and Heyerdahl E.K. (2008) Fine-scale variation of historical fire regimes in sagebrush-steppe and juniper woodland: An example from California, USA. International Journal of Wildland Fire 17:245-254.

Minnich, R. A., Barbour, M. G., Burk, J. H., and Sosa-Ramírez, J. 2000. California mixed-conifer forests under unmanaged fire regimes in the Sierra San Pedro Mártir, Baja California, Mexico. Journal of Biogeography 27:105-129

Moody, T.J., Fites-Kaufman, J., and Stephens, S.L. 2006. Fire history and climate influences from forests in the northern Sierra Nevada, USA. Fire Ecology 2(1):115-142.

Morgan, P., Hardy, C, Swetnam, T.W., Rollins, M.G., and Long, D. G. 2001. Mapping fire regimes across time and space: Understanding coarse and fine-scale patterns. International Journal of Wildland Fire 10 (3-4): 329-342.

Morino, K. A. 1996. Reconstruction and interpretation of historical patterns of fire occurrence in the Organ Mountains, New Mexico. M.S. Thesis, The University of Arizona, Tucson, AZ. 144 p.

Morrison, M.L., Block, W.L., Strickland, M.D., and Kendall, W.L. 2001. Wildlife study design. Springer, New York, NY.

Morrison, P.H. and Swanson F.J. 1990. Fire history and pattern in a Cascade landscape. Pacific Northwest Research Station, USDA Forest Service, PNW-GTR-254.

Norman, S.P. and Taylor, A.H. 2003. Tropical and north Pacific teleconnections influence fire regimes in pine-dominated forests of northeastern California, U.S.A. Journal of Biogeography 30:1081-1092.

Parsons RA, Heyerdahl E.K., Keane RE, Dorner B, and Fall J. 2007. Assessing the accuracy of surface fire histories: Simulation modeling of point fire frequency across landscapes. Canadian Journal of Forest Research 37:1605-1614.

Rollins, M.G, Swetnam, T.W. and Morgan P. 2001. Evaluating a century of fire patterns in two Rocky Mountain wilderness areas using digital fire atlases. Canadian Journal of Forest Research 31(12): 2107-2123.

Romme, W.H. 1980. Fire history terminology: report to the ad hoc committee. *In* Proceedings of the fire history workshop. *Edited by* M.A. Stokes and J.H. Dieterich, J.H. USDA Forest Service, General Technical Report RM-GTR-81. pp. 135-137.

Shapiro-Miller, L.B., Heyerdahl, E.K., and Morgan, P. 2007. Comparison of fire scars, fire atlases, and satellite data in the northwestern United States. Canadian Journal of Forest Research 37:1933-1943.

Sherriff, R.L. and T.T. Veblen. 2007. A spatially explicit reconstruction of historical fire occurrence in the ponderosa pine zone of the Colorado Front Range. Ecosystems 9:1342-1347.

Stephens, S.L. 2001. Fire history of adjacent Jeffrey pine and upper montane forests in the eastern Sierra Nevada. International Journal of Wildland Fire 10:161-176.

Stephens, S.L. and Collins, B.M. 2004. Fire regimes of mixed conifer forests in the north-central Sierra Nevada at multiple spatial scales. Northwest Science 78(1): 12-23.

Stephens, S.L. and Fry, D.L. 2005. Fire history in coast redwood stands in the northeastern Santa Cruz Mountains, California. Fire Ecology 1(1):2-19.

Stephens, S.L., Skinner, C.N., Gill, S.J., 2003. Dendrochronology-based fire history of Jeffrey pine-mixed conifer forests in the Sierra San Pedro Mártir, Mexico. Canadian Journal of Forest Research 33:1090-1101.

Swetnam, T.W. 1993. Fire history and climate change in giant sequoia groves. Science 262:885-889.

Swetnam, T. W. and Baisan, C.H. 1996a. Historical fire regime patterns in the Southwestern United States since AD 1700. *In* Proceedings of the Second La Mesa Fire Symposium, Los Alamos, New Mexico, March 29-31. *Edited by* C.D. Allen. USDA Forest Service, General Technical Report RM-GTR-286. Ogden, UT. pp. 11-32.

Swetnam, T. W. and Baisan, C. H. 1996b. Fire histories of montane forests in the Madrean Borderlands. Rocky Mountain Research Station. *In* Effects of fire on Madrean Province Ecosystems, A symposium proceedings. *Edited by* P.F. Ffolliott, L.F. DeBano, M.B. Maker, Jr., G.J. Gottfried, G. Solis-Garza, C.B. Edminster, D.G. Neary, L.S. Allen, and R.H. USDA Forest Service General Technical Report RM-GTR-289. Ogden, UT. pp. 15-36.

