FIRE HISTORY AND FIRE-CLIMATE RELATIONSHIPS IN UPPER ELEVATION FORESTS OF THE SOUTHWESTERN UNITED STATES

by

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A Dissertation Submitted to the Faculty of the

SCHOOL OF NATURAL RESOURCES

In Partial Fulfillment of the Requirements
For the Degree of

DOCTOR OF PHILOSOPHY
WITH A MAJOR IN WATERSHED MANAGEMENT

In the Graduate College

THE UNIVERSITY OF ARIZONA

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THE UNIVERSITY OF ARIZONA
GRADUATE COLLEGE

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entitled Fire history and fire-climate relationships in upper elevation forests of the southwestern United States
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ACKNOWLEDGEMENTS

This project was funded by Cooperative Agreement No. 99CRAG0024 between the U. S. Department of Interior USGS Biological Survey through the USGS Biological Resources Division, Global Change Program and the University of Arizona Laboratory of Tree-Ring Research. Additional financial support was provided by Scott St. George who paid me to sniff glue and sand wood; Don Falk – Monument Canyon research project; and UofA student tuition that paid for my 3 Teaching Assistanships.

I am especially grateful for the support and guidance of my advisor Dr. Tom Swetnam and the rest of my committee: Dr. Craig Allen, Dr. Andrew Comrie, Dr. Pete Ffolliott, and Dr. Steve Yool. Each member contributed something different to the project and to my development as a scientist.

The field and lab work could not have been completed without assistance from Mike Zummwalt, Pepe Iniguez, Rex Adams, Ari Fitzwater, Rebecca Franklin, and Miguel Villarreal. Many thanks to everyone who participated in discussions of the ideas presented in this dissertation, including Dr. Dave Meko, Scott St. George, Chris Baisan, Dr. Kurt Kipfmueller, Dr. Don Falk, Erica Wise and James Tamerius. Finally, special thanks to everyone else who helped me along the way with those all-important, but not necessarily scientific tasks: the LTRR front office, Calvin Farris, Erica Bigio, Dr. Martin Munro, Dr. Paul Sheppard, all LTRR grad students & staff, & my family.

DEDICATION

This is dedicated to the visionaries who had the foresight to fight for and protect the forests for the enjoyment, education and health of future generations.

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ABSTRACT

Fire history and fire-climate relationships of upper elevation forests of the southwestern United States are imperative for informing management decisions in the face of increased crown fire occurrence and climate change. I used dendroecological techniques to reconstruct fires and stand-replacing fire patch size in the Madrean Sky Islands and Mogollon Plateau. Reconstructed patch size (1685-1904) was compared with contemporary patch size (1996-2004). Reconstructed fires at three sites had stand-replacing patches totaling > 500 ha. No historical stand-replacing fire patches were evident in the mixed conifer/aspen forests of the Sky Islands. Maximum stand-replacing fire patch size of modern fires (1129 ha) was greater than that reconstructed from aspen (286 ha) and spruce-fir (521 ha). Undated spruce-fir patches may be evidence of larger (>2000ha) stand-replacing fire patches.

To provide climatological context for fire history I used correlation and regionalization analyses to document spatial and temporal variability in climate regions, and El-Niño Southern Oscillation (ENSO), the Pacific Decadal Oscillation (PDO) and the Atlantic Multi-decadal Oscillation (AMO) teleconnections using 273 tree-ring chronologies (1732 - 1979). Four regions were determined by common variability in annual ring width. The component score time series replicate spatial variability in 20th century droughts (e.g., 1950's) and pluvials (e.g., 1910's). Two regions were significantly correlated with instrumental SOI and AMO, and three with PDO. Sub-regions within the southwestern U.S. varied geographically between the instrumental (1900-1979) and the pre-instrumental periods (1732-1899). Mapped correlations

between ENSO, PDO and AMO, and tree-ring indices illustrate detailed sub-regional variability in the teleconnections.

I analyzed climate teleconnections, and fire-climate relationships of historical upper elevation fires from 16 sites in 8 mountain ranges. I tested for links between Palmer Drought Severity Index and tree-ring reconstructed ENSO, PDO and AMO phases (1905-1978 and 1700-1904). Upper elevation fires (115 fires, 84 fire years, 1623-1904) were compared with climate indices. ENSO, PDO, and AMO affected regional PDSI, but AMO and PDO teleconnections changed between periods. Fire occurrence was significantly related to inter-annual variability in PDSI, precipitation, ENSO, and phase combinations of ENSO and PDO, but not AMO (1700-1904). Reduced upper elevation fire (1785-1840) was coincident with a cool AMO phase.

CHAPTER 1 – INTRODUCTION

Explanation of Problem

Repeated low severity surface fire was a keystone process in mid-elevation pine dominant forests of the southwestern United States (Arizona, New Mexico and proximate areas) for centuries prior to 20th century fire exclusion (Swetnam & Baisan 1996; 2003). Contemporary fire in many of the same forests has changed to high severity stand-replacing crown fire caused by a combination of increased fuel loads and fuel structure changes, warming temperatures that lengthen the fire season, and severe drought (Allen et al. 2002; Westerling et al. 2006). The lack of effective, landscape-scale fuel treatments and projected continuing warming trends suggest that crown fire may be an increasingly common future occurrence in many forest types of the southwestern U.S. The documented immediate and long-term ecological, hydrological, and social effects of this altered fire regime include ecosystem type conversions, flooding and debris flows, and loss of life and property.

In contrast, infrequent high severity crown fire is within the historical range of variability in some forest and shrub-dominated ecosystems of the western U.S. (e.g., lodgepole pine (*Pinus contorta*) of the southern and central Rocky Mountains (Romme 1982), chaparral shrublands in the southern California foothills (Minnich 1983), and jack pine (*Pinus banksiana*) in the Great Lakes region (Heinselman 1973)). Some species have adapted to, and depend on, the occurrence of stand-replacing crown fire for persistence. Many populations of lodgepole pine in the Rocky Mountains, for example, require high severity crown fire to remove competitors and open serotinous cones to disperse seeds so it can re-colonize the post-fire landscape (Clements 1910; Schoennagel et al. 2003). Seral quaking aspen (*Populus tremuloides* Michx.) within upper montane and subalpine conifer forests also depend on stand-replacing fire to remove shade-tolerant conifers and induce mass vegetative regeneration (Barnes 1966; Jones & DeByle 1985). The beneficial importance of crown fire in specific ecosystems and its detrimental occurrence in others must be differentiated to fully understand the diverse role of fire and apply this knowledge to forest management in the western U. S.

Fire research in the southwestern U.S. has primarily focused on surface fire regimes of the pine-dominant ecosystems (e.g., Weaver 1947; Cooper 1960; Swetnam & Baisan 1996; Swetnam & Baisan 2003). Although high elevation, upper montane forest types (e.g., mixed-conifer, quaking aspen, and spruce-fir) occupy a relatively small percentage of the forested land area, they are extremely valuable in terms of biodiversity and are at high risk of experiencing negative effects from anticipated changes (e.g., climate change and introduced species). Pleistocene relict forest ecosystems atop “Sky Island” mountain ranges in the desert southwest are particularly important and vulnerable. For example, the southern limit of the spruce-fir forest ecosystem is located in the upper elevations of the Pinaleño Mountains of southern Arizona (~32° N). A combination of recent high severity fires, severe drought stress and non-native insect outbreaks have substantially affected this forest type, consequently affecting the suite of species that depend on this locally rare ecosystem type (e.g., federally endangered Mount Graham red squirrel; *Tamiasciurus hudsonicus grahamensis*; (Koprowski et al. 2005)).

Climate variability is an important, if not the dominant, forcing mechanism of variability in fire regimes throughout much of western North America (Johnson 1992; Agee 1993; Veblen et al. 2003). Interannual to centennial-scale climate variability affects surface and crown fire regimes through effects on fuel production and drought occurrence. Climatic controls on surface fire and crown fire regimes can differ, with the former being more limited by fine fuel loads that carry the fire, particularly in the semi-arid regions of the southwestern U.S. (Swetnam & Baisan 1996; Crimmins & Comrie 2004). In contrast, long return interval stand-replacing crown fire regimes in forested ecosystems are generally not fuel limited because they occur within relatively mesic and productive environments. At landscape scales these high elevation sites have abundant biomass, and therefore fire occurrence is primarily limited by drought and extreme fire weather conditions necessary to dry the fuels and promote ignition and fire spread (Turner & Romme 1994; Bessie & Johnson 1995). At the forest-stand scale, successional stage following the last stand-replacing fire determines live fuel levels, but even young stands can burn in extreme fire storms partially fueled by dead and down material from the last fire-killed stand (e.g., 1988 Yellowstone fires; Schoennagel et al. 2003).

In recent decades substantial advances have been made in identifying multiple ocean-atmosphere drivers of climate variability in western North America. The El Niño Southern Oscillation (ENSO) is the most well-studied of these phenomenon. ENSO teleconnections linking equatorial Pacific sea surface temperatures and pressure differences affect the climate of many regions worldwide (Diaz & Markgraf 2000). Winter precipitation variability associated with ENSO at approximately 2-7 year intervals in the southwestern U.S. is a primary driver of variability in fire regimes of the region (Swetnam & Betancourt 1990, 1998). Other ocean-atmosphere phenomenon, such as the Pacific Decadal Oscillation (PDO) (Mantua et al. 1997) and the Atlantic Multidecadal Oscillation (AMO) (Enfield et al. 2001) have recently been associated with multi-decadal climate variability (McCabe et al. 2004; Sutton & Hodson 2005; Dong et al. 2006) and historical fire occurrence in the western U.S. (Kitzberger et al. 2007)

These advances in fire climatology are exciting and have revolutionized the way we look at climate and fire variability at inter-annual to multi-decadal scales. However, the details of the individual and phase combinations of the ocean-atmosphere oscillations, and stability of the teleconnections in mid-latitude western North America are not well understood, especially sub-regional variations (e.g. within the southwestern U.S.). Thus, forecasting variability of fire occurrence based on climate-fire relationships and long-term or lagging relationships in the ocean-atmosphere oscillations still requires much research to identify and resolve these uncertainties.

The variability and uncertainties in regional teleconnections with individual and combined ocean-atmosphere oscillations derive from both the spatial and temporal variability of the teleconnections and synergistic effects between the teleconnections. Associations between local climate and ENSO phase and strength vary geographically within the western U.S. Winter precipitation in the southwestern U.S. is strongly associated with ENSO phase (e.g., cold eastern equatorial Pacific SST's - La Niña - increases drought probability; Andrade & Sellers 1988). However, the association breaks down in the mid-latitudes of the western U.S., and in the northwest U.S. a strong inverse relationship between ENSO phase and winter precipitation exists (e.g., cold eastern equatorial Pacific SST's - La Niña – increases probability of wet conditions). This dipole pattern is evident in both climate and historical fire occurrence patterns (Dettinger et al. 1998; Brown & Comrie 2004; Kitzberger et al. 2007) Thus, it is important to establish a geographic relationship between ocean-atmosphere variability and local or regional climate before taking the next step and testing hypotheses about the role of ocean-atmosphere oscillations in variability of fire occurrence.

Most associations between ocean-atmosphere oscillations and local climate are derived from 20th century instrumental climate data, and commonly only the latter half of the 20th century. This limited window over which relationships have been established is not long enough to capture the temporal variability in these phenomena. If the strength or sign of regional teleconnections do vary through time it is possible that relationships established in the instrumental period may not apply to the pre-instrumental period or vice-versa. For example, although PDO phase has been associated with dominant 20th century drought patterns (McCabe et al. 2004) it may not have been an important mode of climate variability over much of the 19th century (Gedalof et al. 2002). Consequently, PDO-drought or PDO-fire relationships established in pre- or post-1900 periods may not necessarily apply to the other period.

A third source of variability and uncertainty in mid-latitude ocean-atmosphere teleconnections is the synergistic effect of phase combinations. McCabe & Dettinger (1999) described how constructive (same phase) and destructive (opposite phase) combinations of ENSO and PDO respectively amplify and diminish the strength of

ENSO teleconnections in the western U.S. AMO and PDO phase combinations explain 52% of the variance in primary spatial modes of 20th century multi-decadal drought in the continental U.S. (McCabe et al. 2004). Positive AMO coincident with positive PDO occurred during the 1930's Great Plains and Pacific northwest drought, while positive AMO coincident with negative PDO occurred during the 1950's Southwest drought. If these relationships are to be incorporated into fire risk forecasting, then it is important to determine the stability in time and space of amplified or weakened teleconnections during ocean-atmosphere phase combinations.

Approach

In this dissertation I use dendroecological methods, geographic information system (GIS) techniques, principal components-based climate regionalization, time series analysis, and standard fire-climate analysis methods (e.g., superposed epoch analysis) to reconstruct fire history, analyze climate variability, and test for associations between historic fire occurrence and climate variability in the southwestern U.S.

The first study combines multiple lines of tree-ring evidence, including: 1) conifer and quaking aspen age structure, 2) fire scars, 3) fire-killed conifer bark-ring dates and 4) conifer injury dates to reconstruct upper elevation (>2600 m) fire history (including stand-replacing fires) and stand-replacing fire patch size. GIS techniques were used to derive modern fire patch size data sets that were compared with tree-ring reconstructed data to make the first attempt to evaluate whether the sizes of recent crown fire "holes" are outside the historical range of variability.

The second study is a descriptive study of spatial and temporal climate variability within the southwestern U.S. Principal components-based regionalization methods and Pearson product moment correlation coefficients were used to map patterns of primary modes of moisture variability and spatial variability of the teleconnnections with ENSO, PDO, and AMO. These drought and climate teleconnection patterns were used to guide fire-climate analyses in the third study.

The third study analyzes fire-climate relationships between upper elevation (>2700m) fire history, including stand-replacing fires, and Pacific and Atlantic Ocean modes of variability that have been shown to be associated with climate variability in the southwestern U.S. Superposed epoch analysis (SEA), Pearson product moment correlations, ANOVA, Student's t-test, and Chi-squared contingency analysis were used to test for 1) associations between individual and combined phases of AMO, PDO and ENSO indices and moisture variability (PDSI) in the southwestern U.S., and 2) associations between upper elevation fire history data sets (stand-replacing fire years, synchronous fire years, all fire years), and tree-ring reconstructed indices of regional climate (PDSI, precipitation, temperature) and individual and combined phases of tree-ring reconstructed ENSO, PDO and AMO.

Organization of the Dissertation

The dissertation is composed of three papers included as appendices. The format of each paper is defined by the guidelines for the target journal for which it was prepared. Separate literature cited sections are included with each appendix.

Appendix A, titled “Investigating the role of stand-replacing fire in upper elevation (>2600m) forests of the Mogollon Plateau and the Madrean Sky Islands of Arizona and New Mexico” has been prepared for submission to *Ecology or Ecological Monographs*. In this study I reconstructed upper elevation (>2600 m) fire history and stand-replacing fire patch size in four mountain ranges of Arizona and southern New Mexico, and compare historical and contemporary stand-replacing fire patch size.

Appendix B, titled “Sub-regional spatial and temporal climate variability in southwestern North America derived from a network of moisture-sensitive tree-ring chronologies (A.D. 1732-1978)” was prepared for submission to *International Journal of Climatology*. In this study I use principal components-based regionalization techniques, correlation analysis and GIS techniques to analyze a network of 273 moisture-sensitive tree-ring index chronologies from southwest North America. The methods were used to address the following research objectives: (1) identify climatically similar regions and sub-regions within southwest North America derived from common variability in tree-ring width, and test for spatial stationarity through time of the sub-regions and (2) identify associations between the climate regions (sub-regions) and ENSO, PDO and AMO indices, and map the spatial variability in ENSO, PDO and AMO teleconnections recorded by tree-rings to investigate potential causes of the sub-regional climate variability.

Appendix C, titled “Fire-climate relationships of upper elevation (>2700m) fire regimes in the southwestern United States” was prepared for submission to *Journal of Biogeography*. In this study I use fire-climate analyses to investigate associations between variability in interannual and multi-decadal drought occurrence, ocean-atmosphere oscillations, and tree-ring reconstructed upper elevation (>2700 m) fire occurrence (including stand-replacing fire) in the southwestern U.S. (1623-1978).

CHAPTER 2 – PRESENT STUDY

The detailed methods, results and conclusions of this study are presented in papers appended to this dissertation. A summary of each paper is provided below. The combined studies emphasize the variable nature of historical upper elevation fire occurrence (including stand-replacing fire) between and within mountain ranges of the southwestern U.S., which is partially driven by spatial and temporal variability in the effects of ENSO, PDO and AMO on moisture variability. Refining our understanding of the effects of individual and combined ENSO, PDO and AMO teleconnections on drought variability, and consequently variability in fire occurrence, may allow for better forecasting of forest fire risk and response of fire regimes to projected climate change.

Appendix A – "Investigating the role of stand-replacing fire in upper elevation (>2600m) forests of the Mogollon Plateau and the Madrean Sky Islands of Arizona and New Mexico"

Extensive tree-ring based fire histories determined from the mid-elevation pine dominant forests of the southwestern U.S., including the Madrean Sky Islands and Mogollon Plateau of Arizona and New Mexico, have documented the ubiquitous occurrence of repeated, low-severity surface fires for hundreds of years prior to late 19th century fire exclusion (Swetnam & Baisan 1996). Minimal fire history exists for the upper elevation (>2700m) mesic mixed conifer/aspen and spruce-fir forests of the region (but see Grissino-Mayer et al. 1995; Abolt 1997). Margolis et al. *in press* documented 19th century stand-replacing fire occurrence with patch sizes greater than 1000 ha in similar upper elevation vegetation types of the upper Rio Grande region of the southwestern U.S. Recent occurrence of stand-replacing fires in upper elevation forests of the Sky Islands and Mogollon Plateau raises the question; Are observed stand-replacing fire occurrences and/or patch sizes in upper elevation forests of the region within the range of historical variability?

I used dendroecological techniques to reconstruct fire history, including stand-replacing fire occurrence and stand-replacing fire patch size, from tree-ring evidence collected in four mountain ranges in the Sky Islands (Pinaleño and Chiricahua Mountains) and Mogollon Plateau (Mogollon Mountains and San Francisco Peaks). Contemporary stand-replacing fire patch size was estimated from burn severity maps of recent (1996-2004) fires within 100 km of the four fire history sites and compared to historical tree-ring based estimates.

Evidence of repeated low-severity fire was recorded at all sites, particularly on south-facing slopes with a significant grass understory. In the Sky Islands the only historical evidence of stand-replacing fire was found in the spruce-fir zone in the Pinaleño Mountains (521 ha), which likely regenerated following a stand-replacing fire in 1685. At both Mogollon Plateau sites quaking aspen patches greater than 200 ha (maximum – 286 ha) were determined to be the legacy of past stand-replacing fire. Maximum contemporary stand-replacing fire patch size (1129 ha) based on the most conservative contemporary data set (high severity patches above 2600 m in elevation) was double the tree-ring reconstructed estimate. However, the potential exists for larger historical stand-replacing fire patches (>2000 ha) if other spruce-fir forests of the region are determined to be post stand-replacing fire patches.

Appendix B - “Sub-regional spatial and temporal climate variability in southwest North America derived from a network of moisture-sensitive tree-ring chronologies (A.D. 1732-1978)”

In the southwest U.S. sub-regional spatial modes of climate variability (regions) have been identified using multiple instrumental data sets (Comrie & Glenn 1998; Tamerius 2007). However, it is likely that the instrumental period does not represent the full range of variability in the climate system and the location of climate stations (low-elevation valleys) may be recording a different signal than tree-ring sites (upper-elevation montane zone). Individual and combined ENSO and PDO teleconnections strongly influence 20th century southwestern U.S. climate and vary sub-regionally (Brown & Comrie 2002; Brown & Comrie 2004). A relatively strong ENSO and PDO signal is recorded by some tree-ring sites in the region (Stahle et al. 1998; Cook 2000; D'Arrigo et al. 2001) but the explicit spatial variability has not yet been described. The influence of the AMO on climate in the southwestern U.S. has not been analyzed specifically, but broad-scale analyses indicate that the positive AMO phase (warm Atlantic SST’s) was associated with increased drought probability in the region (McCabe et al. 2004).

In this study I describe multi-century variability in spatial modes of sub-regional climate in southwestern North America to determine if 20th century patterns were representative of past climate. In addition, I describe ENSO, PDO, and AMO teleconnections recorded by upper elevation tree rings as potential sources of the sub-regional climate variability. The primary data source is a drought sensitive tree-ring network (273 chronologies) that is regionalized with principal components analysis (1732-1979) and correlated with ENSO (1866-1979), PDO (1900-1979), and AMO (1856-1979) indices.

Four primary spatial modes of climate variability (regions) were described for southwestern North America for the full period of analysis (1732-1979). The component score time series for each region replicates documented spatial variability between regions during 20th century droughts and pluvials and illustrate variability in ENSO, PDO, and AMO teleconnections between regions. Sub-regionalization of the southwestern U.S. region identifies the spatial variability in climate within the region and non-stationarity of the primary spatial modes of drought between instrumental (1900-1979) and pre-instrumental periods (1732-1899). The component score time series for the southwestern U.S. sub-regions indicate sub-regional variability in teleconnections with ENSO, PDO and AMO.

Mapped correlations between ENSO, PDO, and AMO indices and the full 273 site network of tree-ring chronologies illustrate detailed sub-regional variability in teleconnection strength. The concentration of significant correlations with ENSO occurs in New Mexico and Chihuahua, Mexico. Concentration of significant correlations with the PDO index occurs in New Mexico. Areas of consistent significant correlations with AMO were located in northern Utah and eastern Nevada, and southern Mexico. The sub-regional variability with ENSO, PDO and AMO teleconnections should be investigated further as a potential cause of the documented sub-regional variability in the primary modes of drought occurrence.

Appendix C – "Fire-climate relationships of upper elevation (>2700m) fire regimes in the southwestern United States"

Since the seminal research of Swetnam & Betancourt (1990) that linked interannual ENSO variability and fire occurrence in the southwestern U.S., fire-climate associations have been identified across the western U.S. with newly described climate drivers (e.g., PDO and AMO; Kitzberger et al. 2007). Upper elevation, stand-replacing fire-climate relationships from the Rocky Mountains consistently show that fire occurrence is strongly associated with severe drought, which has been linked to local teleconnections with individual and phase combinations of ENSO, PDO and AMO indices (Schoennagel et al. 2005; Sibold & Veblen 2006). The goal of this research was to identify regional climate teleconnections and fire-climate relationships of historical upper elevation (>2700m) fire occurrence (including stand-replacing fire) reconstructed from tree-rings in the southwestern U.S. (Arizona, New Mexico and southern Colorado).

Individual and combined phases of ENSO, PDO and AMO indices were analyzed for associations with PDSI (1905-1978 and 1700-1904) to test for links between these ocean-atmosphere oscillations and regional drought in the southwestern U.S. Tree-ring reconstructed upper elevation (>2700m) fire history from a network of 16 sites in 8 mountain ranges (1623-1978) was analyzed for associations with tree-ring reconstructed drought (PDSI), precipitation, temperature, and individual and combined phases of ENSO, PDO and AMO indices.

Individual and phase combinations of ENSO, PDO, and AMO affected regional moisture variability (PDSI) reconstructed from tree-rings (1905-1978). However, the AMO and PDO teleconnections may have changed between the 20th century fire exclusion period (1905-1978) and the reconstructed fire period (1700-1904). All classes of upper elevation fire year occurrence (all fires, synchronous fires, and stand-replacing fires) were significantly related to inter-annual variability in regional drought index (PDSI) and precipitation anomalies, ENSO phase, and phase combinations of ENSO and PDO, but not AMO (1700-1904). A multi-decadal period of reduced upper elevation fire occurrence and the absence of stand-replacing fire (1785-1840) is coincident with an inter-hemispheric change in fire regimes, possibly driven by a multi-decadal cool AMO phase and/or reduced ENSO amplitude (Kitzberger et al. 2001; Kitzberger et al. 2007).

Summary

Historical upper elevation fire occurrence (including stand-replacing fire), variability in sub-regional spatial and temporal patterns of drought and teleconnections with ENSO, PDO and AMO, and historical fire-climate relationships have been described and evaluated for the southwestern U.S. in this dissertation. The key points are summarized below:

- Upper elevation (>2700m) fire history in the Madrean Sky Islands was characterized by relatively frequent fire and no evidence of stand-replacing fire patches >5ha (except the 521 ha post stand-replacing fire spruce-fir patch in the Pinaleños). In contrast, the Mogollon Plateau had evidence of multiple historical upper elevation stand-replacing fire (quaking aspen) patches > 200 ha and the potential still exists to find historical patches > 1000 ha in the spruce-fir zone.

- The best available estimate of historical (1685-1904) maximum stand-replacing fire patch size (aspen 286 ha, spruce-fir 521 ha) in the Sky Islands and Mogollon Plateau was less than the most conservative estimate of modern (1996-2004) stand-replacing fire patch size (1129 ha). All potential historical stand-replacing fire patches (e.g., spruce-fir patches) need to be sampled to further test the hypothesis that the size of modern upper elevation stand-replacing fire patches is outside the historical range of variability.
- Within the southwestern U.S. sub-regional spatial modes of climate variability (1732-1979), and ENSO (1866-1979), PDO (1900-1979), and AMO (1856-1979) teleconnections vary spatially and temporally. PDO and ENSO have strong and widespread links to moisture variability in New Mexico. The details of sub-regional and temporal climate variability are important to consider when describing climate teleconnections and analyzing fire-climate relationships.
- Interannual variability in historical upper elevation (>2700m) fire occurrence in the southwestern U.S. (Arizona, New Mexico and southern Colorado) is significantly related to regional drought (PDSI) and precipitation anomalies, ENSO phase, and phase combinations of ENSO and PDO, but not AMO (1700-

1904). Reduced upper elevation fire occurrence and the absence of stand-replacing fire from 1785-1840 is coincident with an inter-hemispheric change in fire regimes, possibly driven by a multi-decadal cool AMO phase and reduced ENSO amplitude.

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APPENDIX A

INVESTIGATING THE ROLE OF STAND-REPLACING FIRE IN UPPER ELEVATION (>2600M) FORESTS OF THE MOGOLLON PLATEAU AND THE MADREAN SKY ISLANDS OF ARIZONA AND NEW MEXICO

Investigating the role of stand-replacing fire in upper elevation (>2600m) forests of the Mogollon Plateau and the Madrean Sky Islands of Arizona and New Mexico

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Margolis, E.Q., Swetnam, T.W. and Allen, C.D. Investigating the role of stand-replacing fire in upper elevation (>2600m) forests of the Mogollon Plateau and the Madrean Sky Islands of Arizona and New Mexico. ***To be submitted to*** **Ecology/Ecological Monographs**

Abstract

Fire history was reconstructed using dendroecological techniques for upper montane forests (>2600m) in four mountain ranges located in the Madrean Sky Islands and Mogollon Plateau of Arizona and New Mexico. Three hundred and thirty crossdated tree-ring samples were used to reconstruct 100 fires occurring on 87 unique fire dates (1623-1904). Three fires (PIN - 1685, SFP – 1879, GIL – 1904) were determined to have a stand-replacing component > 500 ha in size based on multiple lines of tree-ring evidence including: 1) quaking aspen (*Populus tremuloides*) and/or spruce-fir age structure, 2) fire-killed conifer bark-ring dates, 3) traumatic resin ducts and/or ring-width changes, and 4) fire scars. Thirty nine percent of all sampled aspen regenerated within five years after fire, ranging from 10.3% to 58.3% between sites. Multiple aspen stems greater than 250 years-old were sampled and tree-ring dated in two of the mountain ranges. The sampled mixed conifer/aspen forests at the two Sky Island sites had no evidence of stand-replacing fire patches (>20 ha) for at least 250 years before the recent (1996-2004) stand-replacing fires. At the Sky Island sites and on the south slope of the San Francisco Peaks, evidence of frequent surface fire within and adjacent to some aspen

stands indicates the potential for 20th century fire exclusion to have shifted stand structure towards dominance by a single mature cohort.

One of the sampled spruce-fir stands (Pinaleño Mountains; 521 ha) was interpreted to be a post-stand-replacing fire patch (1685). A clear stand initiation date was not evident at additional spruce-fir patches sampled in the Mogollon Mountains (319 ha and 1223 ha). These patches contained trees greater than 280 years old and had no direct evidence of fire (e.g., fire scars or charred wood). Multiple age-structure-based methods need to be tested at sites where historical documents indicate late 19th century fires burned in the spruce-fir zone (e.g., San Francisco Peaks Inner Basin, AZ or Santa Fe Ski Basin, NM).