Swetnam, T.W. and Betancourt, J.L. 1998. Mesoscale disturbance and ecological response to decadal climatic variability in the American Southwest. Journal of Climate 11: 3128-3147.

Swetnam, T.W., Allen, C.D., Betancourt J.L. 1999. Applied Historical Ecology: Using the Past to Manage for the Future. Ecological Applications 9(4):1189-1206.

Swetnam, T.W. and C.H. Baisan 2003. Tree-ring reconstructions of fire and climate history in the Sierra Nevada and Southwestern United States. *In* Fire and Climatic Change in Temperate Ecosystems of the Western Americas, Ecological Studies Vol. 160. *Edited by* T. T. Veblen, W. Baker, G. Montenegro, and T. W. Swetnam. Springer, New York, N.Y. pp. 158-195.

Taylor, A.H. 2000. Fire regimes and forest changes in mid and upper montane forests of the southern Cascades, Lassen Volcanic National Park, California, U.S.A. Journal of Biogeography 27:87-104.

Taylor, A.H. and Skinner, C.N. 1998. Fire history and landscape dynamics in a late-successional reserve, Klamath Mountains, California, USA. 111:285-301.

Taylor, A.H., and Skinner, C.N. 2003. Spatial patterns and controls on historical fire regimes and forest structure in the Klamath Mountains. Ecological Applications (13(3):704- 719.

Taylor, A.H. and Beaty, R.M. 2005. Climatic influences on fire regimes in the northern Sierra Nevada mountains, Lake Tahoe Basin, Nevada, USA. Journal of Biogeography 32:425-438

Touchan, R., Swetnam, T.W., and Grissino-Mayer, H.D. 1995. Effects of livestock grazing on pre-settlement fire regimes in New Mexico. *In* Proceedings: symposium on fire in wilderness and park management. *Edited by* J. Brown, R.W. Mutch, C.W. Spoon, and R.H. USDA Forest Service General Technical Report INT-GTR-320. pp. 268-272.

Turner, M.G. and Gardner, R.H., O'Neill, R.V. 2001. Landscape Ecology in Theory and Practice. Springer-Verlag, New York, NY.

Van Horne, M.L., and P.Z. Fulé. 2006. Comparing methods of reconstructing fire history using fire scars in a southwestern USA ponderosa pine forest. Canadian Journal of Forest Research 36(4):855-867

Veblen, T.T., T. Kitzberger, and J. Donnegan. 2000. Climatic and human influences on fire regimes in ponderosa pine forests in the Colorado Front Range. Ecological Applications 10:1178-1195.

Weaver, H. 1951. Fire as an ecological factor in the southwestern ponderosa pine forests. Journal of Forestry 49(2): 93-98.

Zar, Jerrold H. 1999. Biostatistical Analysis. 4th Edition. Prentice-Hall, Inc., Upper Saddle River, NJ.

Table 1. Sample size characteristics of targeted and non-targeted samples for each study area.

	Centennial Forest		Monument Canyon		Mica Mountain	
	Non-targeted	Targeted	Non-targeted	Targeted	Non-targeted	Targeted
Study Area Size (ha)	100	100	256	256	2,780	2,780
Number of Samples						
Trees	612	36	197	45	405	52
Composite Plots	--	--	50	--	60	12
Sample Density (sample units / ha)						
Trees	1/0.2	1/2.7	1/1.3	1/5.7	1/6.9	1/53
Composite Plots	--	--	1/5.2	--	1/46	1/232
Spatial Point Pattern [a]	0.8 (clumped)	0.9 (random)	1.7 [b] (uniform)	0.6 (clumped)	1.4 (uniform)	1.3 (uniform)

[a] Nearest Neighbor Statistic from Boots and Getis (1988); H_o = random distribution = 1.0.

[b] Spatial pattern of non-targeted plots for Monument Canyon

Table 2. Mean topographic characteristics of targeted and non-targeted samples for each study area.

	Centennial Forest		Monument Canyon		Mica Mountain	
	Non-targeted	Targeted	Non-targeted	Targeted	Non-targeted	Targeted
Mean Elevation (meters)	2,193 (0.2)[a]	2,192 (0.5)	2,531 (4)	2,551 (4)	2,308 (21)	2,398 (44)
Mean Aspect Index [b]	1.3 (0.0)	1.4 (0.1)	0.9 (0.1)	0.7 (0.1)	1.2 (0.1)	1.0 (0.2)
Mean Slope (degrees)	1.6 (0.1)	1.6 (0.3)	12.0 (1.1)	9.7 (1.5)	15.1 (1.4)	11.2 (1.0)

[a] (standard error in parentheses)

[b] Aspect values are linear transformed following Beers et al. (1966)

Table 3. Mean Fire Return Interval (MFI) and Natural Fire Rotation (NFR) calculated from targeted and non-targeted fire-scar data. The "non-targeted - partial dataset" column represents the average estimate corrected for sample size (to match the targeted sample size) using a bootstrapping procedure.

	Dataset		
Fire Interval Statistic	Targeted	Non-Targeted – Partial Dataset	Non-Targeted Full Dataset
(a) *Centennial Forest (1707-1873)* [a]	*n = 36 trees*	*n = 36 trees*	n = 612 trees
MFI_{all}	2.4	2.7	1.8
$MFI_{10\%}$	2.9	3.0	2.7
$MFI_{25\%}$	5.0	5.3	5.4
NFR	9.1	9.6	9.0
(b) *Monument Canyon (1709-1892)* [a]	*n = 45 trees*	*n = 9-12 plot/45 trees* [b]	*n = 50 plots/197 trees*
MFI_{all}	4.5	4.1	2.7
$MFI_{10\%}$	6.5	5.1 – 6.9	5.7 – 6.7
$MFI_{25\%}$	8.4	7.3 – 10.5	7.1 – 7.4
NFR	14.1	10.8 –16.5	10.7 – 15.4
(c) *Mica Mountain (1806-1893)* [a]	*n = 12 plots*	*n = 12 plots*	*n = 60 plots*
MFI_{all}	3.0	3.8	2.2
$MFI_{10\%}$	6.7	5.1	6.2
$MFI_{25\%}$	7.3	7.6	8.0
NFR	8.4	9.4	9.2

[a] Common scar-to-scar period used for comparison of the MFI (all filtering levels) and NFR

[b] Lower estimates on the left are composite plot data (n = 9-12) and upper values on the right are from individual tree data (n = 45 trees)

Table 4. Contingency matrices showing the number of fire years identified in common between the targeted and non-targeted datasets for three different levels of filtering. Values within outlined boxes represent calendar years in agreement. Values outside the outlined boxes represent years that meet filtering criteria for only one of the datasets. Total years for each matrix represent the common period of the scar-to-scar recording period for each study area.

	Targeted Data					
	All Fire Years		10% Filter		25% Filter	
Non-Targeted Data	YES	NO	YES	NO	YES	NO
(a) *Centennial Forest (1707-1873)* [a]						
YES	74	28	56	9	26	6
NO	5	59	4	97	8	126
(b) *Monument Canyon (1709-1892)* [b]						
YES	38	41	29	6	22	5
NO	6	98	2	146	1	155
(c) *Mica Mountain (1806-1893)* [c]						
YES	22	25	13	1	11	0
NO	10	30	1	72	1	75

[a] Non-targeted filtering based on 612 trees; targeted filtering based on 36 trees
[b] Non-targeted filtering based on 50 composite plots; targeted filtering based on 45 individual trees
[c] Non-targeted filtering based on 60 composite plots; targeted filtering based on 12 composite plots.

Figure 1. Location of the three study sites in Arizona and New Mexico and targeted and non-targeted fire-scar sampling networks.