Stand-replacing fire patch size was estimated from the aspen patches used to reconstruct fire history in an initial attempt to quantify the natural range of variability. These data represent a minimum patch size estimate due to the uncertainty regarding the percent of the stand-replacing patch that regenerated as quaking aspen. Reconstructed patch size was compared with contemporary fire patch size (1996-2004) from within 100 km of the fire history sites. The largest reconstructed stand-replacing fire (aspen) patch was 286 ha. The most conservative, contemporary fire data set (high severity patches above 2600m in elevation) had five patches greater than 300 ha and a maximum patch size of 1129 ha. This conservative modern estimate of maximum stand-replacing fire patch size is four times greater than the maximum aspen patch and twice as large as the reconstructed post-fire spruce-fir patch (521ha). Based on this preliminary comparison, there is no evidence of historical stand-replacing fire patches in the upper montane forests larger than contemporary stand-replacing fire patches. Further investigation is needed to determine if other mapped big spruce-fir patches (>1000ha) were potentially the result of older, larger stand-replacing fires.

Introduction

Understanding the role of fire is paramount for understanding montane forest ecosystems in the southwestern United States (Arizona, New Mexico and proximate areas). The recent occurrence of large fires with a crown fire component (e.g., Cerro Grande, 2000; Rodeo-Chedeski, 2002; Aspen, 2003) has raised questions about the historical role of stand-replacing fire in all forest types of the region. Contemporary stand-replacing fire patches have primarily occurred in the overstocked, mid-elevation ponderosa pine and dry mixed conifer forests where little evidence of extensive historical stand-replacing fires exists (Swetnam 1990; Covington & Moore 1994; Swetnam & Baisan 1996; Dahms & Geils 1997; Allen et al. 2002). However, seral aspen stands in the upper elevation forests provide evidence that stand-replacing fires occurred in the region as recently as the early 20th century (Abolt 1997; Romme et al. 2001; Kulakowski et al. 2004; Margolis et al. *in press*).

Relatively little is known about pre-Euro-American settlement fire regimes (size, intensity, frequency and seasonality) of upper elevation forests (>2600 m) in the southwestern U.S. (Grissino-Mayer et al. 1995; Swetnam et al. *in press*). The majority of the large body of existing fire research in the region has focused on the middle elevation ponderosa pine and dry mixed-conifer forest types (Weaver 1947; Cooper 1960; Baisan & Swetnam 1990; Swetnam & Baisan 1996; Moore et al. 1999; Swetnam & Baisan 2003;

Fule et al. 2003). These semi-arid pine-dominated forests experienced relatively frequent (2 to 15 year intervals), low intensity surface fires for hundreds of years until grazing and fire suppression led to a cessation of widespread surface fires around circa 1900 (Swetnam & Baisan 1996).

Extensive fire history from upper elevation montane and subalpine forests of Wyoming, Colorado and northern New Mexico indicates that stand-replacing fire is a dominant disturbance in high elevation forests of the Southern Rocky Mountains (Kipfmueller & Baker 2000; Donnegan et al. 2001; Sherriff et al. 2001; Sibold et al. 2006; Kulakowski et al. 2006; Margolis et al. *in press*). This indicates the potential for similar upper elevation forest types throughout the southwestern U.S. to have experienced a fire regime that included stand-replacing fire.

The natural range of variability (sensu Landres et al. 1999) of historical fire regimes at seasonal to centennial scales is best studied with dendrochronological methods (Dieterich & Swetnam 1984; Fritts & Swetnam 1989; Agee 1993a; Johnson & Gutsell 1994) . Fire history studies in the southwestern U.S. have relied almost exclusively on fire-scar samples from living and remnant conifers to reconstruct the frequent surface fire regimes of mid-elevation, pine-dominated forests. Fire history reconstructions in upper elevation forest types require different methodogical approaches due to the relative scarcity of fire-scarred trees (e.g., Romme et al. 2001).

Age structure-based methods for reconstructing fire history were developed in coniferous subalpine and boreal forests of western North America where stand-replacing fire regimes are dominant (Clements 1910; Heinselman 1973; Agee 1993b; Johnson &

Gutsell 1994; Kipfmueller & Baker 1998). By definition, stand-replacing fires leave few living trees that can record direct evidence of fire (e.g., fire scars). In addition, upper montane tree species may be less reliable at recording fire scars due to differing morphological characteristics (e.g., thinner bark) that makes the tree more susceptible to complete cambium mortality around the circumference of the bole. In the rare case when upper elevation trees are scarred by fire, the mesic environment increases wood decay rates and decreases the utility of samples for dendroecological analysis. Thus, post-fire cohorts are the most prevalent evidence of stand-replacing fire and can be combined with the relatively rare direct conifer evidence of fire (e.g., fire scars and death dates) to derive stand-replacing fire dates (Margolis et al. *in press*).

Variations of age structure-based fire history methods have only been applied in a few studies in the southwestern U.S., primarily utilizing quaking aspen age structure as a proxy of stand-replacing fire in upper-elevation forests of the region (Touchan et al. 1996; Abolt 1997; Romme et al. 2001; Margolis et al. *in press*). Romme et al. (2001) reconstructed fires with decadal resolution from aspen stand-age in the La Plata Mountains of southwestern CO, emphasizing the lack of fire-scarred trees in aspen stands as a limitation to dating precision. Abolt (1997) used coincident aspen pith dates and fire scars from lower elevation conifers to date stand-replacing fire patches in mixed-conifer forests of the Mogollon Mountains of southwestern NM. Margolis et al. (*in press)* combined four lines of tree-ring evidence (aspen age structure, conifer fire scars, conifer death dates, and conifer injury dates) to reconstruct stand-replacing fire in upper montane forests of the upper Rio Grande Basin (NM and CO).

These studies indicate the potential for quaking aspen age structure to be used to date historical stand-replacing fires in upper elevation forests throughout the southwestern U.S. The primary goal of the current research was to reconstruct fire history in the upper elevation forests (>2600m) of four mountain ranges in the southwestern U.S., focusing on quaking aspen as an indicator of the timing and minimum extent of past stand-replacing fires.

Although upper elevation, subalpine conifers have been widely used to date post-stand-replacing fire patches in the Southern Rockies of Colorado and Wyoming (e.g., Kipfmueller & Baker 2000; Sibold et al. 20006) the effectiveness of this method is not well established in the southwestern U.S. The spruce-fir forest at the top of the Pinaleños Mountains in southern Arizona is the only site we are aware of where spruce-fir patches have been sampled and interpreted as likely post stand-replacing fire patches (e.g., Grissino-Mayer et al. 1995). Thus, a secondary goal was to attempt to use spruce-fir age structure to expand the reconstruction of stand-replacing fires beyond the range of quaking aspen into the spruce-fir zone.

Fire patch size

How extensive were historical stand-replacing fires in the upper montane forests of the southwestern U.S. and how do they compare with modern fires? The answer to this question within a given study area requires the mapping and dating of all potential post-stand-replacing fire patches, including upper elevation conifers (e.g., Engelmann's spruce and corkbark fir).

Fire size, or more specifically fire patch size, has a strong influence on the ecological effects of fire. Stand-replacing fire patch size is a key determinant of post-fire vegetation composition and structure (Agee 1993a; Turner et al. 1994; Turner & Romme 1994). Following the Yellowstone fires of 1988 the size and intensity of burn patches was shown to affect overall biotic cover, tree seedling recruitment and herbaceous recruitment (Turner et al. 1994). Fire also affects aquatic ecosystems via water temperature and water chemistry changes, increased runoff and severe channel alteration (Minshall et al. 1989; Rieman et al. 2003; Minshall 2003). The magnitude of these effects are linked to the size and intensity of the area burned (Turner et al. 1993).

The size of high-intensity fire patches is also very important in determining the probability of fire-induced flooding or debris flows (Pearthree & Wohl 1991; Cannon & Reneau 2000). High intensity fires remove overstory vegetation and ground cover that dramatically affects watersheds and water resources by altering the important processes of evapotranspiration, interception, surface flow, and subsurface flow (Swanson 1981; Knight et al. 1985). Recent, large stand-replacing fires in the southwestern U.S. have produced runoff and erosion events as much as two orders of magnitude greater than pre-fire conditions (Johansen et al. 2001; Veenhuis 2002). The potential hydrological impacts of large, stand-replacing fires pose serious problems for water resources in a region with a limited water supply and currently experiencing a multi-year drought (Liverman & Merideth 2002).

Stand-replacing fire patches are usually part of a larger fire event that includes moderate and low severity surface fire, as well as unburned islands (Turner & Romme

1994). For example, less than half of the Yellowstone fires of 1988 burned with high severity (Turner et al. 1994). Reconstructing the full spatial extent and range of burn severities of historical fires is not possible. However, stand-replacing (high severity) fire patches have a more persistent, more identifiable legacy and reconstructed stand-replacing fire patch size is a metric that can be compared with contemporary fires even if overall fire size is unknown.

Thus, the third goal of this research was to use tree-ring reconstructed and contemporary (1996-2004) fire patch size data in an initial attempt to quantify and compare the contemporary and historical range of variability in upper elevation forest stand-replacing fires. We did not attempt to reconstruct a complete inventory of stand-replacing fire patches, but to map and date the largest and potentially most ecologically significant patches within defined study areas in the southwestern U.S.

Study area

The study area includes north-central and southeastern Arizona, and southwestern New Mexico (Figure 1). Within this area, we sampled two mountain ranges with the largest quaking aspen and/or spruce-fir stands as potential proxies for stand-replacing fire in each of two geographic provinces: 1) the Madrean Sky Islands and 2) the Mogollon Plateau (Figure 1, Table 1). The Pinaleño Mountains (PIN) and the Chiricahua Mountains (CHI) were sampled within the Madrean Sky Islands of southeastern Arizona (Figures 2, 3). The San Francisco Peaks (SFP) in north-central Arizona and the Mogollon Mountains (GIL) in southwestern New Mexico were sampled on the Mogollon

Plateau (Figures 4, 5). All sites were located on USDA Forest Service land managed by the Coronado, Gila, and Coconino National Forests and all sites but PIN are managed as wilderness areas. Study sites were located in the upper montane forests, above the mid-elevation *Pinus spp.* dominant forests. Mean elevation of the study sites was 2982m (Table 1). Tree-ring samples were collected between 2694m and 3257m.

The precipitation regime within the study area is bi-modal. All sites receive approximately fifty percent of annual precipitation from summer monsoon thunderstorms (June – September) (Adams & Comrie 1997). Cool-season frontal storms and tropical Pacific hurricanes account for the remainder of the precipitation totals (Sheppard et al. 2002). All sites receive winter snow, but snowpack varies widely from year to year depending on the winter stormtrack.

In the northern portion of the study area average annual precipitation is 564 mm (1961-1990), recorded at Fort Valley, AZ. This station is located approximately 40 km from the SFP study site, but approximately 700 m lower in elevation (2243 m). The annual average temperature is 6.2°C, with a maximum monthly average of 17°C (July) and minimum monthly average of -3.2°C (January) (Western Regional Climate Center[1]).

The climate of the three southern sites (CHI, PIN, and GIL) is best represented by data recorded at Palisade Ranger Station in the Santa Catalina Mountains, AZ. This location is approximately 500 m lower than the study sites (2426 m). Annual average precipitation is 815 mm and forty seven percent of the total falls between July and

[1] Western Regional Climate Center (WRCC). Historical climate station data available at: http://www.wrcc.dri.edu/climsum.html

October (1965-1981). The annual average temperature is 9.3°C, with the warmest month being July (18.3°C) and the coolest in January (1.4°C) (Western Regional Climate Center[1]). Actual temperature (precipitation) at all study sites is less (greater) than values reported from the climate stations due to adiabatic processes.

The Madrean Sky Island sites (CHI and PIN) are located in the southern basin and range province. These isolated mountain ranges are surrounded by Sonoran and Chihuahuan desert vegetation. The Pinaleño Mountains are the highest in the province, reaching an elevation of 3267 m. The range is composed of an eroded Precambrian granite-gneiss complex (Swan 1976). The Chiricahua Mountains are an uplifted fault block range composed of rhyolitic tuff and basalt dating to volcanic episodes ceasing 8 million years ago (Lamberton & Garton 2003). The volcanic San Francisco Mountains or San Francisco Peaks (SFP) are the northernmost range sampled. This range is the remnant of a collapsed, composite volcanic cone and is one of only two locations in Arizona with evidence of Pleistocene glaciers (Pewe & Updike 1976). The Mogollon Mountains in the Gila Wilderness Area (GIL) are also of volcanic origin, dating to the close of the Createaceous era (65 million years ago) when an igneous dome elevated within a huge caldera to form the range (Ratte et al. 1979).

The vegetation at the study sites is dominated by quaking aspen adjacent to upper elevation mixed conifer stands that included Engelmann's spruce (*Picea engelmannii* Parry). Associated vegetation varied across the elevation and latitude gradient within the study area. The tree species observed within and adjacent to the aspen stands included ponderosa pine (*Pinus ponderosa* Lawson), southwestern white pine (*Pinus strobiformis*

Engelm), Douglas-fir (*Pseudotsuga menziesii*[Mirb.] Franco.), white fir (*Abies concolor* [Gord. & Glend.] Lindl. Ex Hildebr.), subalpine fir (*Abies lasiocarpa* [Hook] Nutt.), and Rocky Mountain bristlecone pine (*Pinus aristata* Engelm.).

Site-specific vegetation descriptions

Pinaleño Mountains (PIN)

This site (Figure 2) is the southern limit of spruce-fir forests in North America (Little 1971). A relatively large, high elevation (2600m – 3262m) plateau at the top of the range supports the largest pure spruce-fir forest in the Sky Island region (>500ha). Mixed conifer forests are present at lower elevations around the perimeter of the spruce-fir forest, dominated by emergent, large, relatively old (> 500 yrs), surface fire resistant Douglas-fir. Most of these stands contain scattered individuals and small stands of quaking aspen. The recent Clarke Peak Fire (1996, 2,600 ha) and Nuttal-Gibson Fire Complex (2003, 12,029 ha) burned with stand-replacing severity in relatively large patches (>100 ha) across elevation gradients on the mountain, affecting much of the upper montane forests.

Chiricahua Mountains (CHI)

These mountains (Figure 3) are below the latitude/elevation limit of spruce-fir forests and thus only contain small (<5 ha) patches of Engelmann's spruce. This contrasts with the large contiguous spruce-fir stand located less than 100 km north at PIN. The north-south oriented crest of CHI has a maximum elevation of circa 2800m and is dissected by multiple east-west trending ridges. This landscape structure produces alternating north and south-facing slopes and respective mesic and xeric mixed conifer forest types in close proximity. The aspen stands and the few small relict patches of spruce are located on north aspects. The more xeric, mixed conifer forests that contained fire-scarred trees were located on the opposite sides of the ridges, on south-facing slopes. The recent (1994) Rattlesnake fire burned with stand-replacing severity in relatively large patches (>100ha) across elevation gradients on the mountain, affecting much of the upper montane forests. Some crown fire patches burned portions of the aspen forests targeted in this study, consequently reducing the patch size estimates.

San Francisco Peaks (SFP)

Although isolated from the main massif, this range (Figure 4) is similar to the ranges of the Southern Rocky Mountains. This is the only site containing Rocky Mountain bristlecone pine and an upper elevation tree line. These two features exemplify the floristic and physiographic differences between this range and the more southern sites in this study and similarities with Southern Rocky Mountain ranges (e.g., Sangre de Cristo Mountains, NM-CO).

Landscape-scale aspect differences affected the vegetation composition at this site, as well. The south-slope forests were relatively open, with grasslands interspersed between and below the aspen and mixed-conifer stands. The forests adjacent to the grasslands contained a relative abundance of fire-scarred southwestern white pine with multiple scars. In contrast, the north-facing slopes contained, relatively large homogenous aspen patches, surrounded by mesic mixed conifer and spruce-fir forests. The vegetation structure on these north-facing slopes at this site is most similar to the large homogenous aspen stands common in the upper montane forests of the upper Rio

Grande Basin. These mesic, north-facing slopes with large aspen patches had very little direct evidence of fire (e.g., fire-scarred trees), in contrast to the south-facing slopes.

Mogollon Mountains (GIL)

A notable vegetation feature at this site (Figure 5) was high elevation grasslands on south-facing slopes. Similar to the high elevation grasslands at SFP, these features bordered and often bisected mesic mixed conifer and seral aspen stands. Also notable at this site was the presence of relatively old (>250 yrs), co-dominant quaking aspen in spruce-fir stands. This co-dominant aspen/conifer stand-structure and species composition was very different from the large, pure aspen stands found adjacent to and below the spruce-fir stands, often less than 200 m apart.

Land-use history

Fire exclusion resulting from late 19th century grazing and 20th century fire suppression occurred at all sites, similar to most montane sites in the southwestern U.S. (Bahre 1985; Swetnam & Baisan 1996; Allen 2002). There is no evidence of permanent settlement by Native Americans or Euro-Americans in the upper montane forests at any sites. No evidence of mining or logging was observed within any of the sampled stands. There was some evidence (e.g., cut stumps) of 20th century logging at lower elevations near (< 100 m) a few of the SFP and PIN sample locations. However, no logging occurred within any of the sampled aspen or spruce-fir stands. The exact dates of Euro-American settlement and changing land-use practices at each study site varies, but there is no evidence of extensive and intensive land-use changes (i.e., logging or mining) before circa 1880 at any site. Specific land-use history that could have affected fire regimes at CHI is discussed below.

The Chiricahua Mountains were home to the Chiricahua Apaches from at least circa 1600 until Geronimo's surrender in 1886 (Worcester 1979). Localized effects of Native American burning in ponderosa pine and mixed conifer forests have been proposed from evidence in the fire-scar record (Seklecki et al. 1996). For example, at this site (1770-1773), unusual fires were recorded in four consecutive years. An increased proportion of dormant season fires was also recorded at this site compared to other sites in the region, which Seklecki et al. (1996) interpreted as potential evidence of Native American ignitions outside of the dominant pre-monsoon dry lightning season (May and June). Thus, it is possible that Apache burning may have augmented the natural (lightning) fire regime at this site and other specific sites within the southwestern U.S., but effects are likely restricted to localized areas (e.g., travel routes and camps) during particular time periods (Allen 2002).

Field methods

A. Stand-replacing fire dating and analysis using aspen patches

We originally proposed to sample the two largest aspen patches in each of the sampling regions (Madrean Sky Islands and Mogollon Plateau). This approach was used to successfully date stand-replacing fire occurrence in the Southern Rocky Mountains (Margolis et al. *in press*). This sampling method proved to be difficult at these sites due to the relatively small size of the aspen patches and the heterogeneous arrangement of aspen stems within a matrix of conifer stands. This vegetation pattern, particularly in the Madrean Sky Islands, differs from the large (>1000ha) homogeneous aspen stands found in the upper Rio Grande Basin of northern New Mexico and southern Colorado (Figure 6). The smaller, more heterogeneous aspen patches can be partially explained by limited high elevation (>2600m) land area, which decreases the potential habitat for the upper montane conifer species or aspen (Figure 7). Due to the lack of single, large, homogenous aspen stands, multiple smaller patches were sampled in each of the four mountain ranges. The combined data from the multiple aspen patches in each study site were used to evaluate patterns in that area.

To determine the sampling area at each site, the largest aspen patches were mapped using digital vegetation maps, black and white digital ortho-rectified quarter-quadrangle photographs (DOQQ's), and color infrared DOQQ's. Additional site selection criteria included the presence of contiguous spruce-fir and/or mesic mixed-conifer forest directly adjacent to the aspen stands. Targeting seral aspen associated with conifer stands eliminated self-replacing aspen stands and stands within high elevation parklands likely to have experienced frequent surface fires (Jones & DeByle 1985). Tree-ring sample point locations within the stands were pre-determined using a geographic information system (GIS). Points were dispersed to obtain dispersed spatial coverage of the targeted aspen stands. Universal Transverse Mercator (UTM) coordinates were determined for sample points using the GIS. A global positioning system (GPS) was used to navigate to sample points in the field. Less than 10% of the sample point locations were adjusted in the field due to map inaccuracies or topographic barriers. Additional sample points were added in the field at locations with conifer evidence of fire or to verify stand boundaries.

Field sampling

Field sampling was conducted according to previously developed methodology to include collection of four lines of tree-ring evidence for stand-replacing fire occurrence (Margolis et al. *in press*). Increment cores were collected from a minimum of 30 aspen stems at each site, distributed over at least 15 sample points throughout the site as topography allowed. At each sample point, two aspen stems of greatest d.b.h. within a 10m radius were cored (< 0.3m core height) until the pith was present in one sample at the point.

At each sample point and opportunistically between points, partial cross-sections or increment cores were collected from conifers with evidence of fire. These samples included fire-scarred snags or charred, standing-dead snags, stumps, and remnant logs possessing intact bark. Partial cross-sections or increment cores were collected from scarred or potentially injured live trees located adjacent to aspen stands. Fire scars were not collected at CHI or PIN due to the extensive existing fire history data for these areas (Morino et al. 2000: Grissino-Mayer et al. 1995). A GPS unit was used to record UTM coordinates at each sample point and for any samples collected between points. The maximum reported GPS error for coordinate location was 15 m (typical error ~ 5 - 8 m).

All samples were prepared and crossdated according to standard dendrochronological procedure (Stokes & Smiley 1968). Dates from the four lines of tree-ring evidence were plotted to determine fire dates and fire severity. A mapped aspen patch was determined to be a post-stand-replacing fire patch if 1) the aspen recruitment pulse began within five years following a fire event recorded by fire-killed conifer bark-ring dates from within the patch and/or fire scars on the periphery of the patch and 2) a lack of trees that survived the fire. All tree-ring data were entered into a database associated with a GIS to produce a spatial representation of the tree-ring evidence at each site.

B. Stand-replacing fire patch size reconstruction

Quaking aspen

The aspen patches used to reconstruct fire history were used to estimate the historical range of variability of stand-replacing burn patch size. These patches were digitized from DOQQ's and patch area was calculated with a GIS. This data set provides minimal estimates of past stand-replacing burn patch sizes for reasons to be discussed below.

Spruce-fir fire history methods

In addition to using aspen patches as minimum estimates of stand-replacing fire patch sizes we investigated the potential to apply previously developed methods for mapping and dating stand-replacing fires in spruce-fir stands. Fire dates and patch size obtained from the spruce-fir stands would provide a more complete estimate of stand-replacing fire size. Fire patch size estimated from aspen stands probably represents a minimum estimate of stand-replacing fire area. This is because aspen does not always fill the entire area of high severity burn patches. Typically aspen sprouts from an extensive root network only where aspen existed prior to the fire event. The presence of very few living aspen stems in a conifer-dominated forest is often sufficient to maintain a large root network that can reclaim a site following a stand-replacing fire. However, areas that were pure spruce-fir forests with no living aspen stems would not be expected to regenerate as quaking aspen. In these areas past stand-replacing fire patch size must be estimated from the age structure of spruce-fir patches.

We used remotely sensed data and field observations to assess spruce-fir stands at PIN and GIL for evidence of stand-replacing fire. This method is common in the subalpine forests of the Rocky Mountains where the legacy of multiple, overlapping crown fires is present in large, identifiable (mainly by height and bole diameter differentiation) stands of conifer forests. Aerial photographs were analyzed for differences in texture, density, color, or differences in tree height, potentially representing fire boundaries (Johnson & Larsen 1991; Agee 1993b; Johnson & Gutsell 1994; Kipfmueller & Baker 1998). Field observations from ridges and within stands were use to confirm the potential stand-replacing fire patches.

No fire boundaries within spruce-fir stands (e.g. differential canopy heights) were evident from the aerial photos or fire reconnaissance so we treated each spruce-fir stand as a single potential stand-replacing fire patch. Dendrochronological samples were collected within the spruce-fir patches to determine the likelihood, and possibly the date, of past stand-replacing fire(s). To determine the age structure of the patch, increment cores from the base (< 0.3 m core height) of the largest diameter conifers were collected at predetermined points within the patch. If present, partial cross-sections were removed from trees with fire scars along the fire boundary or fire-killed remnant conifers within the patch. Dates from the oldest trees in the patch were compared with proximate fire scar dates to determine the fire year.

Comparing historical and contemporary stand-replacing fire patch size

To assess whether contemporary stand-replacing fire patch size was within the historical range of variability, we identified recent fires (1996-2004) with high and/or moderate severity patches within 100 km of the fire history study sites (Figure 1). Burn severity maps from the burned area emergency rehabilitation (BAER) assessments were acquired from the USDA Forest Service. These maps were not specifically created for analysis of burn patch size, but were created to assess hydrologic damage and erosion potential in the fire area and highlight areas for treatment. Errors inherent in the burn maps are part of the data set we extracted. However, of the burn severity classes, high severity, stand-replacing, crown fire patches are the most easily identified and the most accurately mapped (Carl Key, *personal communication*).

The main challenge was to extract the subset of modern burn patches from vegetation types and elevations similar to the historical stand-replacing fire patches reconstructed from the aspen stands. To make the data sets most comparable, we set an elevation cut-off of 2600m to isolate the forest types most similar to the aspen patches, which had a minimum mapped elevation of 2600m. The isolation of forests above 2600m eliminates recent, large crown fire patches that occurred in the lower elevation oak and/or pine-dominant forests.

We decided that “stand-replacement” in the contemporary fire data set, could result from both high and moderate severity fire. Delayed mortality from crown scorch and insect attack has been documented in moderate severity burn patches in recent fires (McHugh & Kolb 2003; McHugh et al. 2003). Based on the assumption that some percentage of the moderate severity burn patches resulted in stand mortality, high and moderate severity patches were combined in a data set representing a maximum estimate of stand-replacing patch size.

Four burn patch area data sets were extracted from the contemporary burn severity maps: 1) high severity, 2) high plus moderate severity, 3) high severity >2600 m, and 4) high plus moderate severity > 2600 m. The "high severity > 2600 m" data set was the most exclusive. This conservative estimate of stand-replacing burn patch size assumes that there was no mortality in the moderate severity burns. The "high plus moderate severity" data set was the most inclusive. It included lower elevation pine and oak stands and was based on the assumption that all high and moderate severity burn patches were stand-replacing. The inclusion of the lower elevation forest types in this subset of the data made it fundamentally different from the aspen-based reconstruction of stand-replacing fire patch size. The most equivalent data set to the aspen patch size data was likely somewhere between the "high severity >2600 m" and the "high plus moderate severity >2600 m" burn patches.

Results

Field sampling

We sampled 191 aspen stems and 139 conifers, which were crossdated and used to reconstruct upper montane fire history, focusing on stand-replacing fire patches (Table

2; Grissino-Mayer et al. 1995; Morino et al. 2000). Thirty nine percent of all sampled aspen regenerated within five years after fire, ranging from 10.3% to 58.3% between sites. Annually dated, direct conifer evidences of fire (e.g., fire scars and bark-ring death dates) were used to reconstruct 100 fires occurring on 87 unique fire dates (1623-1904) (Table 3). Of these, three fires (1879 - SFP, 1685 - PIN, and 1904 - GIL) had evidence of stand-replacement within mapped patches (Figures 8-11). Evidence of complete stand-replacing fire included aspen and conifer recruitment pulses, coincident fire-killed conifer bark-ring dates, and a lack of trees that survived the fire. The remaining fire dates did not have evidence of complete stand-replacement within mapped patches. Of these, eleven fires were recorded by at least five conifers (including fire scars) at a site, indicating fire spread.

Pinaleño Mountains

No contiguous quaking aspen patches greater than 5 ha were mapped in the Pinaleños (Figure 2, Table 1). Individuals and small groups of aspen stems were scattered throughout the upper montane forest (2870m-3012m), below and within the lower ecotone of the spruce-fir stand. The lack of relatively large homogenous stands of aspen precluded using aspen age structure and patch size to reconstruct stand-replacing fire patches. However, the collective age structure of the scattered aspen was used to determine if regeneration was associated with fire events recorded by fire scars in the mixed-conifer/aspen forests.

No single, large cohort of aspen was present in the age structure data, suggesting the lack of large stand-replacing fire events during the past 250 years (Figure 8). Only ten percent of aspen dated to within 5 years following fires recorded by ≥5 fire-scarred trees. Aspen recruitment was recorded in every decade between 1840 and 1920, with a general lack of recruitment from 1790-1840. Six aspen (20%) dated prior to 1790 and some had ages of greater than 250 years.

Tree-ring evidence of 6 spreading fires recorded by ≥5 trees (1685-1871) in the upper montane forest indicates the potential for these fires to have contributed to the complex aspen age structure. Two potential effects of these relatively frequent, spreading fires on the aspen age structure include: 1) creating small canopy openings that may have stimulated the development of post-fire cohorts and 2) killing post-fire aspen cohorts from previous fires. The relative importance of these effects depends on the spatial pattern of fire severity.