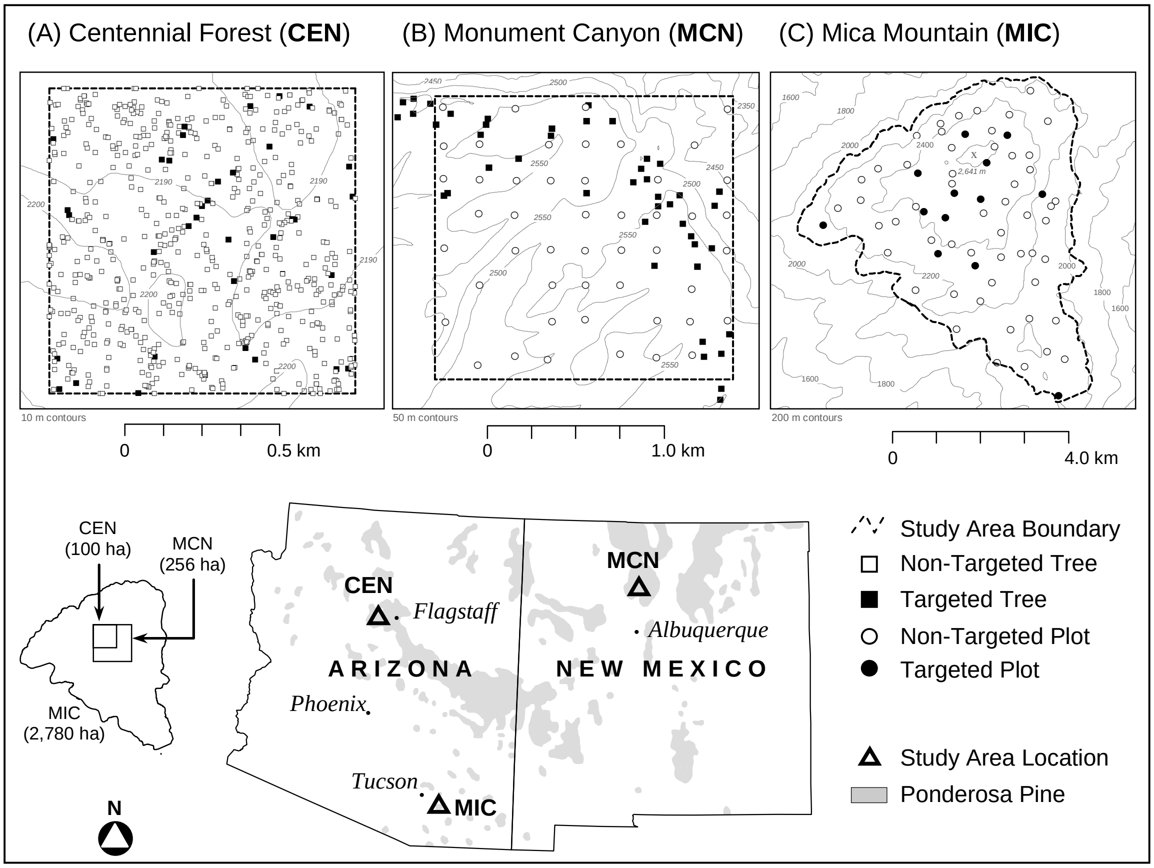

Figure 2. Annual fire-scar synchrony of targeted and non-targeted fire-scar data. Each graphed data point represents a fire-scar year detected in common by both datasets (years without a fire scar recorded by both datasets were not plotted). Data from Centennial Forest and Monument Canyon are for 1700 to 1900 and data from Mica Mountain are from 1800 to 1900.

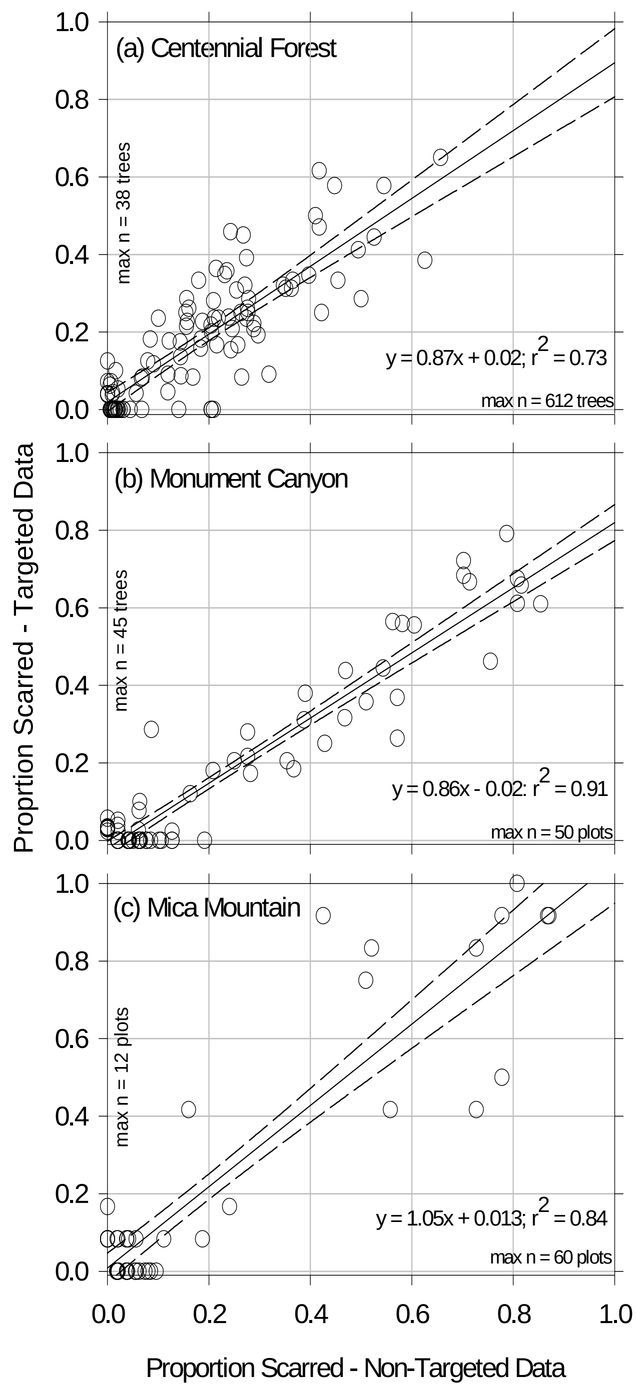

Figure 3. Frequency distribution of composite fire intervals computed for all fire years (left column) and 25%-filtered fire years (right column). The non-targeted intervals represent the mean and standard deviation of 200 bootstrapped estimates from the full dataset samples. The x-axis was of 25%-filtered fires was truncated at 20 years because the probability of bootstrapped intervals > 20 years was <0.5% for CEN (max 40 yrs.) and MCN (max 25 yrs.), and 0% for MIC.

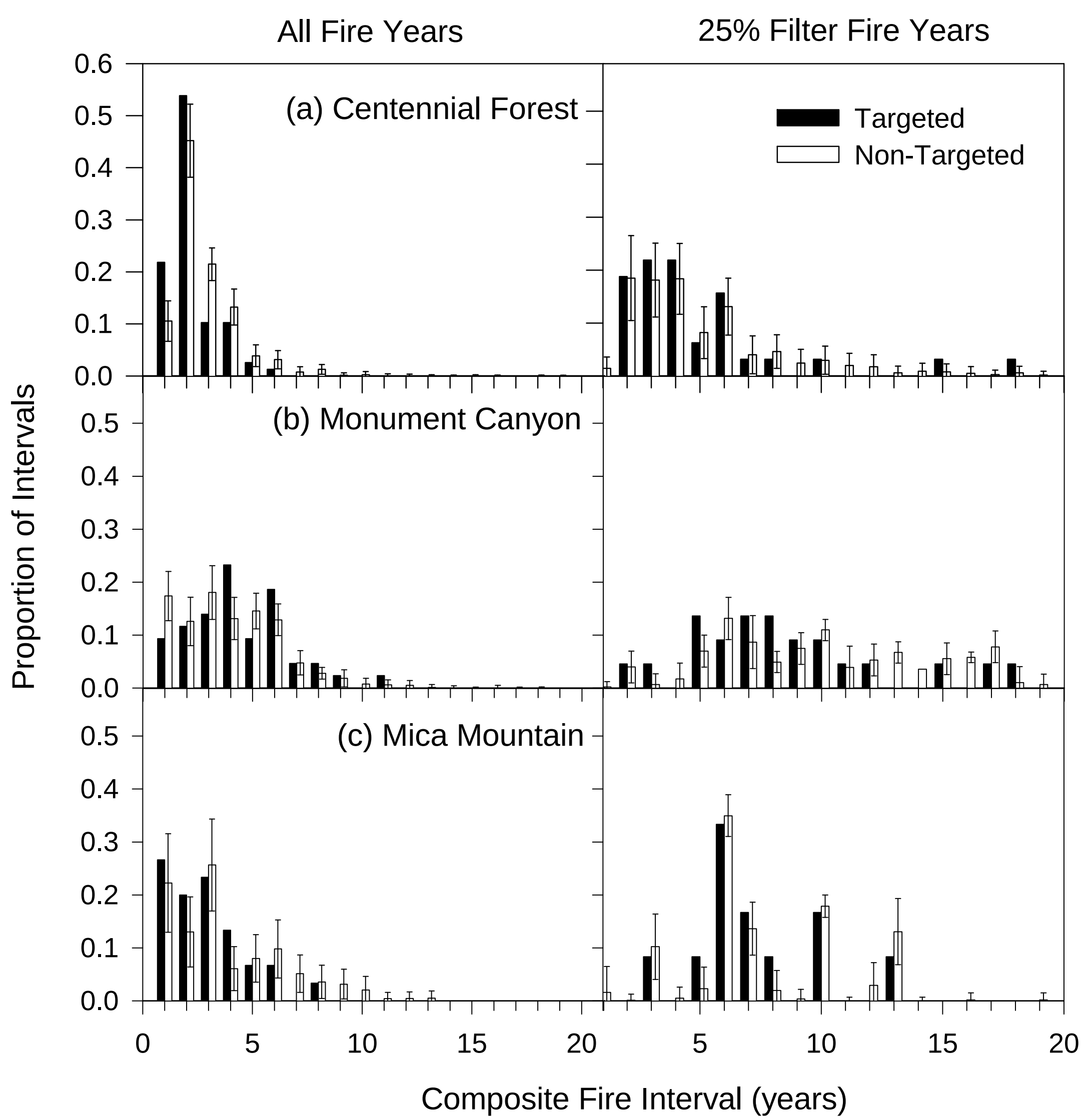

Figure 4. Frequency distribution of natural fire rotation (NFR) intervals calculated from targeted and non-targeted data. Data for Centennial Forest and Monument Canyon are from 1700 to 1900 and data for Mica Mountain are from 1800 to 1900.