Continuous aspen recruitment from circa 1840-1920 across the mixed-conifer portion of the site indicates that no widespread stand-replacing fires occurred after 1842 (i.e., for at least circa 165 years) (Figure 8). If for example, the 1871 fire was a widespread stand-replacing fire, then no aspen stems would pre-date this fire. The presence of aspen stems that predate multiple fire events indicates that these fires were not stand-replacing, or at least not over the entire sampled area. A more sample intensive, spatially systematic sampling method is required to determine the details of the relationship between fire and quaking aspen age structure at this site.

Without large contiguous patches of quaking aspen, the spruce-fir stand itself was the only potential source of information on past stand-replacing fire. The oldest tree (*Picea engelmannii*) from the spruce-fir stand had an inner-ring date of 1692 (Figure 8).

This age structure follows a widespread fire year (1685) that scarred all recording trees just below the spruce-fir stand (Grissino-Mayer et al. 1995). The three trees that pre-date this event were Douglas-fir located below the spruce-fir zone. Thus, we detected no trees in the spruce-fir forest that survived the 1685 fire. Within and around the perimeter of the spruce-fir stand we observed no direct evidence of fire (e.g., charred wood, fire scars). Thus, it is likely that prior to the recent stand-replacing fires (1996 Clark Peak and 2004 Nuttall fires) there was no large stand-replacing fire for over three centuries in the spruce-fir and at least circa 165 years (after 1842) in the sampled mixed conifer forest.

Chiricahua Mountains

Similar to the other Sky Island site (PIN), only small patches of mature quaking aspen were present in the upper elevation forests of the Chiricahua Mountains (Figure 3). Eight patches were mapped, totaling 139 ha (Table 1). In contrast, many large (>200 ha) crown fire patches from the 1994 Rattlesnake fire contained abundant quaking aspen regeneration. Mapping and dating of potential historical stand-replacing fire patches (quaking aspen) was particularly difficult due to the crown fire patches from the 1994 Rattlesnake fire, which probably resulted in lower accuracy in the estimates of patch size than in other cases.

No single post-stand-replacing fire (quaking aspen) cohort was present at CHI (Figure 9). Similar to PIN, multiple aspen cohorts were present, with aspen regeneration recorded in each decade from 1850-1920. Surface fire was relatively frequent (MFI – 11.2 yrs) at this site prior to the 20th century as indicated by existing upper elevation fire history collections (Morino et al. 2000) from south-facing slopes adjacent to the aspen stands. Fourteen fires scarring ≥ 5 trees were recorded (1685-1886), with four fires occurring during the period of aspen regeneration (1851-1886). Forty six percent of aspen dated to within 5 years following these fires.

None of the mapped aspen patches were interpreted to be post-stand-replacing fire patches. This was based on the multi-aged aspen age structure within patches that indicated some aspen stems survived (pre-dated) multiple fires. The most prominent post-fire aspen cohort regenerated after the 1886 fire. This cohort was scattered throughout multiple patches. Stems from this cohort were located adjacent to older aspen stems (e.g. 1852, 1853 inner-ring dates) that survived the 1886 fire. Relatively continuous aspen recruitment at least back to the 1851 fire is evidence for the lack of a widespread stand-replacing fire that affected all sampled aspen patches for at least 160 years.

San Francisco Peaks

The San Francisco Peaks were originally sampled as two sites: (1) north slope and inner-basin, and (2) south slope. However, both sites recorded a fire in 1879 and were combined into one large site consisting of multiple aspen patches totaling 1125 ha (Figure 4, Table 1). The area of the largest patch (223 ha) exceeded the combined mapped aspen patches at both Sky Island sites.

Fifty eight percent of aspen dated to within 5 years following all fires. Multiple lines of tree-ring evidence indicate that the 1879 fire was stand-replacing in some locations (Figure 10). A very distinct and immediate recruitment pulse begins in 1879.

The few aspen that predate 1879 were all from the patch at the southeastern part of the site where there was no fire-scar evidence of the 1879 fire. Tree-ring evidence of the 1879 fire in all but one aspen patch indicates that this fire burned a large proportion of the mountain.

Although the data from the original two sub-sites were combined, there were differences in the fire history and the forests between these areas. The aspen stands sampled on the northern side of the range and on the north slopes of the eastern portion of the "inner basin" had the largest mean reconstructed stand-replacing fire patch size of all the sites (145 ha). The mesic, north aspect of these sites seemed to be conducive to large (>100 ha) stand-replacing fire patches. Monospecific aspen stands, with fire-killed conifers and little evidence of surviving conifers were found on these north aspects.

The more xeric, south-aspect stands contained evidence of a different fire history than the north aspects stands. These stands were connected to the middle elevation pine forests by large grasslands and conifers with multiple fire scars were found within these south-facing aspen stands. The nine fires recorded before the 1879 fire were all from fire-scarred material on the south slope (Figs 4 & 10). This evidence of repeated, relatively frequent lower severity fires in the upper elevation, south-facing aspen stands is unlike the fire regime and forest stands on the north-facing slopes and more similar to the mixed conifer-aspen forests in the Sky Islands (i.e., mixed-conifer forests with evidence of surface fires).

No spruce-fir patches were mapped or sampled at this site, although large patches (>500 ha) of spruce-fir do exist. There is photographic evidence of a large stand-replacing fire in the spruce-fir stands of the inner basin during the late 19th century (Figure 12). One of the sampled aspen patches was at the east end of the inner basin and dated to 1879 (Figure 4). It is possible that the 1879 fire that regenerated the quaking aspen stands also burned the large spruce-fir patches seen in the photograph.

Mogollon Mountains (Gila Wilderness)

The Mogollon Mountains (GIL) had multiple large (>100 ha) quaking aspen patches totaling 812 ha (Figure 5). These homogenous, even-aged seral patches contained fire-killed Douglas-fir and had no evidence of any living trees that pre-dated the dominant aspen. These characteristics are strong evidence that the mapped aspen patches were post-stand-replacing fire patches. Similar to PIN, scattered co-dominant aspen were also present among mixed conifer stands and unique to this site, within the spruce-fir stands.

A relatively continuous distribution of aspen recruitment occurred in almost every decade from 1730-1920 (Figure 11). The co-dominant aspen present in the spruce-fir stands had inner rings dating to the early and mid 1700's. No clear recruitment pulse was evident from these old aspen, which may be due to low sample size in this age range. Many of these old aspen stems in the spruce-fir stands had decomposed heartwood preventing the collection of intact increment core samples containing the earliest years of growth.

Fifty eight percent of aspen dated to within 5 years following all fires. A distinct post-fire recruitment pulse began in 1904 (Figure 11), indicating that the mapped aspen stands clearly regenerated after this stand-replacing fire. The 1904 fire burned with stand-replacing severity in multiple locations and was generally widespread (Figure 13). Additional aspen patches north of the current study area near Whitewater Baldy have stand structure similar to the stands dating to the 1904 fire. These stands may have regenerated following a 1922 fire that was reported to be stand-replacing (Leopold, 1922).

All of the fire-scars were collected from Southwestern white pine located in the south aspect, high elevation parklands directly adjacent to the quaking aspen patches. This material was relatively rare and thus a complete record of fire at this site was probably not obtained, but the coincidence of fires recorded between samples indicates that widespread fires were likely recorded. Between 1773 and 1904 there was no direct evidence of fire (e.g., fire scars). This gap in fire occurrence was not likely an artifact of a decaying record because the 1773 fire was recorded by more fire-scar samples than the more recent 1904 fire.

Similar to PIN, no direct evidence of fire was observed within the spruce-fir stands at GIL. The largest mapped spruce-fir stand (>1123 ha) was twice the area of the PIN spruce-fir stand. The sampled age structure within the spruce-fir patches did not clearly indicate a post-fire recruitment cohort. Relatively continuous conifer establishment was recorded in the decades from 1700-1910. The oldest individual (*Picea engelmannii)* in the spruce-fir patches dated to 1707 and multiple spruce pre-date the oldest crossdated fire scar (1716) recorded adjacent to the spruce-fir patches. The few trees that pre-date 1700 were Douglas-fir located below the spruce-fir forest along the perimeter of the quaking aspen patches. More spruce-fir age structure data and an extended fire-scar record are needed to determine if the spruce-fir patches of the Mogollon Mountains regenerated after stand-replacing fire.

Stand-replacing fire patch size (historical vs. contemporary)

Due to limited success in dating spruce-fir patches the historical stand-replacing fire patch size estimates were derived from mainly from aspen patches and only one spruce-fir patch, and therefore represent a minimum patch size (Table 4). The four modern data sets included: 1) high severity, 2) high and moderate severity >2600m, 3) high severity >2600m and 4) high and moderate severity >2600m. The modern data were limited to patches $\geq$ 35 ha, equal to the minimum reconstructed stand-replacing fire patch size.

We did not test for differences between central tendencies in the reconstructed and modern patch size data for three reasons: 1) the values of interest were the maximum patch size so our sampling was biased toward the largest patches (i.e., extremes of the distribution), 2) the reconstructed and modern patch size data were sampled from different sized search areas, such that they are samples of different populations, 3) the reconstructed patch size data are normally distributed (Kolmogorov-Smirnov Z statistic = 0.86) and the four modern patch size data are not (K-S Z statistics = 2.42 – 5.74; SPSS 14.0). Due to these limitations only qualitative comparisons between maximum patch sizes are reported.

All four modern (1996-2004) stand-replacing burn patch size data sets had a larger maximum patch size than those reconstructed from historical fires using aspen

(286 ha) and spruce-fir (521 ha) patches (1685-1904) (Table 4). The most conservative of the modern fire data sets (high severity >2600 m) had five patches larger than 286 ha and two greater than 521 ha, with a maximum of 1129 ha. The modern fire data set including both high and moderate severity patches >2600 m had seven patches greater than the maximum reconstructed patch, including three greater than 1000 ha and a maximum patch size of 1880 ha. The maximum patch size for the most inclusive modern data set (8288 ha) was an order of magnitude larger than that derived from tree-rings, but it also included lower elevation pine and oak forests, whereas the aspen and spruce-fir patches were all in the montane forests above this zone.

The one spruce-fir patch that was dated to a stand-replacing fire (PIN 521 ha) was only half the size of the largest modern high severity patch >2600m (1129 ha). If all the spruce-fir patches (stands) mapped at GIL are assumed to be post-fire patches of an undetermined date then the maximum reconstructed patch size (1123 ha) would be approximately equal to the most conservative estimate of contemporary fire patch size (1129 ha). However, currently there is no data to indicate that these spruce-fir patches are the result of fire. Larger spruce-fir patches (>2000 ha) do exist at GIL that would need to be mapped and dated to determine if larger stand-replacing patches occurred in earlier times.

Discussion

Reconstructed stand-replacing fires

Two widespread stand-replacing fires were dated using quaking aspen age structure and associated conifer evidence of fire (1904 - GIL and 1879 - SFP). Abolt

(1997) identified 1904 as a widespread fire with a stand-replacing component (estimated area of this fire, including all patches, was greater than 10,000 ha) in the Mogollon Mountains from tree-rings and historical documents. Aldo Leopold (1922) makes reference to a 1904 fire in the Mogollon Mountains while on a fire assignment in the Gila Wilderness. Abolt (1997) also identified a post-fire aspen cohort dating to 1748, a fire recorded by $\geq$5 conifers in our study.

Heinlein et al. (2005) dated a fire in 1879 in the San Francisco Peaks at a lower elevation pine-dominated site using tree-rings. They did not report evidence of high severity fire. Historical photographs do indicate that a circa "1880's" stand-replacing fire affected large parts of the spruce-fir zone in the inner-basin (Figure 12; USFS 1910). Based on the downed snags, it is likely that the fire was decades prior to the photo (1910) and thus could have been the same stand-replacing fire recorded in the mixed-conifer/aspen forests in this study (1879). This photographic evidence of a large historic stand-replacing fire in the spruce-fir zone of SFP potentially makes it a good site to test the efficacy of different age structure methods for dating spruce-fir regeneration cohorts following stand-replacing fires in the southwestern U.S.

The spruce-fir stand at PIN is the only spruce-fir patch that we were able to associate with a fire recorded by direct conifer evidence of fire (i.e., fire scars). The age structure data we collected and the sampling of more than 290 trees by Grissino-Mayer et al. (1995) from the large (521 ha) spruce-fir stand at PIN support the hypothesis of a stand-replacing fire in 1685 (Swetnam et al. *in press,* but see Stromberg & Patten 1991). This year was extremely dry (-5.0 reconstructed PDSI (Cook et al. 2004)) and a common fire year throughout the southwestern U.S. (Swetnam & Baisan 2003). Thus, it is possible that the otherwise mesic spruce-fir zone could have been dry enough to burn in a crown fire.

The spruce-fir age structure data from GIL indicates that individual trees in the spruce-fir stands above the aspen patches were of similar age as the PIN stand (at least 300 years old; inner-ring date 1707). It is possible that these represent old stand-replacing burn patches, but more data is needed to determine if this is the case, or not. Different, more sample-intensive methods are needed to accurately map and date these old, upper elevation conifer stands.

Frequent fire and quaking aspen

We found direct evidence of repeated low intensity fire (e.g., fire scars) within and adjacent to quaking aspen stands in specific locations at multiple sites (e.g., south slope of SFP, mixed conifer forests of PIN and CHI). The surviving conifers that recorded multiple fire scars indicate that the fires were not stand-replacing at these locations. The frequent occurrence of fire in these upper montane forest sites prior to 1900 (PIN - Weibull Mean Probability Fire Interval = 4.2 years, approximately 150 ha sample area (Grissino-Mayer et al. 1995; Swetnam et al. *in press*) and CHI – Mean Fire Interval = 11.2 yrs, approximately 250 ha sample area (Morino et al. 2000)) may have prevented sufficient fuel accumulation to sustain stand-replacing fire. This indicates that the cessation of fire due to late 19th century grazing and 20th century fire suppression may be a cause of fuel structure changes and build up that contributed to the recent occurrence of stand-replacing fire in the mixed-conifer/aspen forests at these sites (Swetnam et al. *in press*).

Similar evidence of frequent low severity fire (i.e., multiple-scarred stumps and living conifers) was present within and adjacent to aspen stands on the south slope of SFP. The lower edges of these aspen stands bordered large grasslands that likely carried fire from the frequent burning, lower elevation pine-dominated forests (Heinlein et al. 2005) into the aspen/mixed-conifer stands we sampled. Based on this evidence of repeated surface fire in the south-aspect stands at SFP it is possible that the present stand structure composed of >20 m tall mature aspen stems may be an artifact of fire exclusion after circa 1879. If the fire-sensitive aspen were historically exposed to frequent fire, these same stands in the 19th century may have been smaller diameter aspen "thickets" that were top-killed and regenerated after each fire (Maini 1960; Allen 1989). A similar hypothesis was proposed regarding the potential for changed quaking aspen stand-structure in response to 20th century fire exclusion on the Kaibab plateau in north-central Arizona (Binkley et al. 2006). The following hypothesis should be tested with future research: The age and stand structure of quaking aspen stands that historically experienced frequent fire have shifted toward dominance by a single mature cohort due to 20th century fire exclusion.

Old quaking aspen

Very old (>250 years) quaking aspen were found at PIN and GIL. Too few samples were obtained to determine if this was a post-fire cohort or intermittent regeneration. This adds to the locations where aspen greater than 250 years old have been documented in the southwestern U.S. (including the Jemez Mountains of north-central NM; Margolis et al. 2001). The survival of these fire sensitive aspen stems provides some evidence for the lack of stand-replacing fire at these upper montane forest sites for the life of the tree (i.e., at least 250 years).

The increasing number of sites where relatively old aspen have been documented suggests that co-dominant aspen persisting for long periods of time in upper montane conifer-dominated forests may be relatively common. Given that aspen regeneration pulses have been associated with both low and high severity fires (Abolt 1997; Romme et al. 2001; Margolis et al. *in press;* this study) these older aspen cohorts may provide information about upper elevation fire regimes of the 1700's. Targeted and/or systematic sampling to determine the age structure of these old aspen individuals and small patches might extend the stand-replacing fire history data set into the 18th century, and thereby provide valuable information about aspen ecology and fire climatology.

Problems associated with sampling old aspen include: 1) decomposed heartwood such that increment cores may not reliably include intact inner rings, and 2) locating these individual stems or relict stands is not easy, since they are not accurately mapped with basic remote sensing techniques due to dominant conifer canopy cover. Finding new locations may be challenging and likely will require a combination of new mapping techniques (e.g., seasonal differencing of NDVI layers to highlight the deciduous aspen), extensive searching and serendipity. Given that multiple mountain ranges containing old aspen have been documented and solid individual stems have been sampled, the challenges do not preclude further investigation of these ecologically interesting and significant trees.

Late 19th century period of stand-replacing fire

The stand-replacing fires reconstructed from quaking aspen patches in Arizona and southwestern New Mexico occurred within the later half of the 19th century (1879-1904). This period is similar to the period of stand-replacing fire reconstructed from quaking aspen in the upper Rio Grande Basin (1842-1901) (Margolis et al. *in press*). In that paper we hypothesized causes to explain this limited period of reconstructed fire occurrence including climate, land-use and potential methodological limitations.

Aspen can live at least 250 years, so the absence of dates in the early 19th century is apparently not due to a limitation of aspen age. However, there are multiple methodological factors that may limit how far back in time stand-replacing fires can be confidently reconstructed using aspen stands. First, more recent fires will burn over older fires so that less evidence of past fires is present on the landscape. It is possible that the period of late 19th century burning was so widespread that most of the older aspen cohorts were top killed. In addition, aspen patch size will likely decline over time or at least will not be monospecific and conspicuous as a patch due to conifer encroachment. Thus, focusing on the largest aspen patches may not detect older patches and may have biased the results toward the late 19th century fires. A more detailed analysis of the role of climate in this period of stand-replacing fire occurrence is the focus of another paper (Appendix C, this volume).

Spruce-fir patch dating

No obvious historical fire boundaries or patch boundaries were evident within the spruce-fir zone based on remotely sensed data and field observations. Entire spruce-fir patches surrounded by lower elevation mixed-conifer/aspen vegetation types were treated as single, potential stand-replacing fire patches. For example, the whole spruce-fir zone at PIN was sampled as one potential stand-replacing fire patch. The lack of burn boundaries within upper elevation conifer stands contrasts with higher latitude, Rocky Mountain landscapes where old stand-replacing fire patch boundaries are visible as obvious stand-height and structural difference and are commonly used to map and date historical crown fires (e.g., Kipfmueller & Baker 2000; Sibold et al. 2006) The general lack of visually identifiable and discrete post-fire recruitment patches in southwestern U.S. spruce-fir may suggest that large crown fire patches were not as common in the study area as they were in the Rocky Mountains, even in the upper elevation forests.

Relatively large patches (>1000ha) of spruce-fir were present at some sites, but only one patch had sufficient data to be interpreted as a stand-replacing fire patch. These data included maximum Engelmann's spruce tree ages throughout the patch dating to less than 10 years after a widespread fire recorded by fire scars in the surrounding mixed conifer forests (Grissino-Mayer et al. 1995; Swetnam et al. *in press*; this study). At the other site (GIL) where spruce-fir was mapped and sampled to determine age structure, a clear stand-replacement date was not obtained. This may have been the result of a sampling method not appropriate to determine such a complex and relatively old (>280yrs) age structure.

A sampling design similar to that successfully used to date post-fire aspen cohorts was adapted in an attempt to age the spruce-fir stands. In a post-stand-replacing fire aspen stand, sampling two stems per point at multiple sample points within a patch is usually sufficient to determine stand age (Margolis et al. *in press*). This is because of the immediate asexual regeneration response of aspen to above-ground stem mortality that creates a distinct recruitment pulse and a single-tiered, even-aged stand. In seral aspen stands, subsequent regeneration is relatively rare and the post-fire cohort is easily identified as the stems with largest dbh (Margolis et al. *in press*).

In contrast, spruce and fir trees recruit from seed so the initial post-fire cohort can lag the fire date and may be distributed over decades (e.g., Antos & Parish 2002). Subsequent cohorts of these shade-tolerant conifers are able to regenerate under the canopy of the initial post-fire cohort. This multiple-aged structure makes the initial post-fire cohort more difficult to identify with age or size structure data. With this in mind we doubled the number of trees cored at each sample point to include the four trees of largest dbh. This still proved to be too few to confidently determine the patch age, due to the relatively old age (>280 yrs) of the sampled stands that created a complex age structure.

An age-structure transect with a higher density of samples may be necessary to determine patch age in old southwestern U.S. spruce-fir forests. However, besides being resource intensive, densely sampled transects provide limited spatial coverage. Stand age may be determined for a small area, but it would not allow for the confident dating of the whole patch or stand. Repeated, sample intensive age structure transects scattered throughout the mapped stands may be the best method to confidently evaluate the age structure of old spruce-fir forests in this region. This would be very labor intensive and still may not provide a stand origin date due to the errors inherent in conifer age structure sampling (e.g., age to core height, pith estimation and lags between fire date and tree germination; Kipfmueller and Baker 1998). An additional problem encountered in these mesic spruce-fir stands is decomposed heartwood in the oldest individuals, such that the pith and inner-rings can not be sampled and dated. It is possible that the sample size could be adjusted based on the estimated age of the stand (e.g., <150 yrs old, >250yrs old) so that only the oldest stands would require intensive sampling to overcome these challenges.

Multiple mapping and age-structure sampling methods should be tested on known and potential post-fire spruce-fir stands. The subalpine forests of the upper Rio Grande Basin or San Francisco Peaks may be ideal test sites, because there are large spruce-fir stands adjacent to large, post-fire aspen patches from historically documented 19th century fires (e.g. Santa Fe Ski Basin, NM & the Inner Basin of SFP). Dating and mapping these sub-alpine conifer stands is the best available method to improve the accuracy of estimates of historical stand-replacing fire area in the southwestern U.S. This is a necessary step for estimating fire frequency statistics (e.g., fire cycle or natural fire rotation) of the stand-replacing fire regimes in the upper montane mesic mixed conifer-aspen and subalpine spruce-fir forests of the region.

Stand-replacing burn patch size (historical vs. modern)

Based on the data we have presented here, there was no evidence of reconstructed (1685-1904) upper elevation stand-replacing fire patches larger than recent (1996-2004) stand-replacing fire patches in the study area. However, because the reconstructed patch sizes are derived primarily from quaking aspen (and one spruce-fir patch), these data represent a minimum stand-replacing patch size. We were only able to confidently reconstruct stand-replacing fires patches from quaking aspen dating to the late 19th century and one spruce-fir patch from the 17th century. The possibility remains for other older stand-replacing fires that may have had larger patches. If the undated (GIL - >300 years old) and unmapped spruce-fir patches (GIL and SFP) are all assumed to be post-fire patches, the potential maximum historical (aspen and spruce-fir) patch size could exceed 2000 ha. This would be larger than the high elevation (>2600m) modern estimates. However, the assumption that all spruce-fir patches are post stand-replacing fire patches has not been established in the southwestern U.S. Limited research in the upper elevation spruce-fir zone exists for Arizona and New Mexico (Grissino-Mayer et al. 1995, Swetnam et al. *in press*), particularly relating to the effects of disturbances (e.g., fire, insect outbreaks, windthrow, and avalanches) on forest age structure.

Were the crown fire patches from the pre-Euro-American era as large as recent fires in Arizona and southern New Mexico? The current available data does not provide evidence of historical stand-replacing fire patches above 2600m in elevation that are larger than modern patches. However, potentially larger historical patches exist and should be the focus of future work. The greater concern may be the 8000 ha modern stand-replacing burn patches that include the lower elevation pine forests. The long, well-replicated and geographically extensive fire-scar record of low severity surface fire in ponderosa pine forests throughout the southwestern U.S. (Swetnam & Baisan 1996, 2003) combined with an increasing body of stand age structure data (Mast et al. 1999; Brown & Wu 2005) provide strong evidence that recent, large stand-replacing fire patches in these forest types are anomalous in this region over the past 300 to 500 years (Allen et al. 2002).

Conclusions

Historical fire regimes in the Madrean Sky Islands and the Mogollon Plateau of Arizona and southern New Mexico exhibited substantial variability among and within upper elevation forest sites (>2600m). This variability includes a stand-replacing fire component at some sites in both the mixed-conifer/aspen and spruce-fir vegetation. Historically frequent fire in some of the mixed conifer forests, particularly in the Sky Island sites, was likely a cause of the relatively continuous aspen age structure. The cessation of these frequent fires around circa 1900 likely affected the current aspen age structure and stand structure.

We collected age structure and fire history data in spruce-fir stands from two mountain ranges in southern Arizona and New Mexico where little is known about this vegetation type. We did not find any direct evidence of fire (i.e., fire scars or charred wood) within the sampled stands. All sampled stands appeared to be at least 280 years old and the PIN spruce-fir stand (>315 years old) likely regenerated following a stand-replacing fire in 1685 recorded as fire scars in the surrounding forests. The evidence of stand-replacing fire in the spruce-fir zone indicates that the 1996 Clark Peak Fire and the 2004 Nuttall Fire in the Pinaleño Mountains that burned with high intensity in this vegetation type are rare events, but not outside the historical range of variability.

We provide the first attempt to put modern stand-replacing fire patch sizes in a historical context in this region. Initial estimates of historical stand-replacing burn patch size in the upper elevation forests of the study area indicate that recent crown fire "holes" (e.g., from the 1994 Rattlesnake Fire in the Chiricahua Mountains, 1996 Clark Peak and 2004 Nuttall Fire in the Pinaleño Mountains) may be larger than those reconstructed from pre-1905 fires. The possibility remains that larger stand-replacing fire patches occurred > 300 years ago in the spruce-fir stands. However, due to methodological challenges of reconstructing the spatial extent of stand-replacing fires, particularly in the old spruce-fir stands, more data is necessary to evaluate this hypothesis.

Acknowledgements

This project was funded by Cooperative Agreement No. 99CRAG0024 between the U. S. Department of Interior US Geological Survey through the USGS Biological Resources Division, Global Change Program and the University of Arizona Laboratory of Tree-Ring Research. Chris Baisan provided valuable comments on earlier drafts of this manuscript. Special thanks go to the many people who helped me with data collection, sample preparation, and during discussions of the ideas presented: Mike Zummwalt, Pepe Iniguez, Rex Adams, Ari Fitzwater, Cal Farris, Rebecca Franklin, and Miguel Villarreal.

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Table 1 Site information.

Site ID	Site name	Vegetation type	Mean elevation (m)	Area 2600-3300m (ha)	Sample points	Aspen area (ha)	Spruce-fir area (ha)
CHI	Chiricahua Mtns	MC/S	2856	2927	26	139	0*
GIL	Mogollon Mtns	MC/SF	3060	12085	32	744	1639
PIN	Pinaleño Mtns	MC/SF	3057	6321	33	0*	521
SFP	San Francisco Peaks	MC/SF	2954	9310	25	1125	----

* Distinctive patches greater than 5 ha of these vegetation types were not present.
-- Vegetation type was not mapped or sampled.

Table 2. Number of crossdated tree-ring samples used to reconstruct fire history.

Site ID	Aspen inner-ring date	Conifer fire scar	Conifer bark-ring date	Conifer growth change/injury	Conifer age structure	Total crossdated tree-ring samples
CHI	57	26*	0	6	0	89
GIL	58	10	1	6	44	119
PIN	31	12*	0	0	25	68
SFP	45	6	1	2	0	54

*Data from Grissino-Mayer et al. 1995 (PIN) and Morino et al. 2000 (CHI).

Table 3. Stand-replacing fires, fires recorded by ≥ 5 trees and all additional fires reconstructed from multiple lines of tree-ring evidence.

Site	Stand-replacing fire dates	Fires recorded by ≥5 trees	All additional fires
CHI*		1685,1711, 1725, 1748, 1763, 1773, 1785, 1817, 1826, 1841, 1851, 1868, 1877, 1886	1654, 1661, 1688, 1697, 1698, 1700, 1701, 1703, 1709, 1716, 1721, 1723, 1727, 1733, 1737, 1739, 1749, 1752, 1760, 1765, 1775, 1779, 1787, 1789, 1794, 1798, 1800, 1805, 1806, 1807, 1818, 1822, 1835, 1838, 1840, 1848, 1849, 1859, 1863, 1875, 1883, 1894, 1903, 1904
GIL	1904	1748, 1773	1716, 1765
PIN*	1685	1773, 1785, 1819, 1842, 1858, 1871	1623, 1648, 1668, 1670, 1674, 1687, 1691, 1696, 1709, 1719, 1733, 1745, 1748, 1752, 1760, 1847,
SFP	1879		1752, 1773, 1809, 1818, 1836, 1840, 1847, 1851, 1855, 1857, 1860, 1863, 1876

*Fire scar data from Morino et al. 2000 (CHI) and Grissino-Mayer et al. 1995 (PIN).