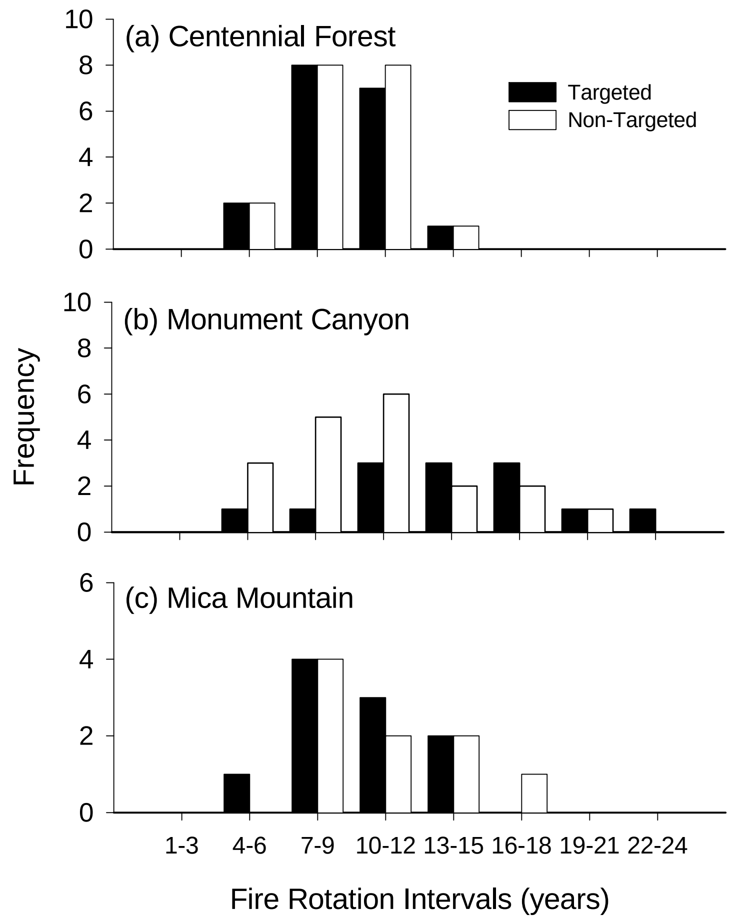

Figure 5. Stand-level Mean Fire Return Intervals (MFI) of targeted plots (n = 12) and non-targeted plots (n = 60) on Mica Mountain during the 19th century. The overall average is 9.1 years for targeted plots and 9.6 years for non-targeted plots.