Table 4. Historical versus modern stand-replacing fire patch area statistics. "Aspen and spruce-fir area" estimates historical stand-replacing fire patch size from tree-ring reconstructions. Other classes are derived from modern fire severity maps (1996-2004). The most conservative modern data set includes high severity patches greater than 2600m in elevation ("2600 h"). The most inclusive modern data set includes high plus moderate severity patches with no elevation limit (h+m). Modern data only include patches greater than 35 ha, equal to the smallest reconstructed historical stand-replacing fire patch.

	Historical burn patches	**Modern burn severity patches**			
Fire area class	**Aspen and spruce-fir area**	**h+m**	**h**	**2600 h+m**	**2600 h**
count	17.0	238.0	147.0	66.0	54.0
mean (ha)	135.7	278.7	163.7	219.4	131.7
median (ha)	86.0	70.5	66.0	87.5	62.5
std dev (ha)	123.5	765.8	323.7	344.4	204.4
max (ha)	521.0	8288.0	2930.0	1880.0	1129.0
total (ha)	2307.0	66324.0	24071.0	14481.0	7113.0

h = high severity; h+m = high plus moderate severity; 2600h = high severity above 2600m; 2600h+m= high plus moderate severity above 2600m.

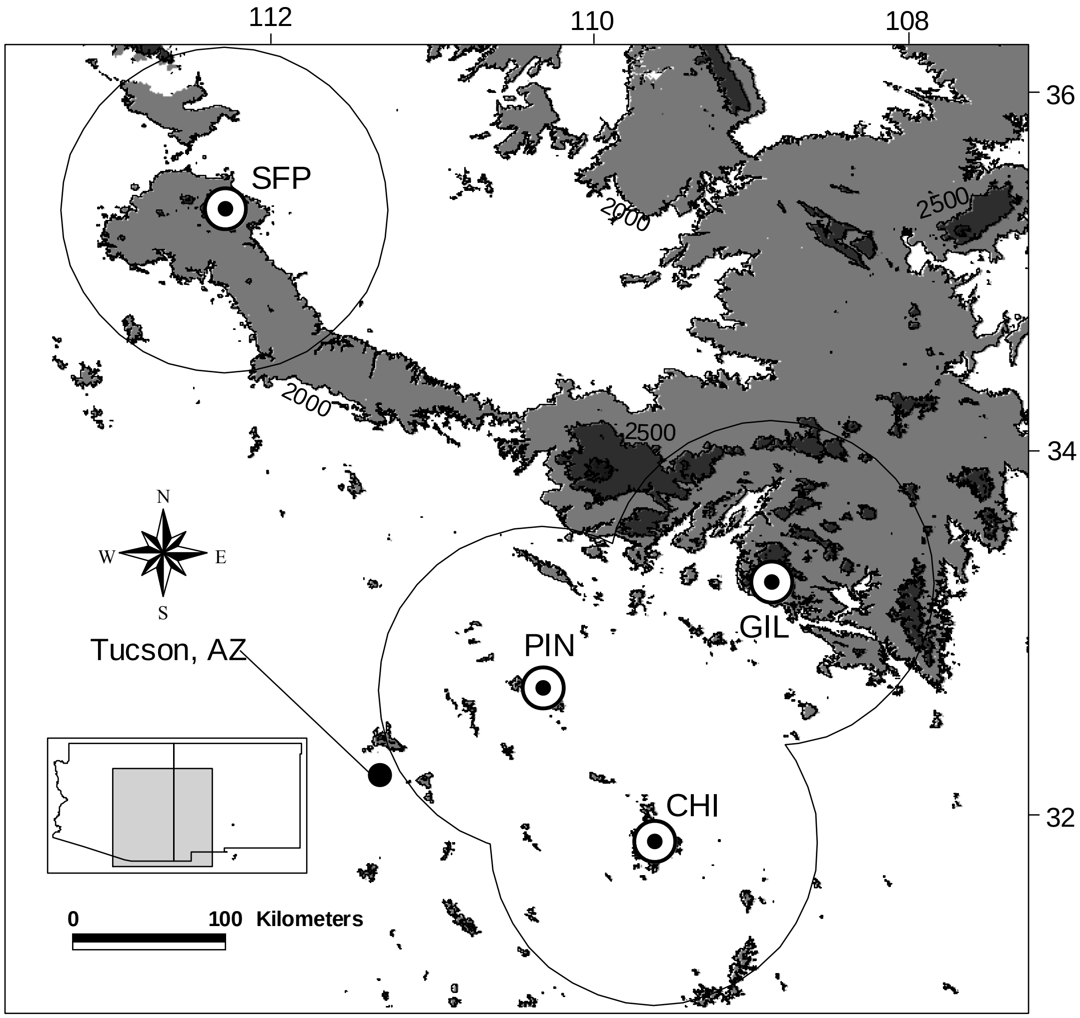

Figure 1. Map of site locations (e.g., SFP) in the Mogollon Plateau and the Madrean Sky Islands of Arizona and New Mexico. Shading indicates major topographic features > 2000 m in elevation at 500m intervals. The circles indicate the 100 km search radius around the fire history sites used to select fires (1996-2004) to quantify the size of contemporary stand-replacing fire patches.

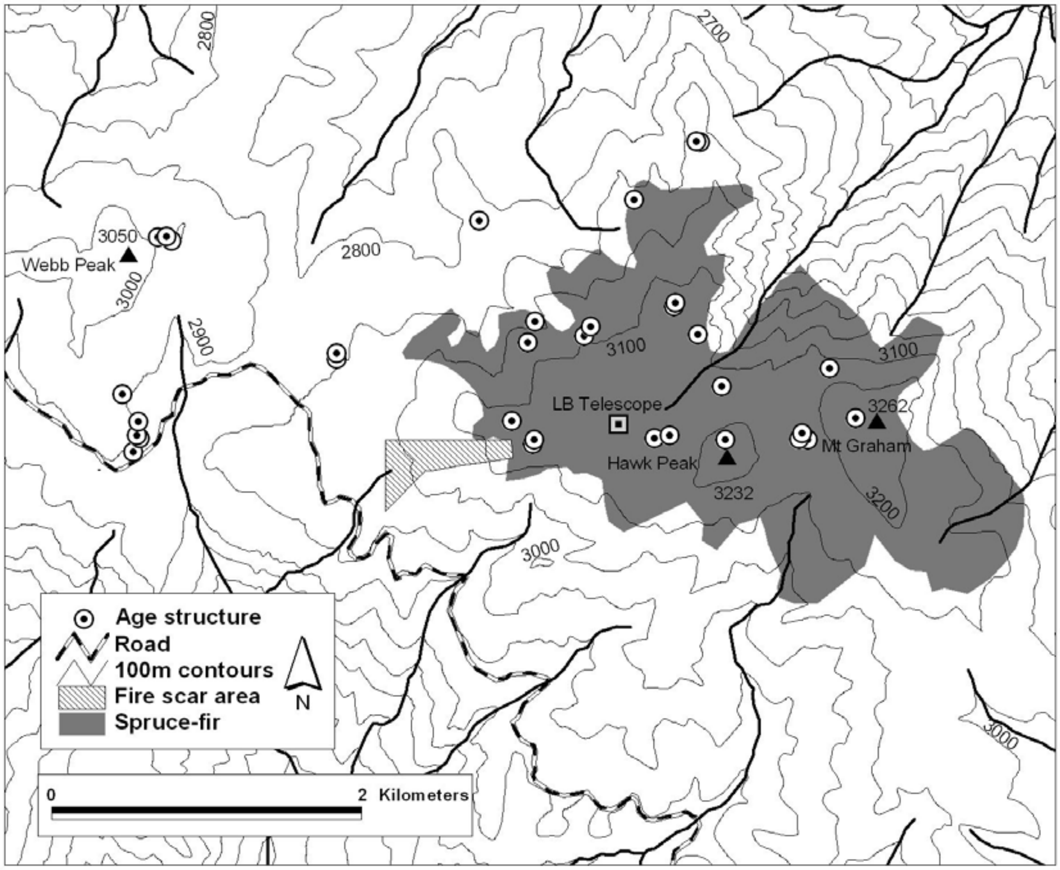

Figure 2. Sample locations and spruce-fir stand in the Pinaleño Mountains, AZ (PIN). Fire scar data from Grissino-Mayer et al. (1995).

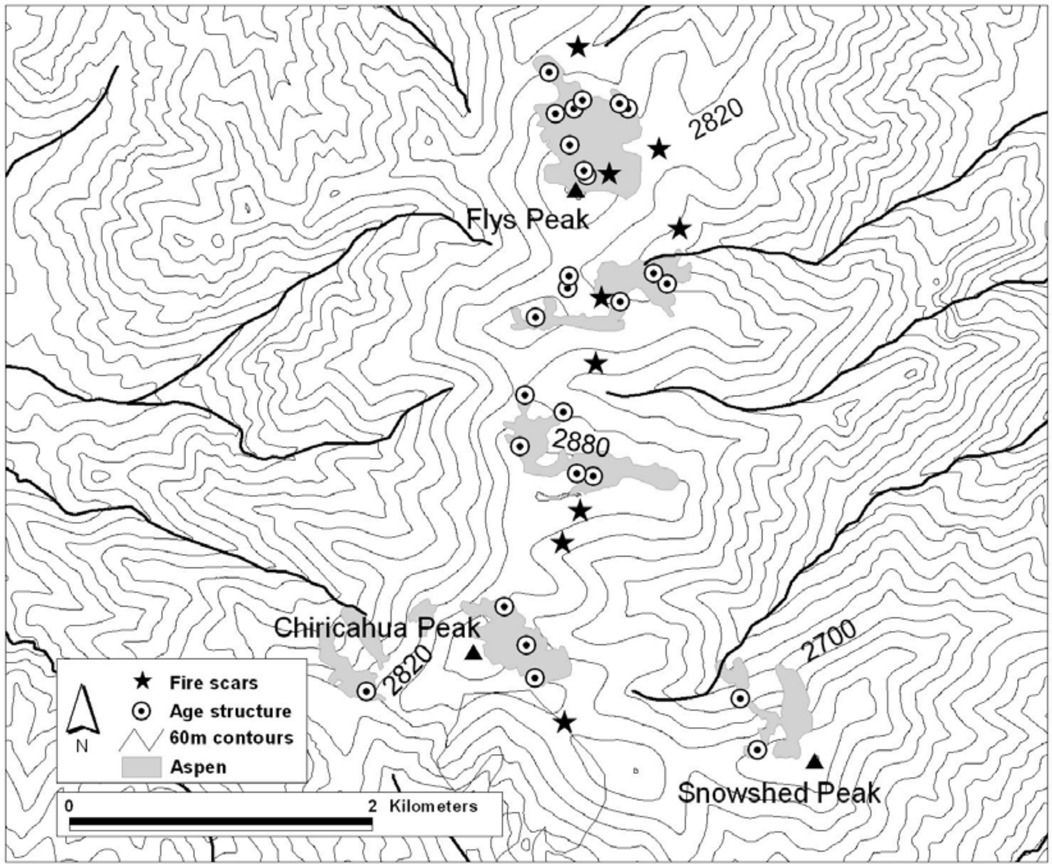

Figure 3. Sample locations and aspen stands in the Chiricahua Mountains, AZ (CHI). Fire scar data from Morino et al. (2000).

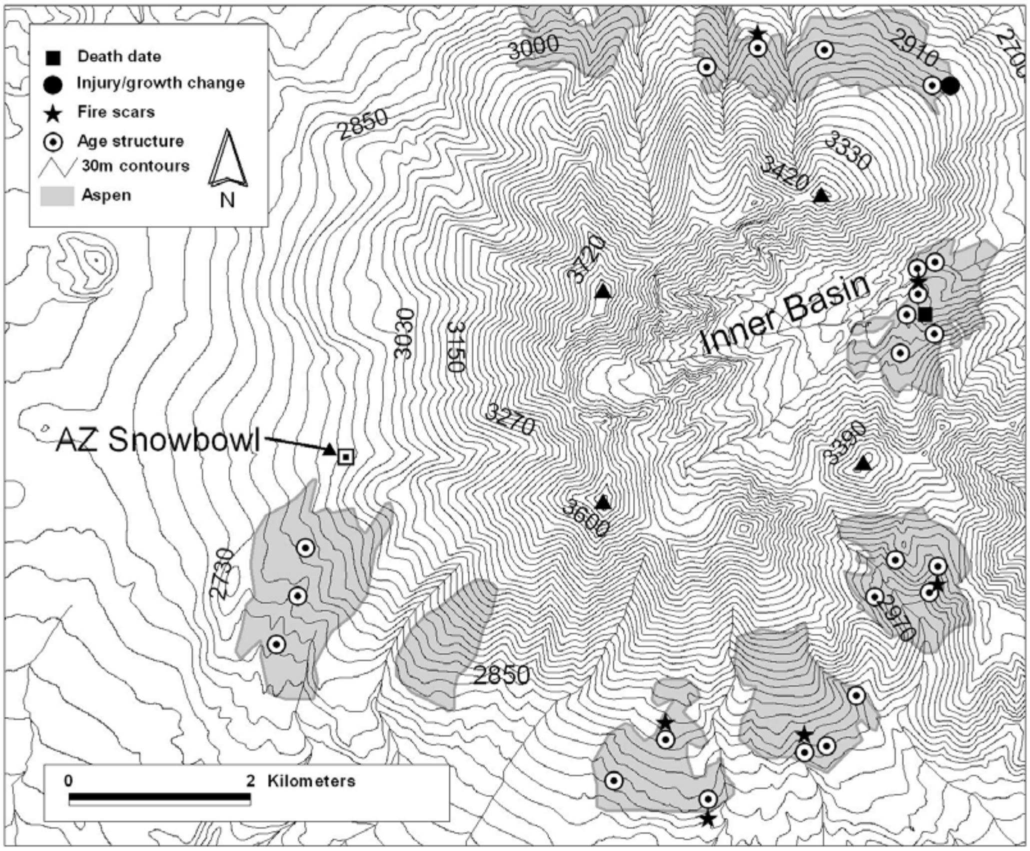

Figure 4. Sample locations and aspen stands in the San Francisco Peaks, AZ (SFP).

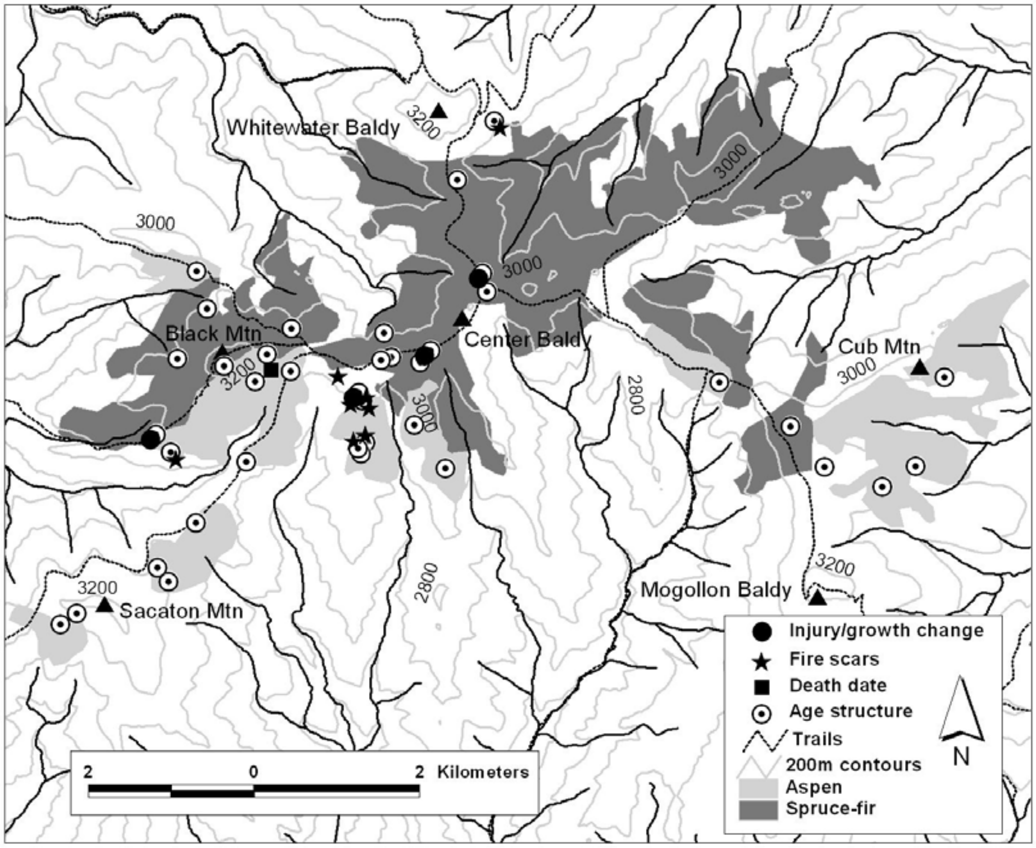

Figure 5. Sample locations, aspen patches, and spruce-fir patches in the Mogollon Mountains, NM (GIL).

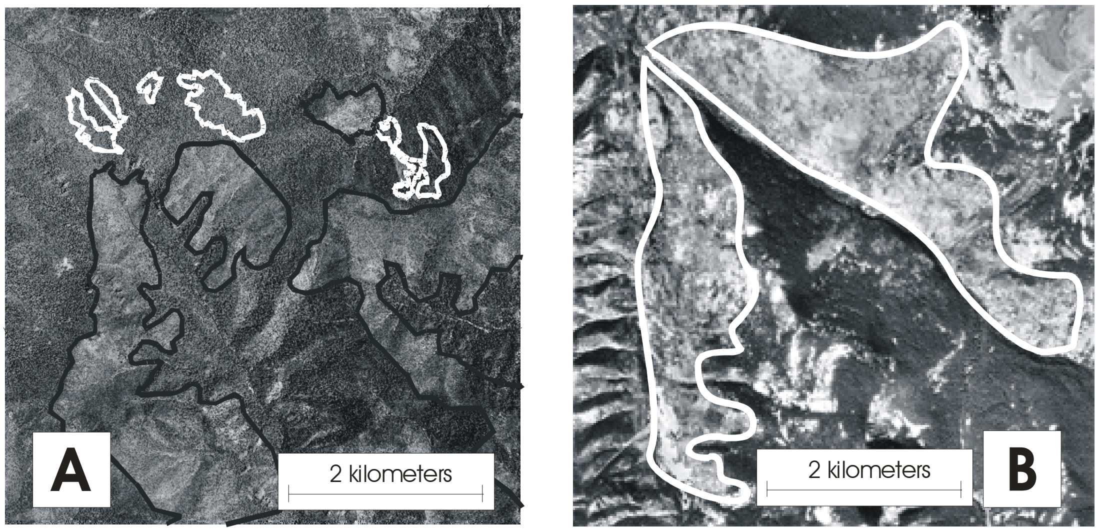

Figure 6. Digital orthorectified quarter quadrangle images from the Chiricahua Mountains, AZ (A), and the Santa Barbara drainage in the southern Sangre de Cristo Mountains, NM (B). Aspen patches in white outline and recent crown fire patches in black outline illustrating smaller aspen patch size in the Madrean Sky Islands compared to the Southern Rocky Mountains and comparatively large recent stand-replacing fire patches in the Sky Islands.

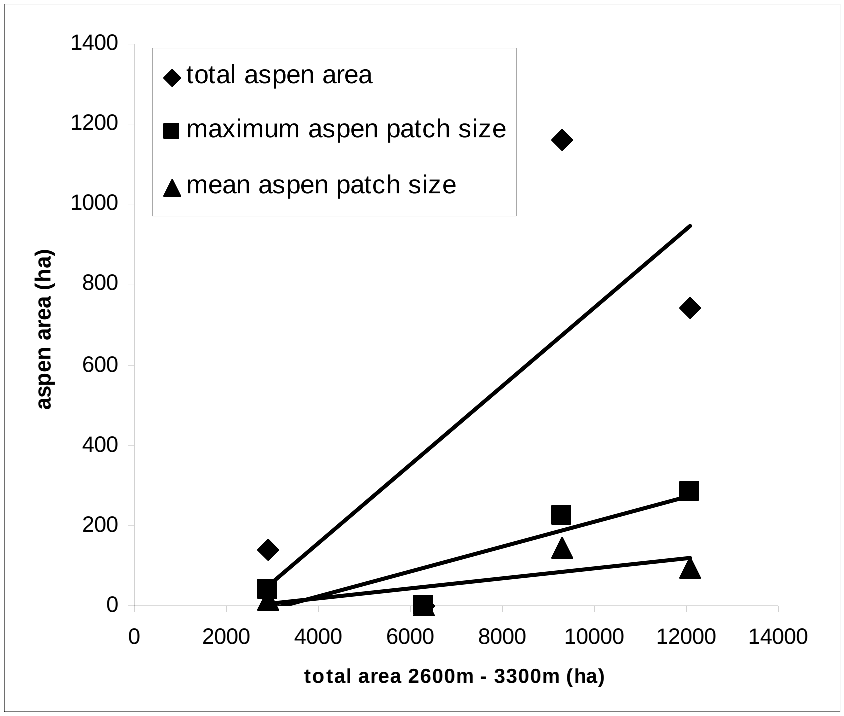

Figure 7. Aspen patch size metrics as a function of potential habitat (total land area from 2600m-3300m) for the four study sites indicating a positive relationship between upper elevation land area and aspen (minimum historical stand-replacing fire) patch size.

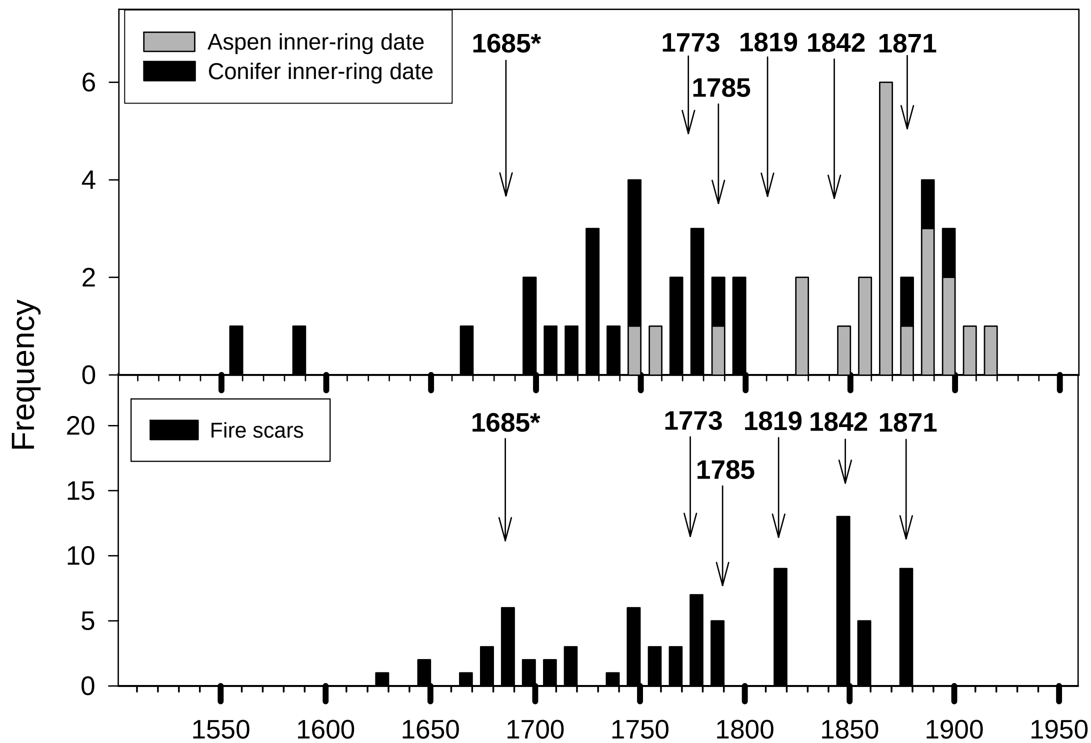

Figure 8. Pinaleño Mountains (PIN) age structure (top) and direct conifer evidence of fire (bottom) in 10-year classes used to reconstruct fire history in the upper elevation forests. Years (e.g., 1685) indicate annually dated fire events recorded by $\geq$5 trees, including fire scars. * Indicates stand-replacing fire date. Fire scar data from Grissino-Mayer et al. (1995).

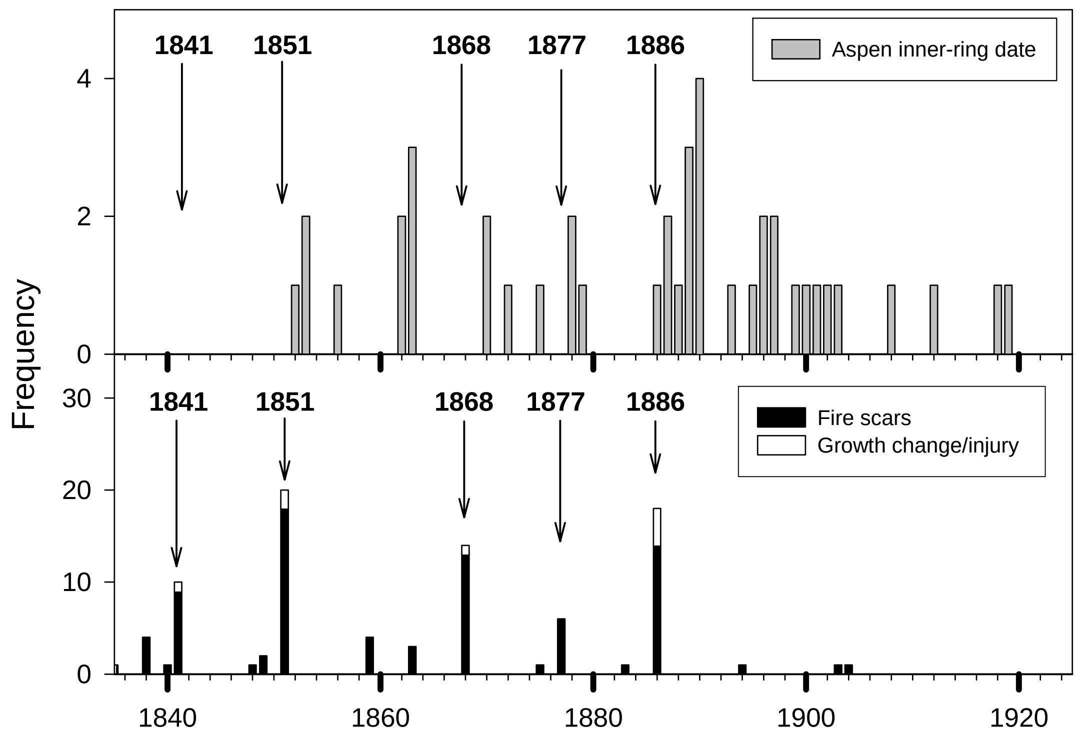

Figure 9. Chiricahua Mountains (CHI) age structure (top) and direct conifer evidence of fire (bottom) in 1-year classes used to reconstruct fire history in the upper elevation forests. Years (e.g., 1886) indicate annually dated fire events recorded by ≥5 trees, including fire scars. Fire scar data from Morino et al. (2000).

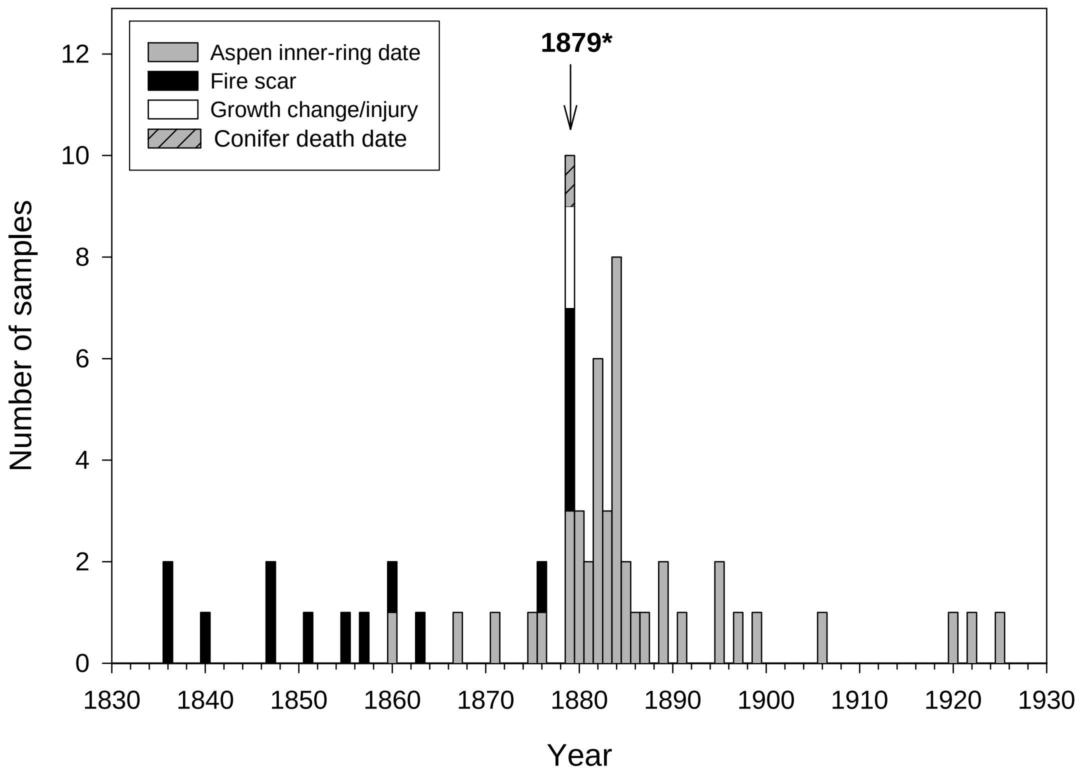

Figure 10. San Francisco Peaks (SFP) tree-ring data in 1-year classes used to reconstruct fire history in the upper montane forests. Years (e.g., 1879) indicate annually dated fire events recorded by ≥5 trees, including fire scars. * Indicates stand-replacing fire date.

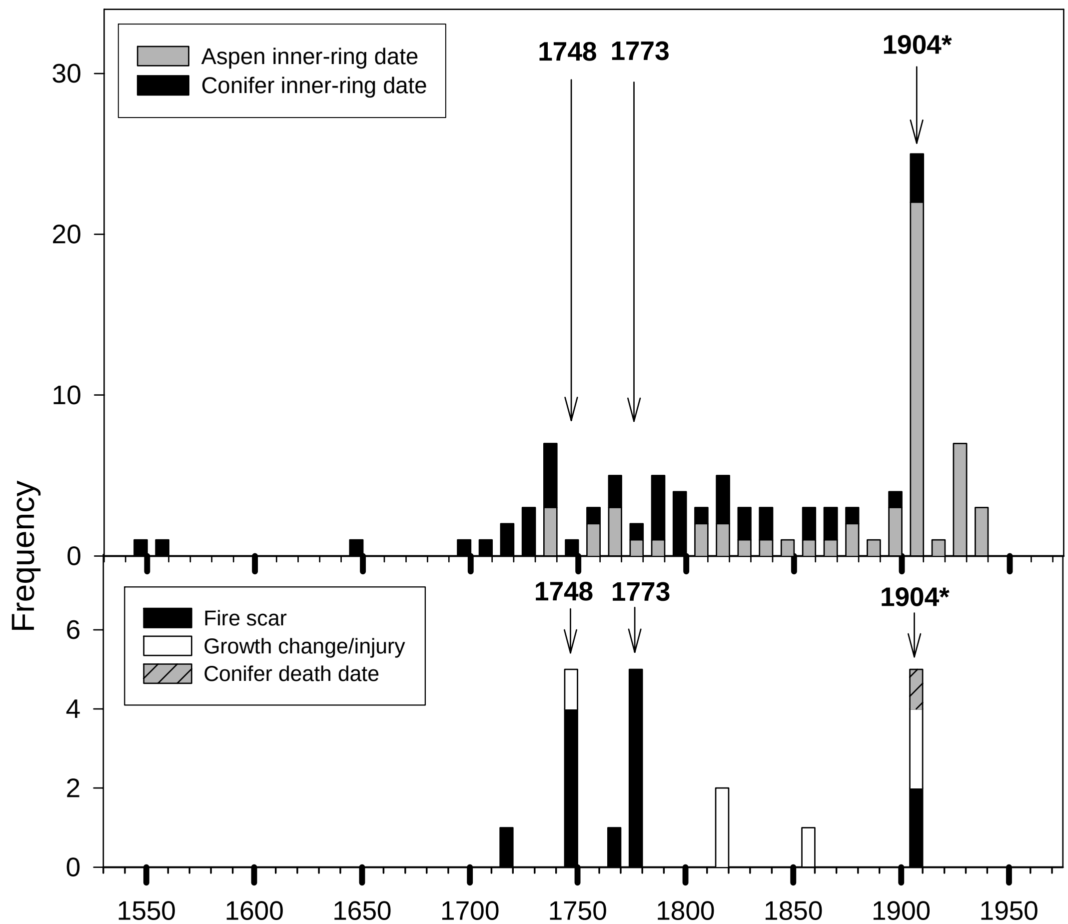

Figure 11. Gila Wilderness (GIL) age structure (top) and direct conifer evidence of fire (bottom) in 10-year classes used to reconstruct fire history in the upper montane forests. Years (e.g., 1904) indicate annually dated fire events recorded by ≥5 trees, including fire scars. * Indicates stand-replacing fire dates.

Figure 12. Photograph taken in 1910 looking east into the inner basin of the San Francisco Peaks (USFS 1910). The extensive downed timber (light areas) resulted from a circa "1880's" stand-replacing fire in forests currently dominated by spruce-fir and mesic mixed conifer-aspen vegetation. The quaking aspen patch we sampled at the east end of the inner basin contained multiple lines of tree-ring evidence dating to an 1879 stand-replacing fire that was likely the date of the fire in the photograph. The lack of quaking aspen recruitment in large areas of this fire patch exemplifies the methodological limitations of using quaking aspen patch size alone to estimate historical stand-replacing fire patch size. The patchy recolonization by spruce-fir seedlings (e.g., dark patch on lower third of nearest N-facing slope) exemplifies the methodological limitations of using the oldest spruce-fir to date stand-replacing fire patches in this vegetation type.

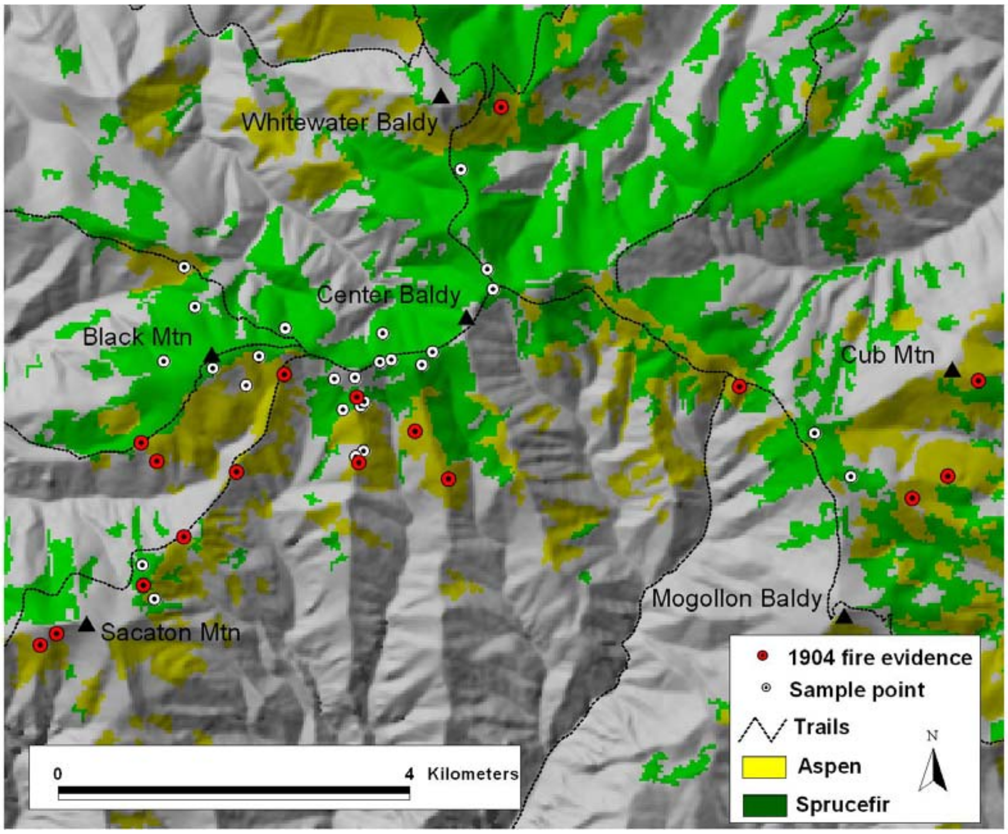

Figure 13. Location of tree-ring sample points with and without evidence of a widespread stand-replacing fire in 1904 in the Mogollon Mountains in the Gila Wilderness, NM (GIL). Note that the 1904 fire was not recorded in sampled areas currently mapped as spruce-fir.

APPENDIX B

SUB-REGIONAL SPATIAL AND TEMPORAL CLIMATE VARIABILITY IN SOUTHWESTERN NORTH AMERICA DERIVED FROM A NETWORK OF MOISTURE-SENSITIVE TREE-RING CHRONOLOGIES (A.D. 1732-1979)

Sub-regional spatial and temporal climate variability in southwestern North America derived from a network of moisture sensitive tree-ring chronologies (A.D. 1732-1979).

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Margolis, E.Q. and Comrie, A.C. ####. Sub-regional spatial and temporal climate variability in southwest North America derived from a network of moisture sensitive tree-ring chronologies (A.D. 1732-1979). *To be submitted to* International Journal of Climatology

ABSTRACT

We use principal components-based regionalization analyses and statistical correlations to document 1) non-stationary sub-regional spatial modes of climatic variability and 2) seasonal and sub-regional spatial variability in teleconnections with ENSO, PDO and AMO for southwest North America. We use PCA with oblique rotation to regionalize a network of tree-ring chronologies sensitive to cool-season moisture (Oct-Mar) from 140 sites over varying periods (1732 to 1979). For the full period we obtained four geographically contiguous regions determined by common variability in annual tree growth: 1) Arizona and New Mexico, 2) central and northern California, 3) northeastern Nevada to northeastern Colorado and 4) northern Mexico and Texas. These regions were relatively insensitive to different techniques for defining region boundaries and changes in rotation parameters of obliquity. The component score time series of the climate regions replicate documented spatial variability in 20th century droughts (e.g., 1930's and 1950's) and pluvials (e.g., 1910's). Regions 1 and 4 (1, 3 and 4) were significantly correlated with instrumental SOI (PDO) from 1866-1979 (1900-1979) and regions 1 and 3 were significantly correlated with instrumental AMO (1856-1979). Sub-regionalization of

PC (region) 1 produced climatic sub-regions for the southwestern U.S. These sub-regions changed geographically, primarily in the Four-Corners region, between the instrumental (1900-1979) and the pre-instrumental periods (1732-1899). The southwestern U.S. sub-regions 1 and 4 (1, 2, and 4) were significantly correlated with instrumental SOI (PDO) from 1866-1979 (1900-1979) and sub-region 3 was significantly correlated with instrumental AMO (1856-1979). Mapped correlations between these ocean-atmosphere oscillations and the network of 273 individual tree-ring chronologies illustrate detailed sub-regional variability in the strength and consistency (i.e., agreement among adjacent sites) of linkages to SOI, PDO, and AMO in southwest North America that may be a cause of the documented change in the southwestern U.S. climate sub-regions.

1. INTRODUCTION

High variability typifies the climate of the southwest United States (Arizona, New Mexico and adjacent areas) (Sheppard et al. 2002) and climate anomalies can have severe and widespread impacts on societies and ecosystems. The current, decade-long drought in the region (1996-2007) is severe, but not unprecedented when viewed in the context of tree-ring reconstructed droughts from prior centuries (Herweijer et al. 2007). Tree-ring based precipitation reconstructions from multiple sites throughout the region indicate equally severe and longer-duration droughts within the past 1,000 years (e.g., Grissino-Mayer 1995; Ni et al. 2002; Salzer & Kipfmueller 2005) that caused significant changes in past societies (Axtell et al. 2002; Cook et al. 2007) and ecosystems (Swetnam &

Betancourt 1998). A broad consensus among climate model projections indicates that under an increased CO_2 emissions scenario southwestern North America will transition to a sustained drier climate through the 21st century (Seager et al. 2007).

Often arbitrarily defined by the state boundaries of Arizona and New Mexico, the "Southwest" is not a homogenous climatic region and consequently climate teleconnections that affect precipitation variability and drought susceptibility differ within the region. The three main sources of precipitation include (1) summer monsoon thunderstorms, (2) winter frontal storms and (3) fall Pacific tropical storms (Adams & Comrie 1997; Sheppard et al. 2002). The relative importance of these moisture sources varies geographically. For example, the percent of total annual precipitation accounted for by the summer monsoon varies sub-regionally between and within New Mexico and Arizona (e.g., Comrie & Glenn 1998, Swetnam & Betancourt 1998). Spatial variability in teleconnections with ocean-atmosphere oscillations (e.g., El Niño Southern Oscillation (ENSO), Pacific Decadal Oscillation (PDO)) differentially affect winter and spring precipitation, such that ENSO (PDO) has greater influence in Arizona (New Mexico) (Brown & Comrie 2002). Sub-regional teleconnections with the Atlantic Multidecadal Oscillation (AMO) have not yet been evaluated for the southwestern U.S.

Current knowledge of spatial variability of climate patterns within the southwestern U.S. has been derived from instrumental data, primarily from the latter half of the 20th century and has not been tested for stability in time. This is a limitation of the relatively short instrumental climate record. It is likely that trends and spatial patterns in the late 20th century climate of the Southwest may not be representative of prior periods, and if so, may not be the best information to use when planning for the future or for comparing with model predictions (Seager et al. 2007).

Factor analysis (eigenvector analysis) is a general group of mathematical techniques used to extract common variables from large, complex data sets (Kachigan 1982). Factor analysis techniques, including principal components analysis (PCA), have been used as a climatological tool to regionalize (divide and classify) networks of instrumental and paleo-climate data into sub-regions with common variance, presumably driven by a common climatic signal (e.g., White et al. 1991; Dean & Funkhouser 1995; Comrie & Glenn 1998; Cook et al. 1999). Spatial classifications based on common climatic variability are useful for simplifying complex climate patterns.

The use of natural climate proxy data (e.g., tree-rings) for regionalization has generally been applied to broad-scale analyses. For the conterminous U.S. nine unique spatial modes of drought variability have been identified with PCA of tree-ring data (Meko et al. 1993; Cook et al. 1999), but these regions were not tested for stability through time. Dean & Funkhouser (1995) analyzed sub-regional scale spatial variability of climate through time in the Four-Corners region (AZ, NM, CO, UT border) using a network of 27 tree-ring chronologies. They document two generally stable climatic sub-regions, 1) the middle Rio Grande and 2) the Colorado Plateau, over the full period (966-1988). However, they found sub-periods of highly spatially variable climate (e.g., circa 1250 – 1450) that were possibly linked to changes in human behavior in the region. Potential causes (e.g., ENSO, PDO, and AMO) of the spatial modes of variability within the southwestern U.S. have not been investigated.

The updated globally unique network of hundreds of moisture-sensitive tree-ring sites distributed throughout southwest North America, collected by dozens of dendrochronologists over many decades, is ideal for extending analysis of variability in drought patterns hundreds of years prior to the instrumental period (pre-circa 1900). The goal of our research was to use this network of moisture sensitive tree-ring chronologies to identify spatial and temporal climate variability between and within sub-regions of southwest North America over a 248-year period (1732-1979) and analyze known climate drivers (ENSO, PDO, and AMO) as possible causes of the spatial variability. Specific research objectives included (1) identifying climatically similar regions and sub-regions within southwest North America from the tree-ring record, and testing for spatial stationarity through time of the sub-regions and (2) identifying associations between the climate regions (sub-regions) and ENSO, PDO, and AMO indices, and mapping the spatial variability in ENSO, PDO, and AMO teleconnections recorded by tree-rings to investigate potential causes of the sub-regional climate variability.

1.2 Background

Tree ring-widths, particularly in the semi-arid montane regions of southwest North America, reflect general moisture availability determined by a combination of temperature and precipitation (Fritts 1976). Annual ring width is highly correlated with cool-season (generally October to March) precipitation, while growing season precipitation is associated with only a small portion (latewood) of total annual ring growth (Fritts 1976; Meko & Baisan 2001). Annual ring-width in southwest North

America is also highly correlated with the commonly used Palmer Drought Severity Index (PDSI). Tree-rings have been used to reconstruct coarse-scale (2.5 X 2.5 degrees) patterns of summer PDSI (June to August) across North America (Meko et al., 1993, Cook et al., 1999, Cook et al., 2004). Due to the general lack of spring precipitation in the southwestern U.S. and the autocorrelation built into PDSI (Palmer 1965), in this region summer PDSI generally reflects prior cool-season precipitation and/or snowpack that determines tree growth. The strong association between PDSI and tree-ring width is well replicated for southwest North America (Meko et al., 1993; Cook et al., 1999; Cook et al., 2004). Thus, tree-ring indices accurately record local drought conditions and provide valuable information in remote, high elevation, montane locations where meteorological data are not available.

Applying climate analysis techniques (e.g., regionalization) to tree-ring data has limitations and benefits when compared to instrumental records (Table 1). The main limitation of tree-ring data is the temporal resolution. Tree-ring data are generally limited to annual or seasonal climate variables (e.g., cool or warm season precipitation) reflected in total ring width, or the less commonly analyzed earlywood or latewood partial ring width. As discussed earlier, in southwest North America, tree growth is generally limited by cool season precipitation, with only some sites and species being sensitive to other climate variables (i.e., summer-temperature sensitive, upper tree line *Pinus longaeva or P. aristata,* or summer-precipitation sensitive, lower forest border *Pseudotsuga menziesii*) (LaMarche 1974; Fritts 1976; Meko & Baisan 2001; Salzer & Kipfmueller 2005). Comparatively, monthly or even daily instrumental climate data are widely available and specific sub-annual time-periods can be analyzed. However, the relatively coarse temporal data resolution of tree rings when compared to instrumental data is outweighed by the potential for millennial-length records that provide insight into pre-instrumental climate variability. Additionally, tree-rings can be used as proxy climate records where climate data were not recorded or are of poor quality.

2. DATA

We began with 351 tree-ring chronologies used in the gridded North American PDSI reconstruction (Cook et al. 2004) covering the area from 16° - 43° N and 94° - 124° W, including 19 states in the U.S. and Mexico (Fig. 1). The original geographic area was set larger than the region of focus, the southwestern U.S. This was done for two reasons: 1) to allow the principal components analysis to delineate a southwest region (that may or may not fall within AZ and NM state boundaries) from a common climate signal recorded by the tree-rings and 2) because accuracy of regions defined near the boundaries of the study area may be low due to methodological limitations of regionalization analysis (Buell 1979). All chronologies cover a common time interval from 1732 to 1979 (248 years). Most of the chronologies extend well before 1732, but some of the shorter chronologies were in locations with limited spatial coverage so this time interval was used. We did not use the full network of 351 chronologies for either the correlation or the regionalization analysis; instead, we analyzed chronologies that we independently confirmed were recording local moisture variability based on correlations with instrumental summer (JJA) PDSI (Cook et al. 2004).

We only retained chronologies for analysis that had significant ($p<0.05$, 1-tailed) positive correlations with the nearest instrumental PDSI grid point. The relationship was tested with Pearson correlation coefficients calculated over the 20th century (minimum analysis period 1900-1979, although more recently collected chronologies extended to 2000). The one-tailed test was used because of the *a priori* assumption of positive correlation based on prior research (e.g., Fritts 1979; Cook et al. 2004). The resulting network of 273 chronologies (Fig 1) was used for correlation analyses with instrumental ENSO, PDO, and AMO indices to identify spatial variability in the effects of these ocean-atmosphere oscillations on climate in southwest North America.

Additional filtering was necessary to produce a data set that could be used for climate regionalization analysis. The spatial distribution of the data is important to consider before proceeding with regionalization analysis because spatially clustered data should not be used (Yarnal 1993). The inherently clustered spatial distribution of the tree-ring data (i.e., multiple chronologies from different species at a single site or multiple sites within a mountain range) may produce artificial regions. Spatial cluster analysis (ArcView 3.3; ESRI, Redlands, California, USA) was used to determine if the network of 273 tree-ring chronologies with significant positive correlations with PDSI was clustered. The network did have a tendency toward clumping (spatial cluster analysis, R=0.580), so we chose to reduce the chronologies to a 50km minimum spacing. The chronology with the highest correlation with instrumental PDSI was retained within all possible 50km buffers. This subset of 140 moisture-sensitive chronologies was randomly distributed (spatial cluster analysis, R=0.935) and was used for the regionalization analysis.

3. METHODS

We used two analytical techniques, regionalization and correlation analysis, to describe and test for spatial variability through time in the climate of southwest North America. The details of these procedures are outlined below.

3.1 Regionalization

We generally applied the recommendations of White et al. (1991) and Yarnal (1993) to regionalize the network of 140 drought sensitive tree-ring chronologies from southwest North America. We applied S-mode PCA (multiple tree-ring sites varying over time) using a correlation matrix. The correlation matrix was chosen, as opposed to the covariance matrix, due to the range of variance between the chronologies (Fig. 2). The use of the correlation matrix has the effect of standardizing relative differences in variance and emphasizes the common coherent signal (White et al. 1991). The PCA groups correlated chronologies based on common variability in tree growth, presumably controlled by a common cool-season moisture signal.

The number of principal components (PC's) retained was based on a combination of methods and interpretability. The recommended number of PC's to retain differed between methods. However, the core geographic location of PC1 (southwestern U.S. – the focus region) was stable. Retaining additional PC's only reduced the geographic extent of PC1 and had minor effects on the component scores. Parallel analysis

(O'Connor 2000), indicated that 11 components had eigenvalues greater than expected by chance at the 95% confidence level. This analysis was run with 100 iterations of a random data set composed of variables with distributions identical to the tree-ring data. The eleven significant components indicated by parallel analysis was less than the 24 components explaining as much variance as an initial variable (i.e., eigenvalue >1). We ultimately retained four regions (PC's) that explained a total of 42% of the variance before rotation. This number produced the most geographically coherent regions and minimized cases where adjacent chronologies loaded heavily on different PC's (maximum loading and/or >0.4).

Principal component rotation methods enhance the interpretability of the retained PC's by reducing domain shape dependence (Richman 1986), but the choice between the various methods can affect the location and geographic extent of the final regions (White et al. 1991). Oblique rotations are recommended for climate regionalization (White et al. 1991; Yarnal 1993). Thus, we chose to rotate the retained components with oblique (direct oblimin) rotation.

Delineating discrete boundaries for climate regions is subjective and somewhat arbitrary due to the variable nature of the climate system. Sites near boundaries experience the climate of both regions and consequently load relatively strongly on multiple PC's. To delineate the final regions and ultimately extract the southwestern U.S. region for further analysis we compared two methods: 1) the maximum loading approach (e.g., Comrie & Glenn 1998) and 2) the loading contour (0.4) approach (e.g., White et al. 1991). The maximum loading approach groups mapped variables based on the maximum rotated loading of each variable on the retained PC's. The alternate approach requires interpolating contours from the rotated loadings and choosing a contour (loading value) to delineate the region boundary. The choice of the cutoff loading value is somewhat arbitrary, but the 0.4 loading contour minimized both overlap and gaps between each region and has been used in prior regionalization studies (e.g., White et al. 1991; Comrie & Glenn 1998).

We performed additional analyses based on the results of the initial regionalization. First, to examine sub-regional variation within the southwestern U.S., we sub-regionalized PC1 using the same methods. These geographic sub-regions were analyzed for geographic stability through time by varying the time period of the sub-regionalization. The different periods include: 1) the full period 1732-1979, 2) the instrumental period 1900-1979 and 3) the pre-instrumental period 1732-1899.

3.2 Correlation

We use Pearson product-moment correlation coefficients to test for association between the network of individual tree-ring sites and instrumental indices of Pacific and Atlantic Ocean-atmosphere oscillations (ENSO, PDO, and AMO). The full set of 273 chronologies with positive PDSI correlations ($p<0.05$) covering southwest North America was used in the analysis. Individual chronologies were correlated with instrumental SOI, PDO, and AMO for multiple seasons prior to, and concurrent with the initiation of tree-ring growth (1900-2000). The seasons were 1) prior fall, October – November (ON), 2) prior winter, December – March (DJFM), and 3) concurrent spring, April – June (AMJ). These seasonal divisions were based on a similar correlation analysis testing for association between instrumental precipitation, SOI, and PDO in the southwestern U.S. (Brown & Comrie 2002). Maps of significant correlations ($p < 0.05$) are used to illustrate spatial variability of associations between ENSO, PDO, AMO and climate conditions that control tree growth (i.e., drought). Correlation analysis is also applied to test for association between indices of ENSO (1866-2000), PDO (1900-2000) and AMO (1856-2000) and the regional and sub-regional component score time series defined by the regionalization analysis.

4. RESULTS & DISCUSSION

4.1 Sensitivity of tree-ring sites to moisture variability (PDSI)

The correlation analysis used to select chronologies that were recording local drought conditions indicates geographic variability in the strength of the association between tree-ring variability and instrumental PDSI (Fig 1). Ninety one percent (273) of the ring-width chronologies had a significant positive ($p<0.05$; 1-tailed test) correlation with instrumental PDSI. A high percentage (96%) of these chronologies had significant correlations at the 0.01 level. The strongest association (maximum $r = 0.734$) exists in the southwestern U.S., which is the geographic area of interest for the study. The significant positive correlations between tree-ring width indices and PDSI is not surprising given the large body of work relating drought and tree growth that ultimately led to a drought reconstruction for much of North America (Meko et al. 1993; Cook et al. 1999; Cook et al. 2004).

4.2 Southwest North America climate regions

Figure 3 shows the loading maps of the four leading components of climate variability in southwest North America derived from the network of 140 moisture-sensitive, spatially distributed tree-ring chronologies (1732-1979). The PC's (regions) explained 42% of total variance in the tree-ring width data before oblique (direct oblimin) rotation. Percent variance explained for individual PC's is not reported because there is shared variance between PC's in obliquely rotated solutions. Similar to Comrie & Glenn (1998) we found little difference when varying the obliquity paramater (delta) in the rotation and reported results were obtained with a delta value of zero.

Both the maximum loading approach and the 0.4 loading contour approach resulted in a similar PC (region) 1 geographically centered on Arizona and New Mexico, but also included adjacent sites in southern California, Nevada, Utah, Colorado and north Baja California, Mexico. PC (region) 2 consisted of sites in central and northern California and west Nevada and PC (region) 3 included Texas and north Mexico. PC (region) 4 has maximum loadings from northeast Nevada to northeast Colorado and most sites from the Great Plains load most heavily on this PC. Region 4 is the least spatially contiguous and likely includes multiple sub-regions. The problems with this region are likely caused by its location at the edge of the study area and where the spatial coverage of sites is most sparse. Because the focus of the study was the southwestern U.S. region (PC1) we were not concerned with the spatial discontinuity of region 4.

The component score time series for each of the four regions were examined as additional evidence of practical climatic differences between the geographic regions (Fig. 4). Correlations between the component score time series from each PC (region) range from -0.098 to 0.281. The low correlations suggest that the regions do not have similar interannual variability. Each regional time series replicates documented regional climatic anomalies (e.g., 1950's drought in region1). The component scores from regions 1 and 4 had significant ($p<0.05$) negative correlations with instrumental SOI (1866-1979) (Table 2). The component scores from regions 1 and 4 also had significant ($p<0.05$) positive correlations with instrumental PDO (1900-1979), while region 3 had a significant negative correlation (Table 3). The component scores from regions 1 and 3 had significant ($p<0.05$) negative correlations with instrumental AMO (1856-1979).

The geographic boundaries of regions 1 and 2 were similar to regions derived from tree-ring analyses of broad-scale modes of drought variability for the conterminous U.S. (Meko et al. 1993) and from similar analyses using instrumental PDSI data (Karl & Koscielny 1982). Subsequent analysis of a more complete tree-ring network for the conterminous U.S. resulted in a somewhat different SW region, centered on Colorado (Cook et al. 1999). Region 2 was similar to the Mediterranean region delineated by Comrie and Glenn (1998) from regionalization of instrumental monthly precipitation distributions. Although the tree-ring width predominantly reflects variability in winter precipitation, similarities to regions with limited input from summer precipitation would be expected (e.g., California).

Regions 3 and 4 do not correspond geographically with regions from prior research. As mentioned above, region 4 is limited by the study area boundary and the limited spatial coverage of the tree-ring network east of the Rocky Mountains. The inclusion of northern Mexico in region 3 limits comparisons, because the only prior study that included data from Mexico was based on monthly precipitation (Comrie & Glenn 1998). The importance of summer rains in the climate of this region and the lack of sensitivity of the tree-rings to summer precipitation make comparisons difficult.

Other observed differences between the current study and prior regionalization research may have been due to the use of tree-ring series processed with different statistical analyses. Meko et al. (1993) recommended using residual (pre-whitened) tree ring-width chronologies with stabilized variance for analyzing spatial modes of drought variability. Residual chronologies were recommended so that differences in autocorrelation between species do not artificially result in different regions**.** This recommendation was considered, but given the availability of standard index chronologies (containing the original autocorrelation) and the high correlations between standard and residual chronologies we performed the analyses with standard annual tree-ring width index chronologies. The recommendation to stabilize variance is due to artificially increased variance resulting from low samples size in the early part of chronologies. The use of the correlation matrix in the PCA eliminates potential effects of artificially inflated variance due to sample size.