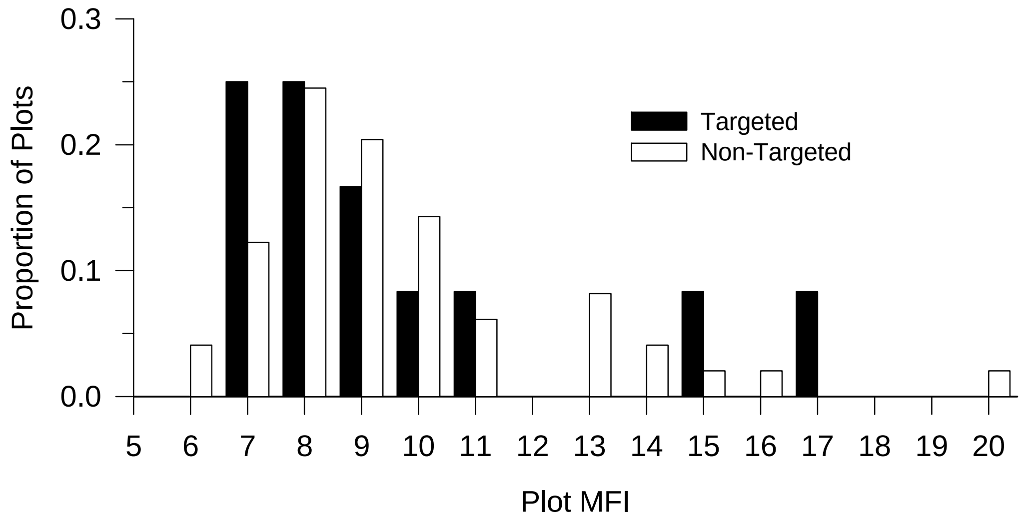

Figure 6. Influence of sample size on the detection of unfiltered and 25%-filtered fire years. The mean (symbols) and standard deviation (brackets) of 200 randomly drawn combinations of samples for a given sample size are plotted. Values for Centennial Forest and Monument Canyon were calculated using individual trees between 1700 and 1900. Values for Mica Mountain were calculated using composite plots from 1800 to 1900.

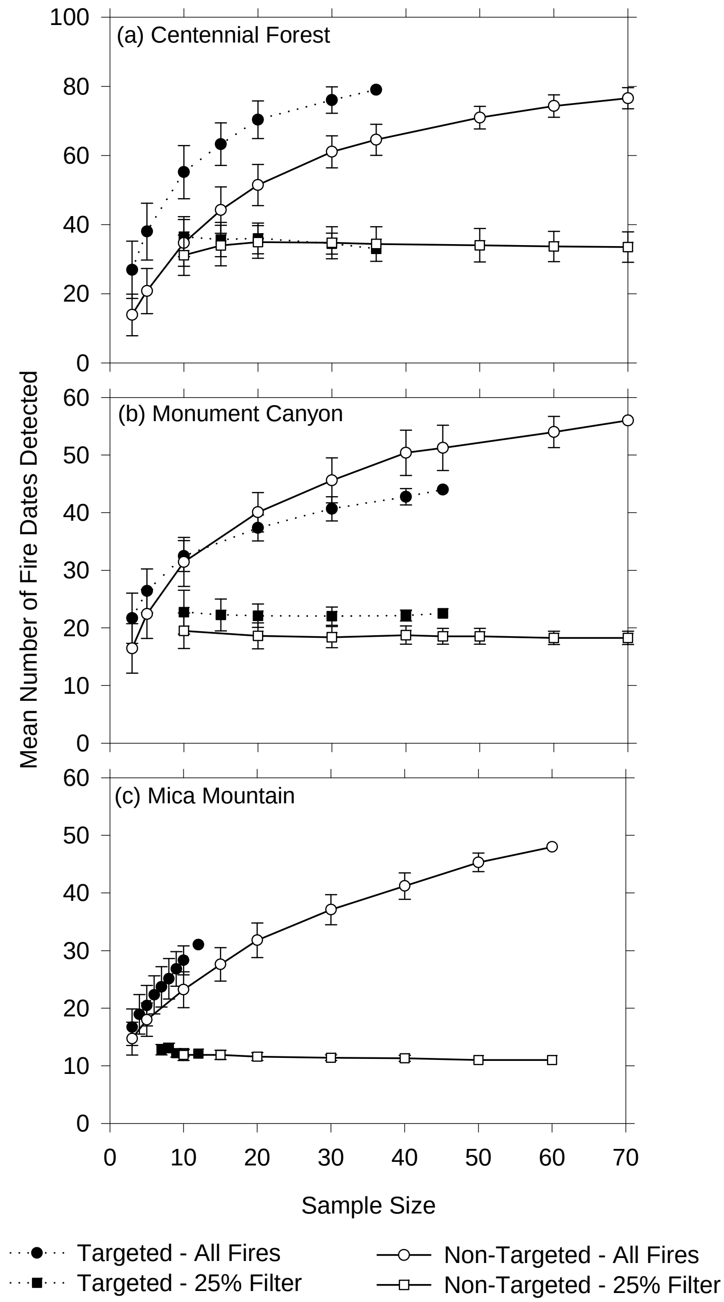

Figure 7. Average number of fire scars per sample unit for targeted and non-targeted sampling during the study period. Sample unit at CEN and MCN are individual trees from 1700-1900, and sample unit at MIC is for composite plots from 1800-1900.