4.3 Southwestern U.S. sub-regions

Four sub-regions (PC's) were retained within the Southwest (original PC1) using the same regionalization techniques applied to the full network, over the full period (1732-1979) (Fig 5). The PC's (sub-regions) explained 62% of total variance in the tree-ring width data before oblique (direct oblimin) rotation. Correlations between components range from 0.346 to 0.560. As with the full network of sites, both the maximum loading and the 0.4 loading contour approach yielded similar region boundaries. The four regions for the full period include 1) northern New Mexico, 2) southern California 3) southern Utah and western Colorado and 4) southern Arizona and southern New Mexico. The two sites in northern Baja California (Mexico) had loadings of greater than 0.4 on both regions 2 and 4.

Component score time series for each of the four southwest sub-regions indicate sub-regional variability in duration and magnitude of climate anomalies within the southwestern U.S. (e.g., 1950's drought in regions 1 vs. 3) (Fig 6). The component scores from Southwest sub-regions 1 and 4 had significant ($p<0.05$) negative correlations with instrumental SOI (1866-1979) (Table 2). The component scores from Southwest sub-regions 1, 2, and 4 had significant ($p<0.05$) positive correlations with instrumental PDO (1900-1979) (Table 3). The component score from Southwest sub-region 3 had a significant ($p<0.05$) negative correlation with the instrumental AMO (1856-1979) (Table 4).

Tamerius (2007) derived 4 similar regions from PCA-based regionalization using cool-season precipitation PRISM data over a slightly smaller geographic area that did not include California or Mexico. Comrie and Glenn (1998) sub-regionalized the Monsoon region of southwest North America, but the importance of the summer North American monsoon in this region and the general lack of tree-ring response to summer precipitation makes it difficult to compare results. However, as noted earlier, regions with minimal influence from summer precipitation should correspond to regions derived from the tree-rings. The Desert region from Comrie & Glenn (1998) has minimal input from summer precipitation and is geographically similar to the southwest sub-region 2. The general lack of summer precipitation in this region would allow trees to record the same variability that exists in the monthly instrumental data (i.e., predominantly cool season).

4.4 Changing spatial modes of climate variability within the southwestern U.S.

Varying the time period of the sub-regionalization analysis affected the geography of climate sub-regions within the southwestern U.S. Excluding the instrumental period (1732-1899) resulted in the combination of the original sub-regions 1 and 4, such that southern Arizona and all of New Mexico became one sub-region (Fig. 5). Analysis of just the instrumental period (1900-1899) produced regions similar to that of the full period (1732-1979) (Fig. 5). These results suggest that the spatial patterns of climate variability change through time and that the instrumental and pre-instrumental periods differ.

The minimum length of the analysis period was limited by the number of chronologies in the southwest region (61). Spurious regions may result if the input matrix for the PCA has fewer observations (years) than variables (sites). Thus, variability in spatial patterns of climate within the southwestern U.S. at less than 60-year time scales can not be analyzed using this approach. Analysis of spectral properties of the regional and southwest sub-regional component scores could be used to test if significant variance exists at these shorter (decadal and inter-annual) wavelengths.

4.5 Instrumental PDO & SOI correlations with individual tree-ring width indices

Correlations between SOI, PDO, AMO, and the 273 individual tree-ring chronologies were similar to the results using the regional and sub-regional component score time series, but provided more spatial detail. Significant correlations varied both by season and by geographic location (Figs 7, 8, & 9). Maximum correlation with SOI (-0.514, winter) occurred in northeast Mexico (Table 5). The maximum correlation with PDO (0.547, fall) was located in northwestern New Mexico. The maximum correlation with instrumental AMO (-0.528, fall) was located in northwestern Colorado.

Fall, winter and spring SOI prior to, and concurrent with, the onset of tree growth is significantly correlated with individual tree-ring indices in specific regions of southwest North America. The significant negative correlations ($p<0.05$ and 0.01) are strongest and most geographically extensive in winter and fall, decreasing in spring and summer (Fig. 7, Table 5). The negative sign of the correlation indicates an inverse relationship between SOI and tree-growth (i.e., enhanced tree growth during El Niño – warm eastern tropical Pacific). Winter SOI correlates with the largest number of chronologies over the largest geographic area, centered in the New Mexico-Texas-Chihuahua (Mexico) border region. The pattern of correlations with fall SOI is similar to winter, but reduced in geographic area. The area of significant correlations is even further reduced in spring and is all but non-existent by summer, except for a small cluster of sites in eastern Nebraska and Oklahoma (results not included).

All three seasons of the PDO index (fall, winter and spring) have significant positive correlations ($p<0.05$ and 0.01) with individual and groups of tree-ring chronologies throughout southwest North America (Fig. 8, Table 5). Positive correlation indicates enhanced tree-growth (i.e., more available moisture) during positive phases of the PDO. Differing from the dominant winter SOI signal, fall PDO is correlated with the largest number of sites over the largest geographic region. Areas of strong correlations are concentrated in New Mexico–west Texas and southern Arizona–southern California. This general geographic pattern persists through subsequent seasons (winter and spring), but correlations weaken and become more geographically restricted. Interestingly, across all seasons the correlations are more robust (i.e., stronger and more consistent between sites) in New Mexico and southern California than in Arizona.

All three seasons of the AMO index (fall, winter and spring) have significant negative correlations ($p<0.05$ and 0.01) with individual and groups of tree-ring chronologies throughout southwest North America (Fig. 9, Table 5). The correlations are generally less consistent between sites within a particular geographic area than with the SOI and PDO, particularly in the southwestern U.S. The geographic areas with consistently significant correlations between adjacent sites are the Utah/Nevada border region (fall) and southern Mexico (spring).

The patterns of correlations between instrumental SOI, PDO and standard tree-ring width indices support some results from prior sub-regional climate analysis within the southwestern U.S. The stronger relationship with PDO in New Mexico, compared to Arizona, was present in the instrumental precipitation record (1950-2000) (Brown & Comrie 2002). However, the geographic difference between Arizona and New Mexico in climate links with SOI indicated by the tree-rings was not present in the instrumental precipitation data.

The discrepancies between patterns of correlation from the tree-ring and precipitation-based SOI studies have multiple potential explanations including: 1) differing locations of the data sources (high elevation, montane tree-ring sites vs. low elevation, valley locations of precipitation records, 2) differing time periods of analysis (1900-1979 vs. 1950-2000), 3) differences in interpolation methods, and/or 4) differential response of the trees to ENSO teleconnections. If the latter explanation was the cause of the differences, similarities should exist between the PDSI-tree-ring correlation strength (Fig. 1) and the SOI-tree-ring correlation patterns, which is not the case. For example, the area of highest correlation between PDSI and tree-growth (Utah-Colorado border), indicating high sensitivity to moisture variation, is not a region of high SOI correlations.

5. CONCLUDING DISCUSSION

Multiple spatial modes of climate variability are clearly evident between and within regions and sub-regions of southwest North America. The variability evident in tree-ring records from montane regions support prior findings derived from the instrumental record and add new information not available from the instrumental record. Climatically similar regions and sub-regions within southwest North America were identified from the tree-ring record. At the sub-regional scale the geography of these regions is not stationary in time (e.g., instrumental period (1900-1979) vs. pre-instrumental period (1732-1899)). Correlations between instrumental SOI, PDO, and AMO, a network of 273 individual tree-ring chronologies, and regional and sub-regional component score time series indicate seasonal and spatial variability in the effects of teleconnections from ocean-atmosphere oscillations on climate within southwest North America.

Links between the spatial variability of teleconnnections with ENSO, PDO, AMO and the identified climate regions and sub-regions are not immediately apparent. However, the time-scales of variability tested (>60 years) would not be expected to detect changes at the dominant time-scales of variability for the Pacific ocean-atmosphere oscillations (e.g., ENSO, 2-11 years and PDO, ~25 years). Phase combinations of multiple indices (e.g., PDO and AMO) could be explored as possible drivers of geographic variability in climate regions.

The identified spatial variability in climate regions and climate teleconnections with ENSO, PDO, and AMO could ultimately be applied to test questions relating to the spatial and temporal variability of ecological or geophysical process affected by climate variability. For example, contemporary and historic forest fire occurrence might be expected to co-vary in time and space with the teleconnections from these ocean-atmosphere oscillations and/or partition geographically with the identified modes of climate variability. In addition, refinement of the sub-regional differences in the effects of ENSO, PDO and AMO teleconnections on local climate could ultimately lead to more spatially precise forecasting.

ACKNOWLEDGEMENTS

We thank Dr. Ed Cook for providing the tree-ring chronologies used in the analysis. Dr. Dave Meko provided valuable comments and advice.

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Table 1. Comparing instrumental data and tree-ring data for climatic regionalization.

Instrumental data	Tree-ring data
(e.g., Comrie & Glenn, 1998 White et al., 1991)	(e.g., Meko et al.1993; Dean & Funkhouser 1995; Cook et al.,1999)
Data source	
Meteorological and climate records	Derived from annually dated tree-rings
a) rain gauge data	a) annual tree-ring width
b) temperature records	b) partial ring-width
	c) ring density (latewood density)
Data resolution	
Hourly - annual	Seasonal – annual
a) monthly distribution of annual rainfall	a) O - M precipitation - (annual ring width)
b) daily temperature	b) JJA temperature – (latewood density)
Spatial distribution	
Predominantly low elevation (climate stations)	Predominantly high elevation (> 2000m)
Mostly urban areas, possible heat island effects	Possibly more clustered in mountain ranges
Other Limitations	
Missing data, recording errors	Generally limited to geographic range of cross-dateable trees
Limited in time to instrumental record (20th century)	
Other Benefits	
More continuous spatial coverage	Potential to extend back thousands of years prior to instrumental records

Table 2. PC (region) component score correlations with seasonal instrumental SOI (1866-1979)

Southwestern North America Regions (PC's)		ON(t-1)	D(t-1)JFM	AMJ
Arizona & New Mexico (PC 1)	Pearson Correlation	-.274(**)	-.316(**)	-0.111
	Sig. (2-tailed)	0.003	0.001	0.240
	N	113	113	114
Central & Northern California (PC 2)	Pearson Correlation	-0.148	-0.142	-0.082
	Sig. (2-tailed)	0.118	0.133	0.383
	N	113	113	114
Northern Utah & Colorado (PC 3)	Pearson Correlation	-0.040	-0.047	-0.068
	Sig. (2-tailed)	0.675	0.618	0.475
	N	113	113	114
Central & north Mexico & Texas (PC 4)	Pearson Correlation	-.287(**)	-.483(**)	-.316(**)
	Sig. (2-tailed)	0.002	0.000	0.001
	N	113	113	114
Southwestern U.S. Sub-Regions (PC's)		**ON(t-1)**	**D(t-1)JFM**	**AMJ**
Northern New Mexico (PC 1)	Pearson Correlation	-.330(**)	-.411(**)	-0.171
	Sig. (2-tailed)	0.000	0.000	0.069
	N	113	113	114
Southern California (PC 2)	Pearson Correlation	-0.163	-0.093	0.040
	Sig. (2-tailed)	0.084	0.327	0.672
	N	113	113	114
Southern Utah & Western Colorado (PC 3)	Pearson Correlation	-0.133	-0.143	-0.071
	Sig. (2-tailed)	0.161	0.130	0.451
	N	113	113	114
Southern Arizona-New Mexico (PC 4)	Pearson Correlation	-.269(**)	-.400(**)	-.223(*)
	Sig. (2-tailed)	0.004	0.000	0.017
	N	113	113	114

Table 3. PC (region) component score correlations with seasonal instrumental PDO (1900-1979)

Southwestern North America Regions (PC's)		ON(t-1)	D(t-1)JFM	AMJ
Arizona & New Mexico (PC 1)	Pearson Correlation	.419(**)	.288(*)	.271(*)
	Sig. (2-tailed)	0.000	0.010	0.015
	N	79	79	80
Central & Northern California (PC 2)	Pearson Correlation	0.047	0.010	0.133
	Sig. (2-tailed)	0.681	0.932	0.239
	N	79	79	80
Northern Utah & Colorado (PC 3)	Pearson Correlation	0.027	-.228(*)	-.258(*)
	Sig. (2-tailed)	0.810	0.043	0.021
	N	79	79	80
Central & north Mexico & Texas (PC 4)	Pearson Correlation	.345(**)	.302(**)	.222(*)
	Sig. (2-tailed)	0.002	0.007	0.048
	N	79	79	80
Southwestern U.S. Sub-Regions (PC's)		**ON(t-1)**	**D(t-1)JFM**	**AMJ**
Northern New Mexico (PC 1)	Pearson Correlation	.455(**)	.363(**)	.333(**)
	Sig. (2-tailed)	0.000	0.001	0.003
	N	79	79	80
Southern California (PC 2)	Pearson Correlation	.290(**)	.255(*)	.252(*)
	Sig. (2-tailed)	0.010	0.023	0.024
	N	79	79	80
Southern Utah & Western Colorado (PC 3)	Pearson Correlation	0.134	-0.126	-0.070
	Sig. (2-tailed)	0.238	0.269	0.540
	N	79	79	80
Southern Arizona-New Mexico (PC 4)	Pearson Correlation	.391(**)	.295(**)	.235(*)
	Sig. (2-tailed)	0.000	0.008	0.036
	N	79	79	80

Table 4. PC (region) component score correlations with seasonal instrumental AMO (1856-1979)

Southwestern North America Regions (PC's)		ON(t-1)	D(t-1)JFM	AMJ
Arizona & New Mexico (PC 1)	Pearson Correlation	-.190(*)	-0.166	-0.037
	Sig. (2-tailed)	0.035	0.066	0.683
	N	123	123	124
Central & Northern California (PC 2)	Pearson Correlation	-0.016	0.094	0.003
	Sig. (2-tailed)	0.863	0.303	0.972
	N	123	123	124
Northern Utah & Colorado (PC 3)	Pearson Correlation	-.355(**)	-.276(**)	-.273(**)
	Sig. (2-tailed)	0.000	0.002	0.002
	N	123	123	124
Central & north Mexico & Texas (PC 4)	Pearson Correlation	-0.085	0.049	0.174
	Sig. (2-tailed)	0.351	0.594	0.053
	N	123	123	124
Southwestern U.S. Sub-Regions (PC's)		ON(t-1)	D(t-1)JFM	AMJ
Northern New Mexico (PC 1)	Pearson Correlation	-0.115	-0.070	0.096
	Sig. (2-tailed)	0.204	0.442	0.289
	N	123	123	124
Southern California (PC 2)	Pearson Correlation	-0.170	-0.159	-0.130
	Sig. (2-tailed)	0.061	0.080	0.151
	N	123	123	124
Southern Utah & Western Colorado (PC 3)	Pearson Correlation	-.238(**)	-.188(*)	-.214(*)
	Sig. (2-tailed)	0.008	0.038	0.017
	N	123	123	124
Southern Arizona-New Mexico (PC 4)	Pearson Correlation	-0.155	-0.114	0.068
	Sig. (2-tailed)	0.086	0.207	0.455
	N	123	123	124

Table 5. Pearson correlations between seasonal instrumental SOI, PDO, and AMO (1900-2000) and all tree-ring chronologies having a significant positive correlation with PDSI (n=273)

	Maximum correlation	Number of chronologies p<0.05	Number of chronologies p<0.01
SOI (fall)	-0.412	106	57
SOI (winter)	-0.514	125	85
SOI (spring)	-0.390	47	19
PDO (fall)	0.547	135	94
PDO (winter)	0.480	106	61
PDO (spring)	0.464	106	67
AMO (fall)	-0.528	136	79
AMO (winter)	-0.433	104	55
AMO (spring)	-0.389	47	16

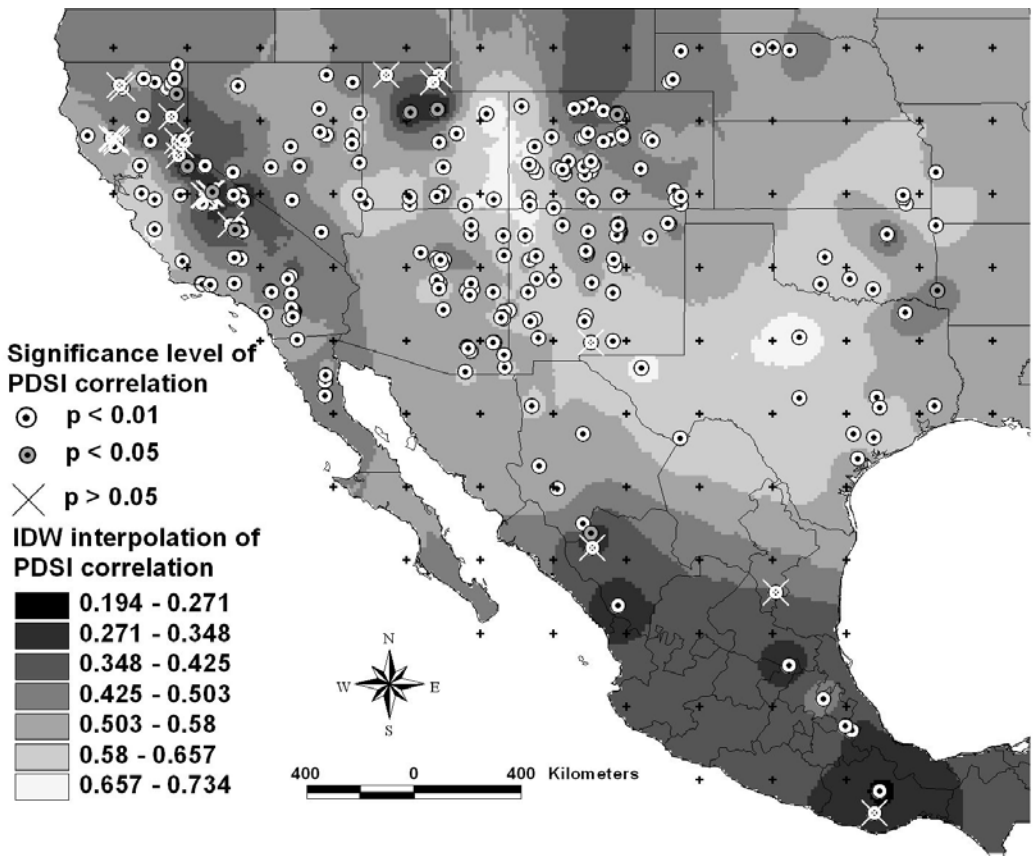

Figure 1. Pearson correlations between tree-ring width index chronologies (inner ring ≤ A.D. 1750) and the nearest instrumental PDSI grid point (crosses). Shading indicates interpolated surface from significant positive Pearson correlation coefficients ($p<0.05$; 1 tailed). Chronologies with non-significant correlations were excluded from the network used in the PCA analysis. Many of the non-significant chronologies in California (e.g., Snow, Kaiser Pass) were from high elevations that presumably have sufficient moisture for growth, but are limited instead by growing season temperature.

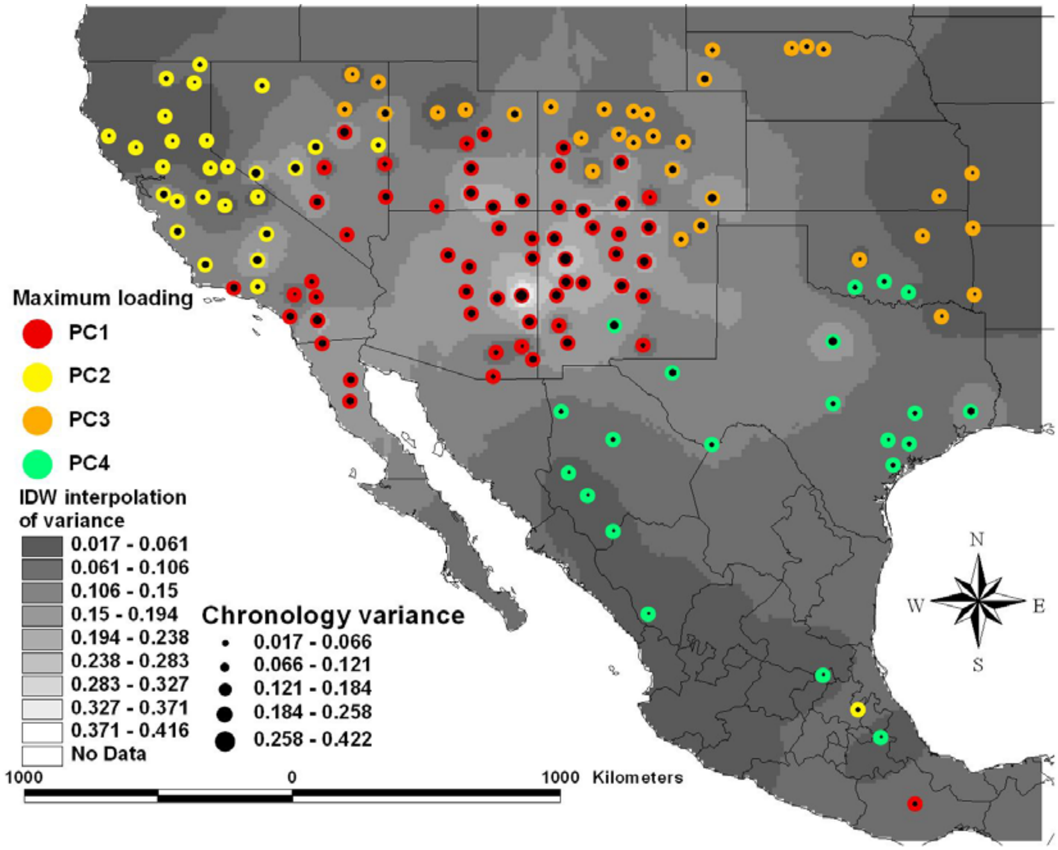

Figure 2. Ranked variance and interpolated variance surface of individual tree-ring chronologies (largest black points have four times the variance of the smallest). Colors indicate maximum loading on each of first four PC's. Due to the observed intra-site variability in chronology variance, which may be an artifact of intra-site variability in sample size or species differences, the PCA was evaluated with a correlation matrix to eliminate the effect of the differing variance on the regionalization.

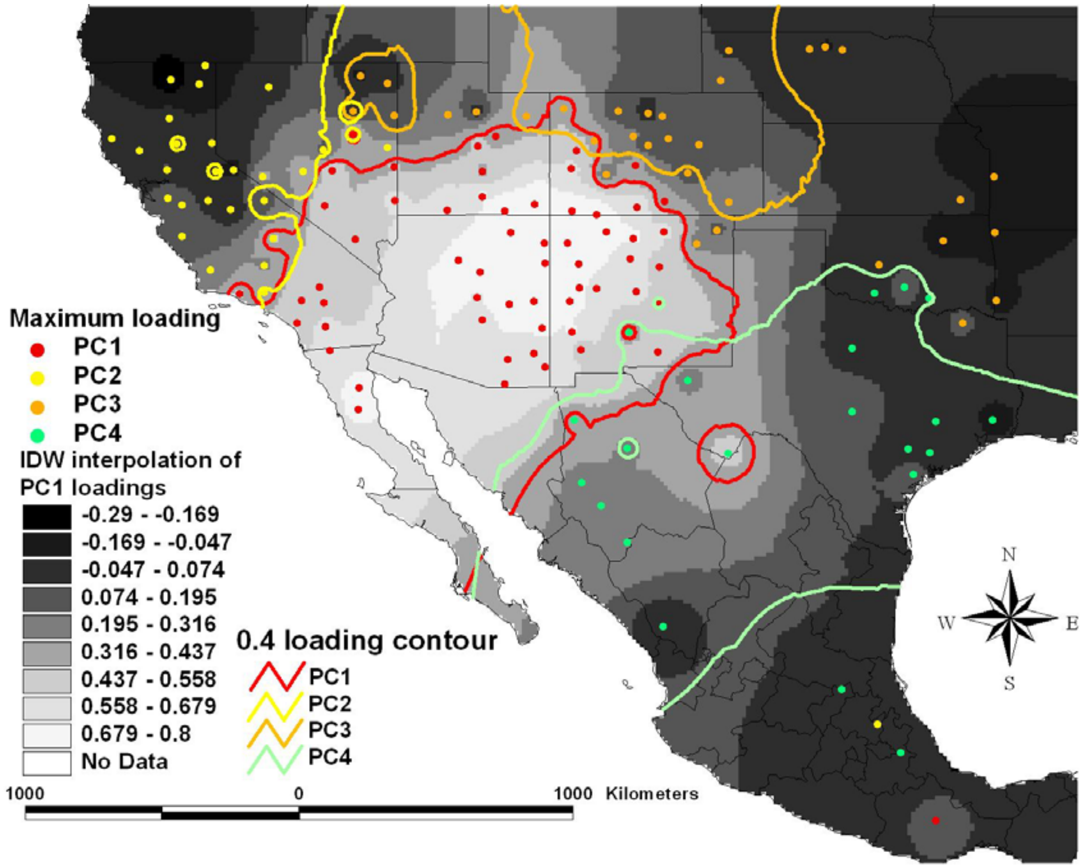

Figure 3. Four regions (PC's) indicated by maximum loading (colored points) and the 0.4 loading contour from PCA using a correlation matrix and direct oblimin rotation (delta =0). The network of 140 tree-ring index chronologies is significantly correlated with instrumental PDSI ($p<0.05$) and has a minimum spacing of 50km. For PC1 (Southwest) the maximum loading and 0.4 contour approaches resulted in a similar region with minimal overlap with other regions. The southwestern region defined by the 0.4 loading contour approach was then subjected to further sub-regionalization. The loadings of all chronologies on the Southwestern PC are indicated by the interpolated surface.

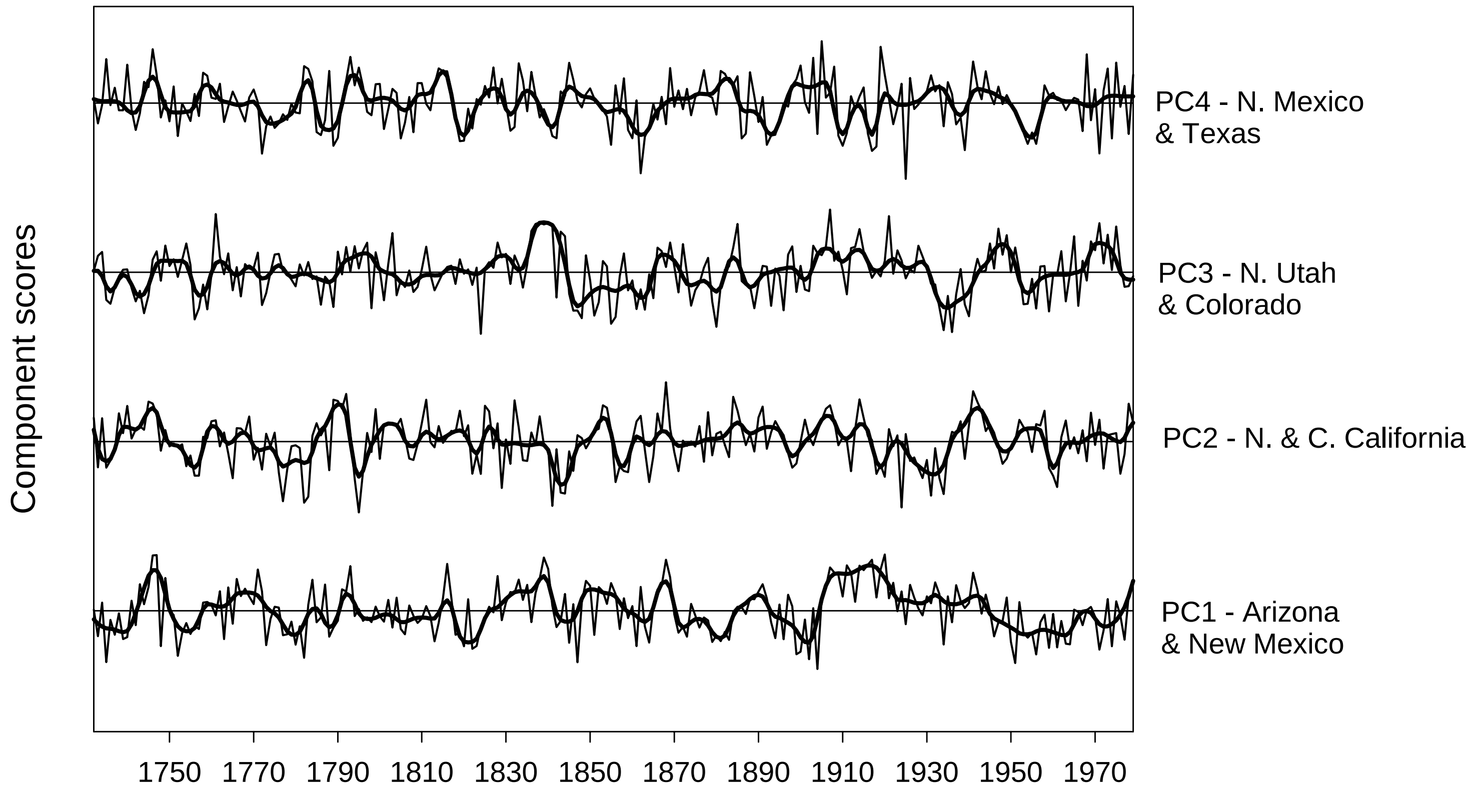

Figure 4. Component scores for the first four PC's (regions) of southwest North America (1732-1979). Horizontal references lines plotted at zero and smoothed curves emphasize low-frequency variation.

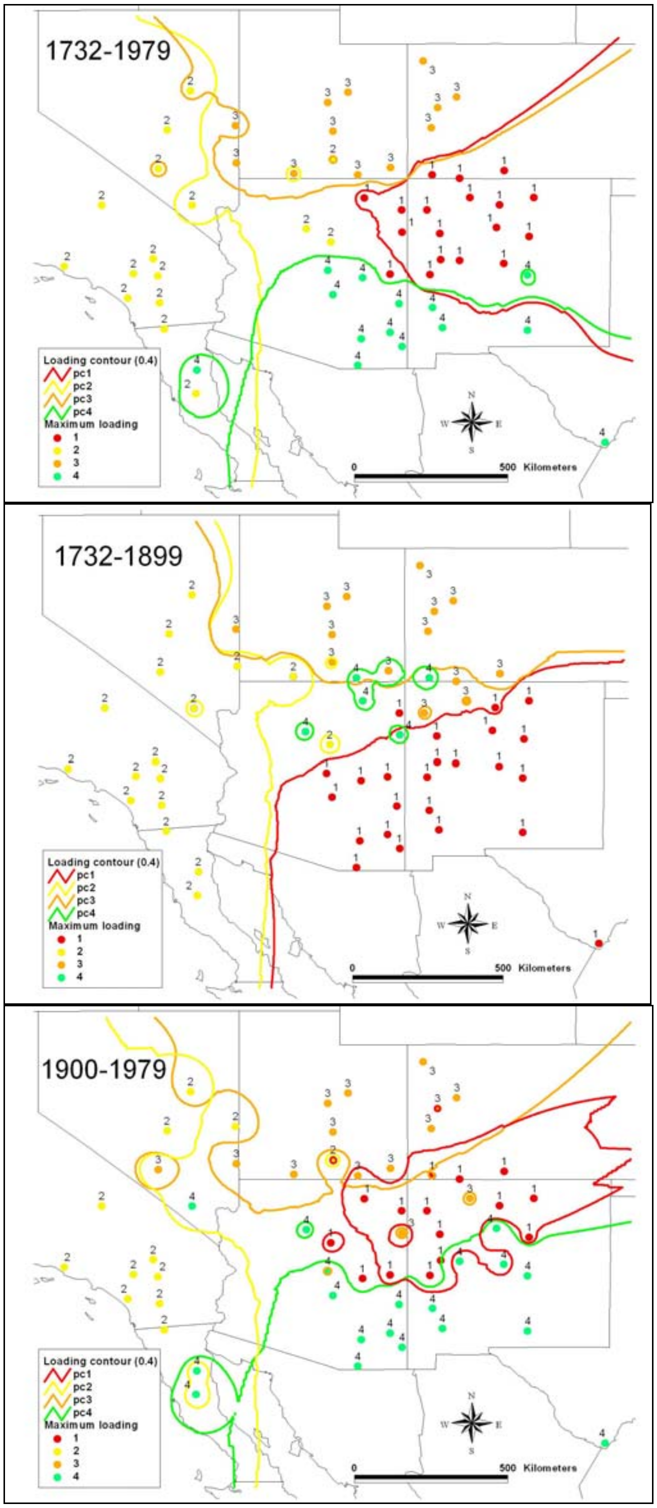

Figure 5. Southwestern U.S. sub-regions (PC's) for the full period (1732-1979), pre-instrumental period (1732-1899), and instrumental period (1900-1979) indicated by the maximum loading (numbers) and 0.4 loading contour lines.

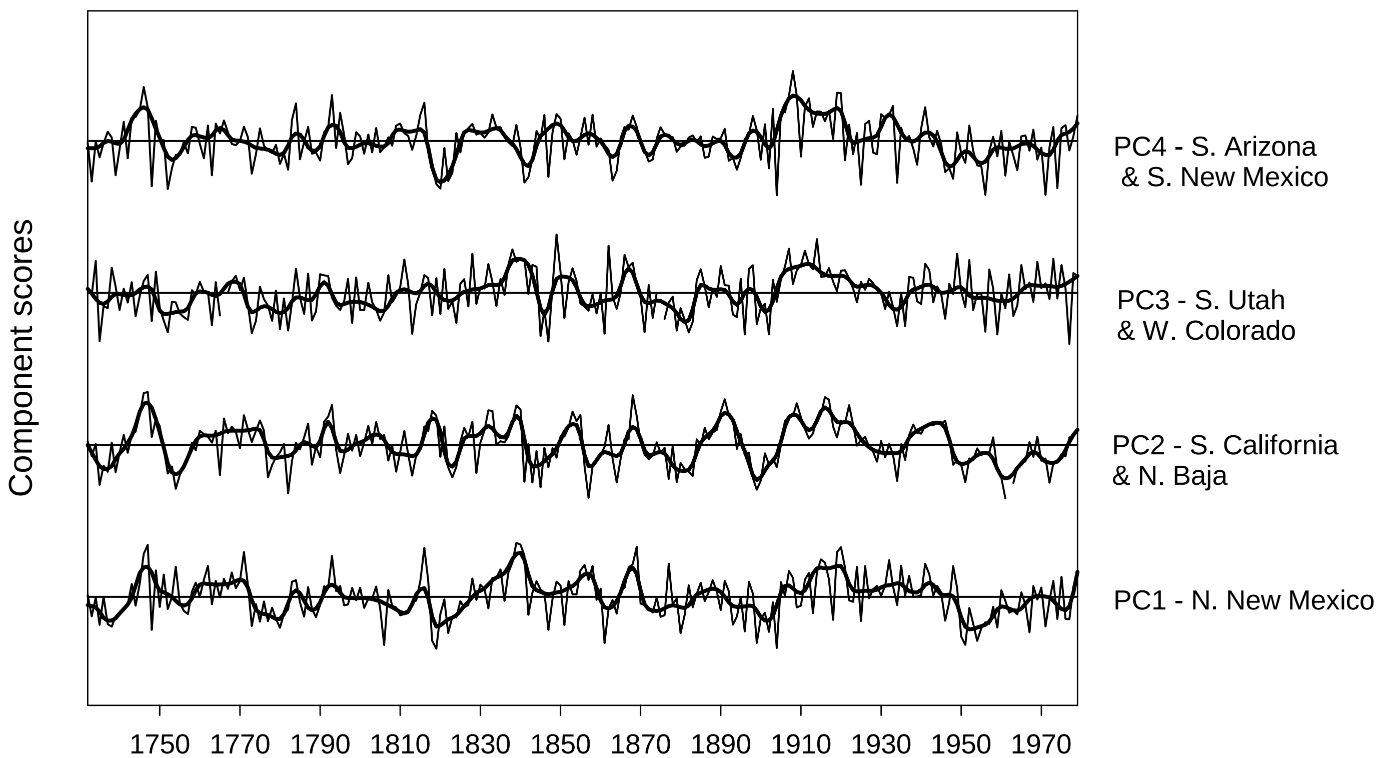

Figure 6. Component scores of the first four PC's (regions) for the southwest sub-region delineated by the 0.4 contour approach (1732-1979). Horizontal references lines plotted at zero and smoothed curves emphasize low-frequency variation.

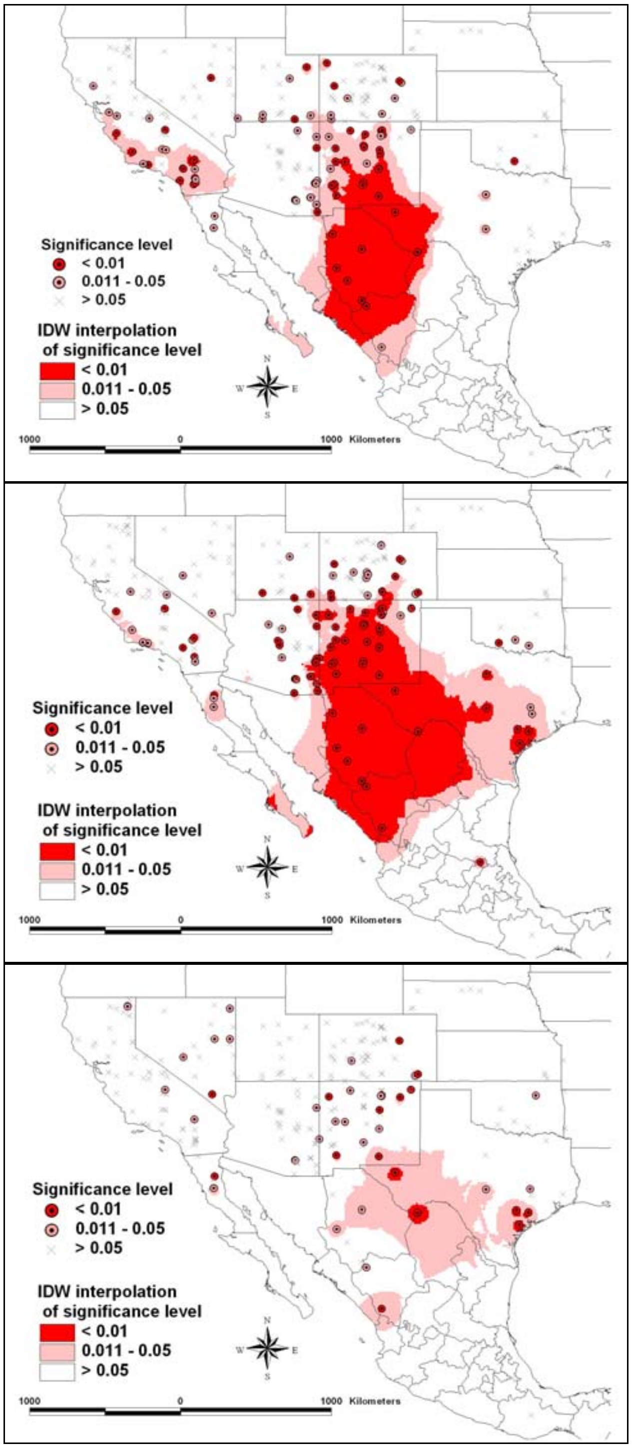

Figure 7. SOI correlation maps illustrating relationship between prior Fall (October – November), prior Winter (December - March), and prior Spring (April – June) instrumental SOI (1900-2000) and a network of moisture sensitive tree-ring sites. Light (dark) shading represent sites and interpolated regions of correlation at the alpha=0.05 (alpha=0.01) level.

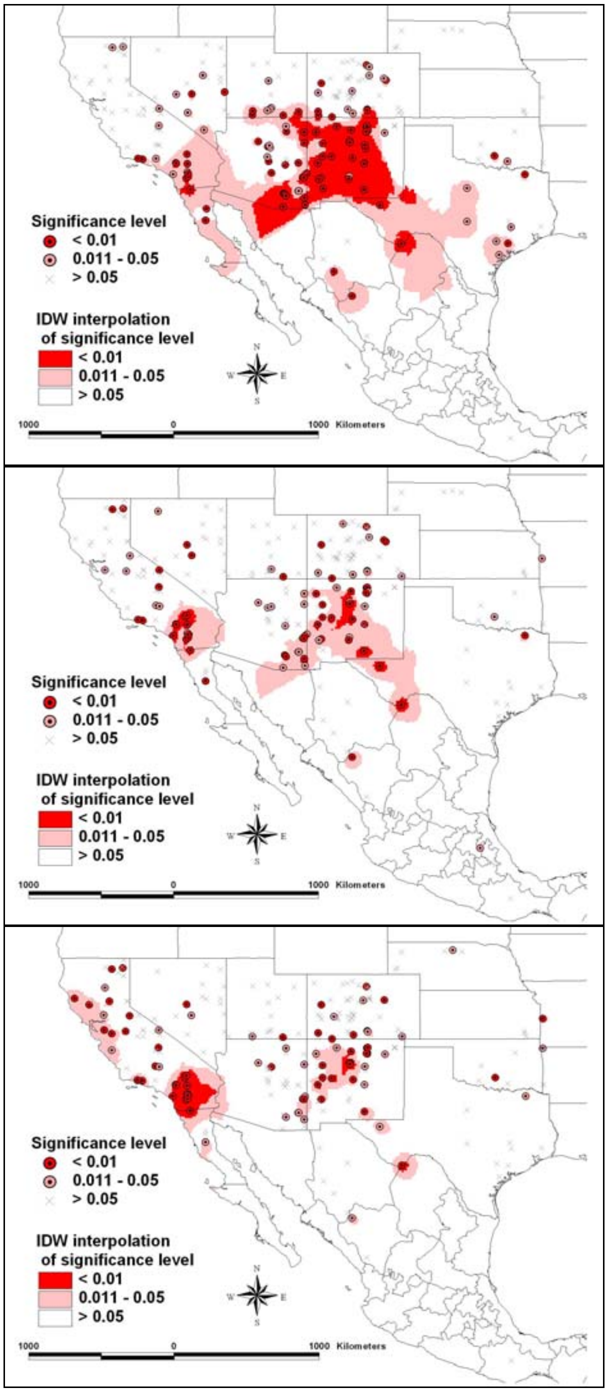

Figure 8. PDO correlation maps illustrating relationship between prior Fall (October – November), prior Winter (December - March), and prior Spring (April – June) instrumental PDO (1900-2000) and a network of moisture sensitive tree-ring sites. Light (dark) shading represent sites and interpolated regions of correlation at the alpha=0.05 (alpha=0.01) level.

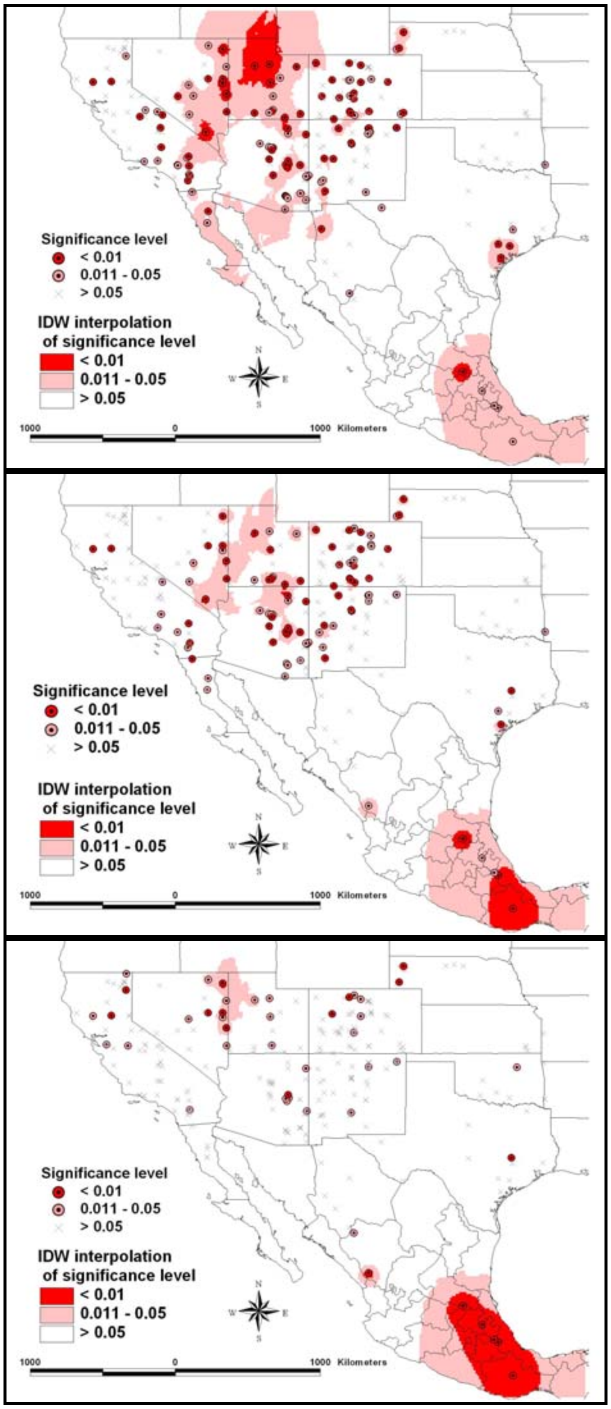

Figure 9. AMO correlation maps illustrating relationship between prior Fall (October – November), prior Winter (December - March), and prior Spring (April – June) instrumental AMO (1900-2000) and a network of moisture sensitive tree-ring sites. Light (dark) shading represent sites and interpolated regions of correlation at the alpha=0.05 (alpha=0.01) level.

APPENDIX C

FIRE-CLIMATE RELATIONSHIPS OF UPPER ELEVATION (>2700M) FIRE REGIMES IN THE SOUTHWESTERN UNITED STATES

Fire-climate relationships of upper elevation (>2700m) fire regimes in the southwestern United States

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Margolis, E.Q. and Swetnam, T.W. ####. Fire-climate relationships of upper elevation (>2700m) fire regimes in the southwestern United States. *To be submitted to* Journal of Biogeography.

ABSTRACT

Understanding relationships between variability in historical fire occurrence and Atlantic and Pacific Ocean-atmosphere oscillations provides opportunities for fire forecasting and projecting changes in fire regimes under climate change scenarios. We analyzed regional climate teleconnections, and fire-climate relationships of upper elevation fire occurrence, including stand-replacing fires, from 16 sites in 8 mountain ranges in the southwestern U.S. (Arizona, New Mexico and southern Colorado). Climate telconnections were identified by testing associations between regional PDSI and individual and combined phases of ENSO, PDO and AMO indices for both the fire exclusion (1905-1978) and reconstructed fire periods (1700-1904). Upper elevation tree-ring reconstructed fires (115 fires; 84 fire years; 1623-1904) in three classes (all fires, synchronous fires, and stand-replacing fires) were compared with tree-ring reconstructed drought (PDSI), precipitation, temperature, and individual and combined phases of ENSO, PDO and AMO indices. Individual and phase combinations of ENSO, PDO, and AMO affect regional moisture variability (PDSI) reconstructed from tree-rings, but the AMO and PDO teleconnections may have changed between the 20^{th} century fire exclusion period (1905-1978) and the reconstructed fire period (1700-1904). All classes of upper elevation fire year occurrence were significantly related to inter-annual variability in

regional drought index (PDSI) and precipitation anomalies, ENSO phase, and phase combinations of ENSO and PDO, but not AMO (1700-1904). Reduced upper elevation fire occurrence and the absence of stand-replacing fire from 1785-1842 is coincident with an inter-hemispheric change in fire regimes, possibly driven by a multi-decadal cool AMO phase and/or reduced ENSO amplitude. The +AMO+PDO+ENSO phase combination was associated with no historical upper elevation stand-replacing or synchronous fires (1700-1904), thus increased frequency of occurrence of this phase combination (1905-1978) may in part explain the lack of early- to mid-20th century upper elevation fire occurrence.

INTRODUCTION

Fire is arguably the most important ecological disturbance process in the western United States, affecting both ecosystems and societies. Identifying the drivers of variability in fire occurrence can benefit both natural resource management and fire hazard planning. An intuitive, inverse relationship between moisture levels and fire occurrence is well established (i.e., drought promotes more fire), but in addition, more complex lagging relationships have been demonstrated for some ecosystems (e.g., semi-arid low to mid-elevation pine and/or oak dominated forests; Swetnam & Baisan 2003; Heyerdahl & Alvarado 2003; Crimmins & Comrie 2004). Upper elevation and/or stand-replacing forest fire regimes are consistently associated with severe drought during the fire year, which is necessary to sufficiently dry the abundant fuels and allow fire spread in these relatively cool and mesic environments (Kipfmueller & Swetnam 2000; Schoennagel et al. 2005; Sibold & Veblen 2006; Margolis et al. *in press*). Although the drought-fire relationship is well established at inter-annual time scales, less is known about multi-decadal variability in fire occurrence and factors controlling climate variability (e.g., ocean-atmosphere oscillations) that ultimately drive mesoscale variability.

Climate variability in the southwestern U.S. at inter-annual to multi-decadal scales is associated with modes of variability in both the Pacific and Atlantic Oceans. Tropical Pacific ocean-atmosphere variability at 2-7 year time scales (El Niño - Southern Oscillation; ENSO) is the best understood driver of North American climate variability (Diaz & Markgraf 2000). La Niña-like (cool equatorial Pacific SST) conditions have been associated with drought in the southwestern U.S. in the modern era and pre-instrumental periods (Fye et al. 2003; Seager et al. 2005; Herweijer et al. 2007; Cook et al. 2007). Extra-tropical ENSO teleconnections can strongly affect winter moisture variability, which is a primary factor in determining spring and summer fire risk in the southwestern U.S. (Westerling et al. 2002; Crimmins & Comrie 2004).

Multi-decadal variability in the northern Pacific Ocean (Pacific Decadal Oscillation; PDO) affects western North America climate at bi-decadal to penta-decadal time scales (Mantua et al. 1997; Minobe 1999; Mantua & Hare 2002) . Interactions between phases of the equatorial and northern Pacific Ocean oscillations can amplify or diminish the effects on western North American climate (Gershunov & Barnett 1998; McCabe & Dettinger 1999; Brown & Comrie 2004). In addition to the Pacific Ocean, recently identified multidecadal variability in the north (0° - 70°) Atlantic Ocean (Atlantic Multidecadal Oscillation; AMO) has been associated with North American climate variability at ~60 yr time-scales (Enfield et al. 2001). Mechanisms of this association are not clear, but both modeling and observational studies independently strengthen interpretations that the teleconnection is genuine (Hidalgo 2004; Sutton & Hodson 2005; Dong et al. 2006). Phase combinations of PDO and AMO can strengthen (weaken) the teleconnections and enhance (reduce) the effect on regional climate variability, such that the most severe North American 20th century droughts (1930's - Great Plains, Pacific Northwest and 1950's - Southwest) have been associated with warm phase AMO coincident with warm (1950's) and cool (1930's) phases of the PDO (McCabe et al. 2004). Although associations between ocean-atmosphere variability and climate have been identified in the 20th century, it is important to remember that the teleconnections are not necessarily stable in time or space. For example, multi-decadal variability associated with the PDO may not have been a primary mode of climate variability during much of the 19th century (Gedalof et al. 2002).

Substantial progress has been made in identifying and quantifying the links between variability in ocean-atmosphere oscillations, local climate teleconnections, and fire occurrence since the work of Swetnam & Betancourt (1990). They established the association between increased (reduced) contemporary and historic fire occurrence, dry (wet) years, and the La Niña (El Niño) phases of ENSO for the southwestern U.S. This had major implications for understanding, and potentially forecasting, variability in fire occurrence as ENSO teleconnections were better understood and forecasts based on this association became feasible (e.g.,Westerling et al. 2002). Similar developments in ENSO-based fire forecasting have proceeded in Florida (Beckage & Platt 2003) and more broadly in the U.S. (NIFC 2007). Subsequent fire-climate research with newly identified climate drivers (e.g., PDO and AMO) demonstrated that variability in historic fire occurrence in many locations of western North America was associated with variability and phase combinations of ocean-atmosphere oscillations (Heyerdahl et al. 2002; Norman & Taylor 2003; Westerling & Swetnam 2003; Hessl et al. 2004; Schoennagel et al. 2005; Sibold & Veblen 2006; Brown 2006; Kitzberger et al. 2007). As global and regional down-scaled global climate models improve and are able to simulate the oscillations of ocean and atmospheric variability (e.g., Sutton & Hodson 2005), the potential also improves for applying fire-climate relationships to forecasting the response of fire regimes to changing climate.

Here, we evaluate historical fire-climate (drought, precipitation, temperature) relationships for upper elevation fires (>2700m), including stand-replacing fires, reconstructed from a network of tree-ring sites in the southwestern U.S. We also identify individual and phase combinations of ocean-atmosphere drivers (e.g., ENSO, PDO, AMO) of climatic conditions associated with upper elevation fire occurrence, including stand-replacing fires.

DATA SETS AND ANALYTICAL METHODS

Fire history data

Fire history data from sixteen upper elevation sites (>2700m) in eight mountain ranges throughout the southwestern U.S. (Grissino-Mayer et al. 1995; Morino et al. 2000; Margolis et al. 2007 *in press*; Appendix 3 - this volume) (Figure 1) were compared with existing proxy precipitation, temperature, drought (PDSI) and ocean-atmosphere indices (ENSO, PDO, and AMO). All fire history data were from mesic mixed-conifer/quaking aspen and spruce-fir/aspen forest stands making this network qualitatively different from prior tree-ring based fire-climate research in the southwestern U.S. Previous studies have primarily based fire event reconstruction on fire-scar samples from the pine-dominated, mid-elevation forests of the region (e.g., Grissino-Mayer & Swetnam 2000; Swetnam & Baisan 2003).

Three sets of reconstructed fires were included in the analysis: 1) all fires (115 fires, 84 fire years, 1623-1904), 2) synchronous fires (42 fires, 20 fire years, 1685-1904), and 3) stand-replacing fires (17 fires, 10 fire years, 1685-1904) (Table 1). We "filtered" the fire data into these subsets to minimize the noise and stochasticity related to all fire occurrence (e.g., site-level inter-annual differences in lightning ignitions, fuel and fire weather) and highlight the mesoscale fire-climate signal (Swetnam & Betancourt 1998). Synchronous fires and stand-replacing fires are non-independent subsets of all fires. Synchronous fires were defined as fires recorded at two or more sites on the same year. Stand-replacing fire dates were determined from multiple lines of tree-ring evidence including: 1) quaking aspen (*Populus tremuloides* Michx.), and/or Engelmann's spruce (*Picea engelmannii*) and sub-alpine fir (*Abies lasiocarpa*) inner-ring dates, 2) conifer fire scars, 3) conifer bark-ring dates, and 4) conifer injury or growth change dates. We interpreted the coincidence of direct evidence of fire (e.g., fire scar or fire-killed conifer bark-ring dates), a recruitment pulse (beginning within 5 years post-fire – quaking aspen; beginning within 10 years post-fire - spruce-fir), and no fire survivors within the patch as evidence of a stand-replacing fire patch. Reconstructed stand-replacing fire area ranged from 30 ha to 1173 ha (Margolis et al. *in press*; and Appendix 1 this document).

Regional drought was represented by averaging tree-ring reconstructed PDSI values from the five grid points (2.5° spacing) within the study area from the Cook et al. (2004) network (grid points 104-105, 118-120). Two tree-ring based precipitation reconstructions from within the study area were used as local or sub-regional climate variables: 1) Southern Colorado Plateau reconstructed precipitation (Salzer & Kipfmueller 2005) and 2) El Malpais, NM reconstructed precipitation (Grissino-Mayer 1996). A tree-ring based temperature reconstruction from the Southern Colorado Plateau was also included as a sub-regional climate variable (Salzer & Kipfmueller 2005).

As a proxy index of ENSO we used the tree-ring reconstructed Niño3 index (Cook 2000) of winter (December – February) sea surface temperature (SST) from the eastern equatorial Pacific Ocean (5°N - 5°S, 90° – 150°W). Fourteen tree-ring width chronologies from the southwestern U.S. and northern Mexico were used in the Niño3 reconstruction. Positive (negative) Niño3 index values represent warm SST's - El Niño (cool SST's - La Niña). We used the D'Arrigo et al. (2001) annual PDO index reconstruction derived from temperature sensitive tree-ring sites from coastal Alaska (5) and Oregon (1), and two tree-ring reconstructed PDSI grid points in northern Mexico (Cook et al. 1999). Positive (negative) index values correspond with warm (cold) phases of the primary mode of variability in Pacific Ocean SST's polewards of 20°N (Mantua et al. 1997). We used the Gray et al. (2004) tree-ring width based reconstruction of the AMO index derived from 12 tree-ring chronologies from southeast North America, Europe, Scandinavia, North Africa and the Middle East. Positive (negative) index values indicate warm (cold) values of the 10-year running mean of detrended SST anomalies in the North Atlantic Basin (0°-70° N). All climate reconstructions used for analysis extended prior to the earliest reconstructed fire (1623) except the PDO reconstruction, which begins in 1700. The common period for all data sets was 1700-1978.