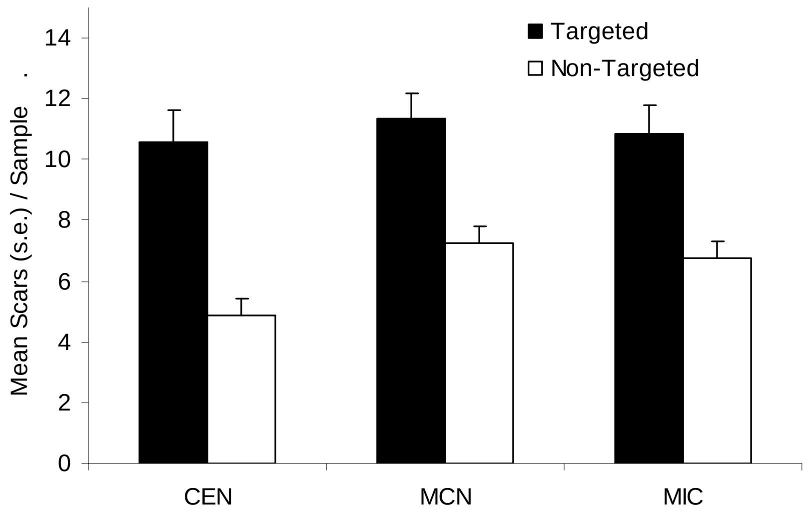

Figure 8. Sample depth of targeted and non-targeted fire-scar data. Sample depth for (a) Centennial Forest and (b) Monument Canyon are based on the percentage of actively recording individual trees; sample depth for (c) Mica Mountain is based on the percentage of actively recording composite plots.

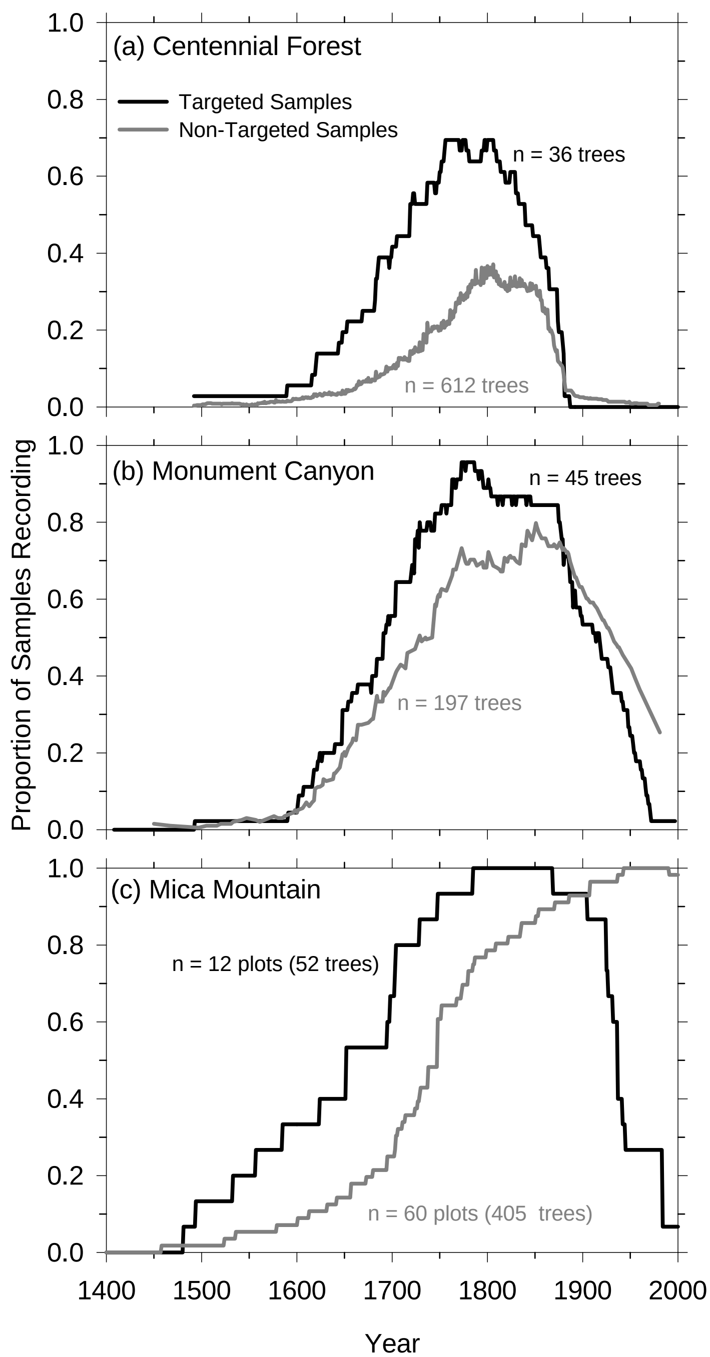

Figure 9. An example of differential fire-scar formation on two adjacent trees in the Mica Mountain study area. The tree on the left is a Southwestern white pine and has eight visible scars. The tree on the right is a ponderosa pine and has no visible scars. Both species are considered to be good recorders of fire scars.