Analytical methods

To test for effects of ocean-atmosphere oscillations on regional climate within the study area we used ANOVA to compare mean regional PDSI during all eight phase combinations of ENSO, PDO, and AMO. To test for dominant effects of individual ocean-atmosphere oscillations on regional climate during all phase combinations we used a contrast t-test test (SPSS 14.0). Specifically, we used this test to compare mean regional PDSI during the four phase combinations including negative versus positive phases for each of the three reconstructed ocean atmosphere indices (e.g., PDSI during all four phase combinations including +AMO vs. all four including –AMO). This analysis was conducted for both the reconstructed fire (1700-1904) and fire exclusion (1905-1978) periods to test for changes in dominant effects of individual ocean-atmosphere oscillation on regional climate through time. The frequency of occurrence (percent of total years) for each phase combination was determined for both periods to examine changes in the frequency distribution of ocean-atmosphere oscillation phase combinations. To test for stability in the effects of phase combinations of ocean-atmosphere oscillations on regional climate we used a student's t-test to compare mean

PDSI values for each phase combination between the reconstructed fire and the fire exclusion periods.

Inter-annual fire-climate relationships

Inter-annual fire climate relationships were examined using a combination of graphical and statistical methods. Maps of North American PDSI (Cook et al. 2004) were visually analyzed to determine if consistent spatial patterns of drought occurred during all individual stand-replacing fire years. All fire years, synchronous fire years, and stand-replacing fire years were plotted on the regional PDSI time series to illustrate fire-climate relationships through time. We tested for inter-annual associations between all upper elevation fires, synchronous fires and stand-replacing fires, and reconstructed climate variables (regional PDSI, Niño3 index, PDO index, AMO index, southern Colorado Plateau precipitation, El Malpais precipitation, and southern Colorado Plateau temperature) using superposed epoch analysis (SEA; Baisan & Swetnam 1990; Swetnam & Betancourt 1992). SEA tests for departures of mean climate values from the period mean during, before, and after fire event years using 1000 Monte Carlo simulations to derive confidence intervals around the period mean. We tested a seven-year window around the fire year spanning four years before and two years after the fire event. The period of analysis varied depending on the overlap in time of the fire and climate data.

We tested for association between fire occurrence, individual and phase combinations of ocean-atmosphere oscillations using contingency analysis. Chi-squared analysis was used to test for independence between observed fire occurrence and that expected by chance during negative and positive phases of individual AMO, PDO and

Niño3 indices and the eight possible phase combinations (e.g., +A-P-N). Expected fire occurrence was derived from the frequency of occurrence of the different climate phase combinations (e.g., if +A-P-N occurred during 10% of the years, then 10% of the fire years were expected to occur on +A-P-N years). Analyses were limited to the common period of all reconstructed climate indices and fires. The *a priori* level of significance for all statistical tests was set at $p<0.05$.

RESULTS

Ocean-atmosphere effects on climate

During the reconstructed fire period (1700-1904) mean PDSI during all eight AMO, PDO and Niño3 phase combinations was significantly different (Fig 2, Tables 2, 3). Mean PDSI during all four phase combinations including negative Niño3 (i.e., La Niña years) was significantly lower (drier) than all combinations including positive Niño3 (i.e., El Niño years). Mean PDSI during all four phase combinations including negative PDO years was significantly lower (drier) than those including positive PDO. Mean PDSI was not significantly different between negative and positive AMO phase combinations.

For the fire exclusion period (1905-1978), mean PDSI during all eight AMO, PDO and Niño3 phase combinations was significantly different (Fig 2, Tables 2, 3). Mean PDSI during all four phase combinations including La Niña years was significantly lower (drier) than all combinations including El Niño. Mean PDSI was not significantly different between negative and positive PDO phase combinations. Mean PDSI during all four phase combinations including positive AMO years was significantly lower (drier) than all combinations including negative AMO.

The frequency (percent) of occurrence of all eight AMO, PDO, and Niño3 index phase combinations was similar between the fire reconstruction period and the fire exclusion period (Figure 3). However, the +A+P+N phase combination occurred with greater than twice the frequency during the fire exclusion period (1905-1978; 20%) compared to the reconstructed fire period (1700-1904; 9%), which was greater than expected by chance (χ^2=10.79, $p < 0.01$).

The effect of all eight ocean-atmosphere phase combinations on regional drought in the southwestern U.S. was not entirely stable through time (Fig. 2, Table 2). Although the phase combinations were consistently associated with dry or wet conditions (negative or positive PDSI) the magnitude of the effects changed. The mean tree-ring reconstructed regional PDSI value for the -A-P-N phase combination during the reconstructed fire period (1700-1904, -1.83) was significantly less (drier) than during the 20^{th} century fire exclusion period (1905-1978, -0.54) ($t = -2.198$, $p < 0.05$). The mean PDSI value for the –A-P+N phase combination increased by a factor of 3 between periods (from 0.47 to 1.44), but the change was not statistically significant (Table 2, Fig 2).

Inter-annual fire-climate relationships

All stand-replacing fires occurred during regional negative PDSI (dry) years (mean reconstructed PDSI = -2.59; Figs 4, 5). Visual analysis of spatial patterns of drought (PDSI) during stand-replacing fire years (1685-1904, n=10) indicates a wet/dry dipole pattern in the western U.S. (Fig 5). Regional drought (negative PDSI) in the southwestern U.S. during stand-replacing fire years was associated with wet (positive PDSI) conditions in the northwest U.S. in 9 out of 10 stand-replacing fire years. Only during 1842 was there joint drought between the two regions.

Eighteen of 20 synchronous fire years (i.e., years when fire was recorded at two or more sites) occurred during negative PDSI years (mean reconstructed PDSI = -2.35) (Fig 4). Seven of 10 stand-replacing fire years occurred on synchronous fire years. Including all fire years, 59 of 84 years (70%) were associated with negative PDSI years. All fires occurring on years with positive PDSI (wet) were from the two sites in the sky islands of southeastern Arizona (CHI and PIN) except 1840 (SFP).

The results of the SEA indicate that all fire years, synchronous fire years and stand-replacing fire years were significantly associated with negative (dry) departures from mean summer PDSI and southern Colorado Plateau precipitation (Fig. 6). All fire years and synchronous fire years were also associated with negative (dry) and positive (wet) departures from mean El Malpais, NM precipitation. All fire years, synchronous fire years and stand-replacing fire years were associated with negative (cool ocean phase) SST departures from the mean Niño3 index. Fire occurrence was not associated with inter-annual variations in PDO (Fig. 6), southern Colorado Plateau temperature or AMO (results not shown).

Observed stand-replacing, synchronous, and all fire year occurrence was significantly less (greater) than expected during all ocean-atmosphere oscillation index phase combinations that included positive (negative) Niño3 index years (Fig 7, Table 4).

We did not reject the null hypothesis of independence between fire year occurrence and phases of the individual PDO or AMO, or combined phases of Niño3, PDO, and AMO. The maximum number of all fire (n=15, 21%), synchronous fire (n=6, 32%) and stand-replacing fire years (n=3, 33%) occurred during negative Niño3 (La Niña), negative PDO phase combinations. No single phase combination of all three ocean-atmosphere indices was dominantly associated with all fire, synchronous fire, or stand-replacing fire occurrence. However, the maximum percentage of all classes of fire occurrence was coincident with the -A-P-N phase combination, which had the lowest mean PDSI (-1.83) during the reconstructed fire period (1700-1904). The minimum percentages of stand-replacing (0%, 0%) and synchronous (0%, 6%) fire years occurred during the two +P+N phase combinations (+A, -A), which had the highest (wettest) mean PDSI (0.51, 1.00). No stand-replacing or synchronous fire years, and 7% of all fire years occurred during the +A+P+N phase combination, which occurred during 9% of the reconstructed fire period (1700-1904) and 20% of the fire exclusion period (1905-1978).

DISCUSSION

Ocean-atmosphere oscillation teleconnections

Our results support the dominance of ENSO teleconnections on southwestern U.S. moisture variability during both pre-and post-20th century periods (Diaz & Markgraf 2000). PDO phase was associated with variability in mean annual PDSI only in the pre-20th century period, while AMO phase was only associated with PDSI variability during the 20th century (Table 5). This result and the change in the effects of combined

AMO/PDO/ENSO phases on regional PDSI between the reconstructed fire period (1700-1904) and the 20th century fire exclusion period (1905-1978) suggest that the teleconnections may not be stable through time. The instability of the teleconnection may be in terms of the magnitude of the effects on PDSI, since the phase relationships were generally stable between periods (i.e., negative equaled dry and positive equaled wet consistently between periods). For example, the -A-P-N phase combination was associated with dry (negative PDSI) conditions in both periods, but mean regional PDSI was drier (-1.83) during the reconstructed fire period (1700-1904) than during the 20th century fire exclusion period (-0.54). This change could affect fire-climate relationships such that a phase combination associated with extreme drought and fire in past centuries may not exceed the required drought threshold (i.e., for stand-replacing fire) to produce similar fire occurrence under modern climate conditions.

These results are based on tree-ring reconstructions of PDSI, and the three ocean-atmosphere oscillation indices that explain the most variance during the instrumental calibration period. Other reconstructions exist for ENSO and PDO (e.g., Stahle et al. 1998; Biondi et al. 2001; MacDonald & Case 2005) and they all differ in some respects. Similar analyses with combinations of existing, new or alternative paleo-proxy reconstructions (i.e., corrals) could be used to test the strength of the results. The comparisons between southwestern U.S. regional PDSI and the reconstructed Niño3 index are not completely independent, because of some shared tree-ring chronologies between the reconstructions. The comparisons between southwestern U.S. regional PDSI and the PDO and AMO reconstructions are independent in the sense that none of the tree-ring width chronologies used in these reconstructions were the same.

Fire-drought relationships

Dry conditions during the fire year are significantly associated with all three classes of upper elevation (>2700m) fire occurrence in the southwestern U.S.: 1) all fire years, 2) synchronous fire years, and 3) stand-replacing fire years. A similar fire year-drought relationship exists in other upper elevation and stand-replacing fire regimes in the Southern, Central and Northern Rocky Mountains (Kipfmueller 2003; Schoennagel et al. 2005; Sibold & Veblen 2006). This finding supports the interpretation that upper elevation forests generally contain sufficient fuel for burning, are not dependent on prior moisture conditions, and only require sufficiently dry conditions for successful ignition and fire spread (Schoennagel et al. 2004). The mean PDSI departure from normal conditions during synchronous and/or stand-replacing fire years was 2 - 4 times as dry as that associated with all fire years, suggesting that the occurrence of synchronous and/or stand-replacing fire years generally requires exceptional dry conditions (fig 4, 6). Perhaps further quantification of this fire-drought relationship may reveal a minimum threshold PDSI value that must be exceeded for stand-replacing fire occurrence or values below which a high probability of stand-replacing fire occurrence exists. The probabilistic approach may be more appropriate based on the observation that some extremely dry years occurred without evidence of stand-replacing fire.

Variability in fire-climate relationships between classes of upper elevation fire occurrence and potential differences between some upper elevation southwestern U.S. sites and higher latitude Rocky Mountain sites was indicated by our results. The occurrence of 30% of all fires during positive PDSI (wet) years and a significant prior year wet lag for all fires using the El Malpais precipitation reconstruction was not expected for these generally mesic upper-elevation sites. Neither synchronous nor stand-replacing fire years were associated with prior year wet lags and generally did not occur during positive PDSI (wet) years, suggesting that these fire classes were qualitatively different from all fires. The "all fire" class included many fires recorded by multiple-scarred conifers, predominantly located on relatively open and relatively xeric south aspects at the four southernmost sites (CHI, GIL, PIN, and SFP). The south aspects below circa 2900 m at these sites contained patches of relatively open grasslands that wouldn't require severe drought to burn and where fine fuel loads may be sensitive to antecedent moisture at inter-annual scales (Swetnam & Baisan 1996). All but one of the fire years co-occurring with wet conditions were from the two southernmost Sky Island sites in southeastern Arizona. The climatology of southern Arizona includes a dry and hot pre-monsoon period (May-June) every year (Sheppard et al. 2002). This local climate feature can be sufficient to override a prior moisture surplus, desiccate fine fuels and allow fire occurrence, particularly on south-facing slopes.

Fire-ocean-atmosphere oscillation relationships

No single phase combination of all three ocean-atmosphere indices was dominantly associated with any class of fire occurrence (Table 5). However, the maximum percentage of all three classes of fire occurrence was coincident with the -A-P-N phase combination, which had the lowest mean PDSI (-1.83). Sibold & Veblen (2006) found that the +A-P-N phase combination was associated with 71% of large fires recorded in sub-alpine forests of Rocky Mountain National Park in northern CO and produced the driest conditions. Brown (2006) also found greater than expected tree-ring reconstructed fire occurrence during this climate phase combination in Ponderosa pine (*Pinus ponderosa*) forests of the Black Hills, South Dakota-Wyoming. The +A-P-N phase combination in our study was associated with the second highest frequency of occurrence of the three classes of fire occurrence and the second driest conditions (mean PDSI -1.79, 1700-1904). Thus, constructive (i.e., same sign) cool phases of PDO and ENSO are consistently important for drought and upper elevation fire occurrence in the southwestern U.S. and northern Colorado, but teleconnections and fire occurrence relationships with AMO are inconsistent. Schoennagel et al. (2005) found that constructive cool phases of ENSO and PDO were more important for sub-alpine fire and drought occurrence in the Southern Rockies than the individual phases. Kitzberger et al. (2007) report that constructive cool phases of ENSO and PDO were important for synchronous fires burning within and between sub-regions of the southwestern U.S. Their results also show that the greatest synchrony of fires over western North America from southern British Colombia to northern Mexico occurred during positive AMO coincident with constructive cool phases of ENSO and PDO. Thus, although the AMO has been associated with the dominant modes of 20th century drought and historical fire synchrony over the western U.S. (including southern British Columbia, Canada and northern Mexico), AMO phase was apparently not as important for regional, inter-annual variability in fire occurrence within the southwestern U.S.

Climate linked to early 20th century fire exclusion?

No reconstructed stand-replacing or synchronous fires were coincident with the +A+P+N phase combination (1700-1904). This phase combination was coincident with consistently wet regional conditions in the southwestern U.S. in pre- and post-1904 periods. It is notable that this phase combination occurred with twice the frequency during the fire exclusion period (1905-1978; 20%) compared to the reconstructed fire period (1700-1904; 9%). If the fire-climate relationship remained stable through time the increased occurrence of this "no-fire," wet climate phase combination during the 20th century would be expected to result in decreased stand-replacing and/or synchronous upper elevation fire occurrence.

The cessation of mid-elevation surface fires in the southwestern U.S. due to the removal of fine fuels by late 19th century livestock and the successful active suppression of fires after circa 1940 has been well documented (Pyne 1982; Swetnam & Baisan 1996). However, the effects on upper elevation and stand-replacing fire regimes in the region have not been previously investigated. Fire suppression effects on upper elevation and/or stand-replacing forest fire regimes in the Rockies are thought to be minimal, because these systems are generally not fuel limited and suppression tactics are often ineffective in large conflagrations (Sibold et al. 2006, Schoennagel et al 2004; but see Kipfmueller and Baker 2000).

Extensive mid-elevation pine forests, historically characterized by frequent surface fire occurrence, adjacent to upper elevation forests with stand-replacing fire regimes may provide a geographically unique mechanism for decreased 20th century upper elevation fire occurrence in the southwestern U.S. Margolis et al. (*in press)* hypothesize that cessation of lower elevation surface fires adjacent to upper elevation forests could decrease ignition sources (i.e., fire spread from lower to upper elevations), thereby potentially reducing upper elevation stand-replacing fire occurrence. Here we provide evidence of increased frequency of occurrence during the 20th century of a non-conducive climate condition that would be expected to result in decreased upper elevation stand-replacing and/or synchronous fires. It's not likely that a single factor will ultimately account for the observed 20th century cessation of upper elevation fire, but the combined effects of climatic variability, land use history and active fire suppression should be the focus of future research.

The "gap"

Multiple fire history studies in southwest North America (north Mexico, Arizona, New Mexico, and Colorado) and southern South America document a gap, or a period of decreased fire occurrence between circa 1780 and 1840 (Swetnam 1990; Swetnam & Betancourt 1998; Grissino-Mayer & Swetnam 2000; Kitzberger et al. 2001; Stephens et al. 2003; Grissino-Mayer et al. 2004; Sibold et al. 2006). This change in fire frequency was associated with a period of decreased ENSO amplitude (Kitzberger et al. 2001) and a negative AMO phase (Sibold & Veblen 2006; Kitzberger et al. 2007), both of which may lead to fewer droughts and reduced variability in climate. We observed a similar decrease in fire occurrence from circa 1785-1840 in synchronous and stand-replacing upper elevation fires (fig 4) and all fires (fig 8). The maximum interval between synchronous fire years (1806-1840, 37 yrs) occurred during this period. Mean intervals between synchronous fire years prior to (1685 – 1785) and after (1840-1904) the gap were 8.0 yrs and 11.6 yrs respectively. No stand-replacing fires were reconstructed between 1685 and 1842. Methodological limitations of quaking aspen-based stand-replacing fire methods and a site selection bias toward younger (19^{th} century) aspen stands may be one explanation (Margolis et al. *in press*). However, coincident decreases in all upper elevation fires and synchronous upper elevation fire occurrence makes a stronger case for a coincident change in upper elevation and/or stand-replacing fire regimes in the southwestern U.S. during this period.

This study demonstrates that multiple classes of upper elevation fire occurrence, in the southwestern U.S., including stand-replacing fires, relate to moisture variability and variability in individual and phase combinations of Pacific and Atlantic Ocean-atmosphere oscillations. Instability of the individual and combined AMO and PDO teleconnections in time are not well understood and require future study to be beneficial in assessing and potentially forecasting climate-based fire risk in the region.

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Table 1. All fire, synchronous fire, and stand-replacing fire dates from upper elevation sites (>2700m) in the upper Rio Grande Basin, and Mogollon Plateau and Sky Islands. Synchronous fire years (two or more sites recording fire on the same year) in bold.

Site	Stand-replacing fires	All additional fires
Upper Rio Grande Basin		
GAR	**1873**	
SQU	1876	
CHA	**1851**	1880
COL	**1851**	
VES	**1851**, **1879**	**1748**
JAR	----------------	**1847**, 1860, **1861**, 1870, **1873**
POL	**1861**	
JIC	**1842**	
SBA	**1861**	
CAN	**1861**, 1893	
SKI	**1861**, **1879**	**1806**
CRS	1901	
Mogollon Plateau and Sky Islands		
CHI*		1654, 1661, **1685,** 1688, 1697, 1698, 1700, 1701, 1703, **1709**, 1711**, 1716**, 1721, 1723, 1725, 1727, **1733**, 1737, 1739, **1748**, 1749, **1752**, **1760**, 1763, **1765**, **1773**, 1775, 1779, **1785**, 1787, 1789, 1794, 1798, 1800, 1805, **1806**, 1807, 1817, **1818**, 1822, 1826, 1835, 1838, **1840**, 1841, 1848, 1849, **1851**, 1859, **1863**, 1868, 1875, 1877, 1883, 1886, 1894, 1903, **1904**
GIL	**1904**	**1716**, **1748**, **1765,** 1773
PIN*	**1685**	1623, 1648, 1668, 1670, 1674, 1687, 1691, 1696, **1709**, 1719, **1733**, 1745, **1748**, **1752**, **1760**, **1773**, **1785**, 1819, **1842**, **1847**, 1858, **1863**, 1871
SFP	**1879**	**1840**, **1847**, **1851**, 1857, **1863**

*Fire scar data from Morino et al. 2000 (CHI) and Grissino-Mayer et al. 1995 (PIN).

Table 2. The percent of expected (E) and observed (O) number of all fire years, synchronous fire years (i.e., fires occurring at multiple sites) and stand-replacing fire years during each of eight possible phase combinations of the Atlantic Multidecadal Oscillation index (A; Gray et al., 2004), the Pacific Decadal Oscillation index (P; D'Arrigo et al. 2001) and Niño3 SST index (N; Cook et al. 2000). Capital (lower case) superscript letters indicate phase combinations including positive (negative) phases of Niño3 (N,n), PDO (P,p) and AMO (A,a) with significantly different (p<0.05) mean PDSI between phases (contrast t-test with unequal variance; SPSS 14.0).

	+A+P+N		-A+P+N		+A-P+N		-A-P+N		+A+P-N		-A+P-N		-A-P-N		+A-P-N	
	E	O	E	O	E	O	E	O	E	O	E	O	E	O	E	O
All fire years; n=70 (1700-1904)	9	7	19	13	17	11	16	14	4	4	7	10	14	21	15	19
Synchronous fire years; n=20 (1700-1904)	9	0	19	6	17	17	16	6	4	6	7	17	14	33	15	17
Stand-replacing fire years; n=9 (1842-1904)	14	0	13	0	25	11	8	11	3	11	3	0	10	33	25	33
Fire exclusion period (1905-1978)	20	--	15	--	12	--	14	--	8	--	3	--	11	--	18	--
Mean PDSI value (1700-1904)	$0.51^{N,P}$		$1.00^{N,P}$		$0.32^{N,p}$		$0.47^{N,p}$		$-1.00^{n,P}$		$-0.82^{n,P}$		$-1.83^{n,p,+}$		$-1.79^{n,p}$	
Median PDSI value (1700-1904)	0.54		0.74		0.50		0.32		-1.11		-0.32		-2.05		-1.87	
Mean PDSI value (1905-1978)	$0.58^{N,A}$		$1.13^{N,a}$		$0.13^{N,A}$		$1.44^{N,a}$		$-0.86^{n,A}$		$-1.06^{n,a}$		$-0.54^{n,a,+}$		$-2.27^{n,A}$	
Median PDSI value (1905-1978)	0.51		1.38		0.25		1.35		-0.77		-1.06		-0.40		-2.48	

+ indicates significantly different (p<0.05) mean PDSI between 1700-1904 and 1905-1978 periods (Student's t-test).

Table 3. Contrast t-test statistics (assuming unequal variance; SPSS 14.0) testing the null hypothesis of equal mean PDSI between all phase combinations including negative versus positive phases of Niño3, PDO and AMO. ANOVA statistics testing the null hypothesis of equal mean PDSI during all eight possible phase combinations of Niño3, PDO and AMO indices.

	-N vs +N phase combinations	-P vs + P phase combinations	-A vs +A phase combinations	All Niño3/PDO/AMO phase combinations
Mean PDSI (1700-1904)	t = 8.57	t = 2.79	t = -0.86	F = 16.90
	p<0.001	p<0.01	p=0.395	p<0.001
Mean PDSI (1905-1978)	t = 6.29	t = 0.79	t = -2.66	F = 9.337
	p<0.001	p=0.43	p<0.05	p<0.001

Table 4. Chi-squared statistics testing independence between fire occurrence and the positive/negative phases of the individual Niño3, PDO, and AMO indices, and all eight combined phases of Niño3, PDO, and AMO. Expected fire year occurrence values were derived from the frequency of occurrence of each climate phase for the period of analysis. All tests include the positive cases only (e.g., all years with fire occurrence during +Niño3 vs –Niño3). Analysis period for PDO and combined index phases was limited to overlap with the period of the PDO reconstruction (all fire yrs, 1700-1904; synchronous fire years, 1700-1904; stand-replacing fire years, 1842-1904).

	Niño3	PDO	AMO	Niño3/PDO/AMO
all fire years (1623-1904)	$\chi^2 = 10.19$ p<0.001	$\chi^2 = 0.53$ p=0.465	$\chi^2 = 0.88$ p=0.349	$\chi^2 = 6.99$ p=0.430+
synchronous fire years (1685-1904	$\chi^2 = 10.52$ p<0.001	$\chi^2 = 1.19$ p=0.274	$\chi^2 = 0.106$ p=0.745	$X^2 = 11.72$ p=0.110+
stand-replacing fire years (1685-1904)	$\chi^2 = 6.85$ p<0.01+	$\chi^2 = 2.85$ p=0.091+	$X^2 = 0.00$ p=0.977+	$X^2 = 10.80$ p=0.147+

+ indicates expected values less than the recommended minimum (5) for Chi-squared analysis

Table 5. Summary table of individual Niño3, PDO, and AMO phases significantly ($p<0.05$) associated with dry (negative) regional mean PDSI and three classes of tree-ring reconstructed upper elevation fire year occurrence in the southwestern U.S.

	Niño3 phase	PDO phase	AMO phase	Niño3/PDO/AMO phase combinations
Regional PDSI reconstructed fire period (1700-1904)	-N (La Niña)	-P	Not significant	-----------
Regional PDSI fire suppression period 1905-1979)	-N	Not significant	+A	------------
(All fires (1623-1904)	-N	Not significant	Not significant	Not significant
Synchronous fires (1685-1904)	-N	Not significant	Not significant	Not significant
Stand-replacing fires (1685-1904)	-N	Not significant	Not significant	Not significant

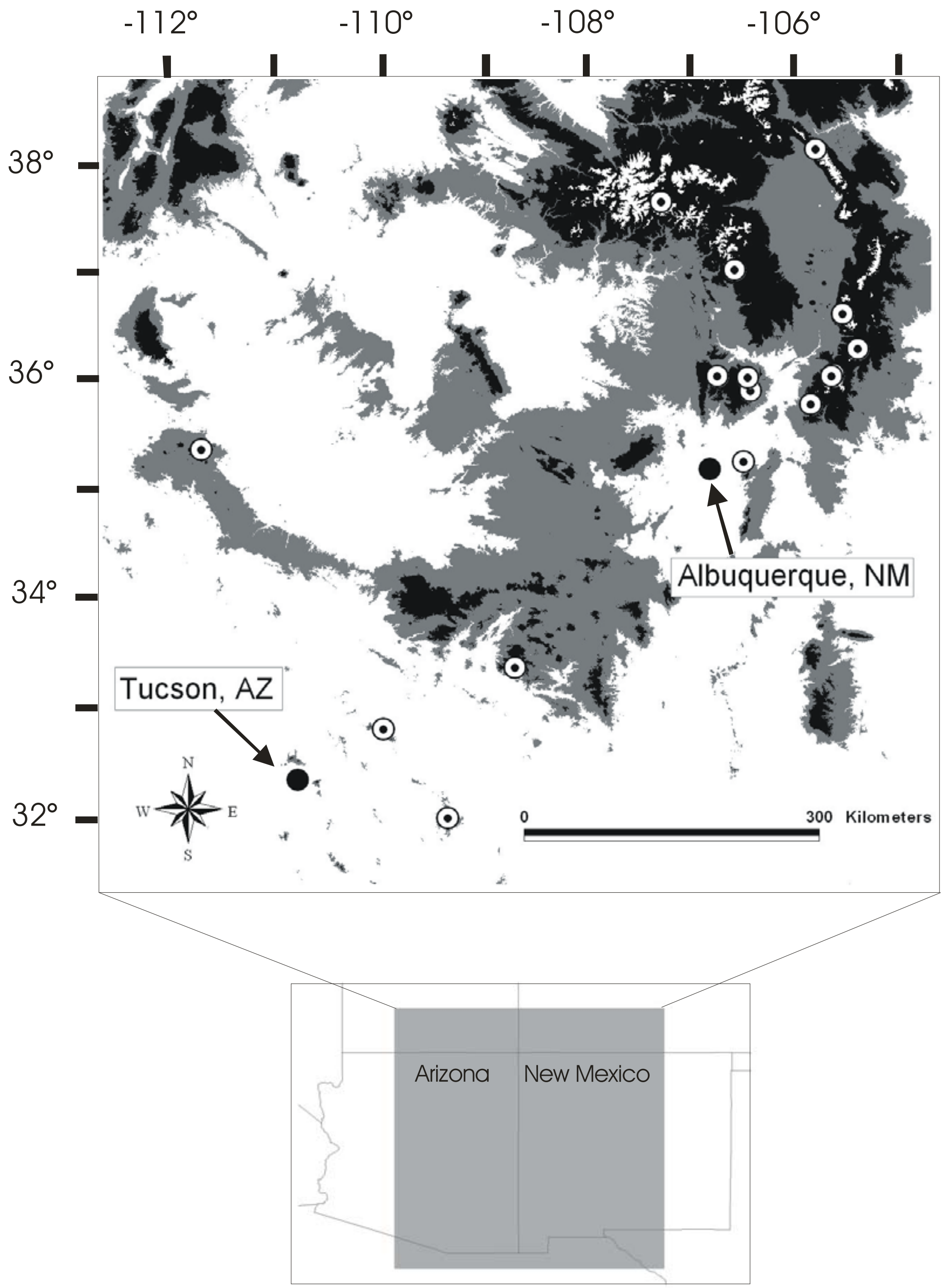

Figure 1. Map of upper elevation (>2700m) fire history study sites and major topographic features >2000m at 500m intervals in Arizona, New Mexico and southern Colorado

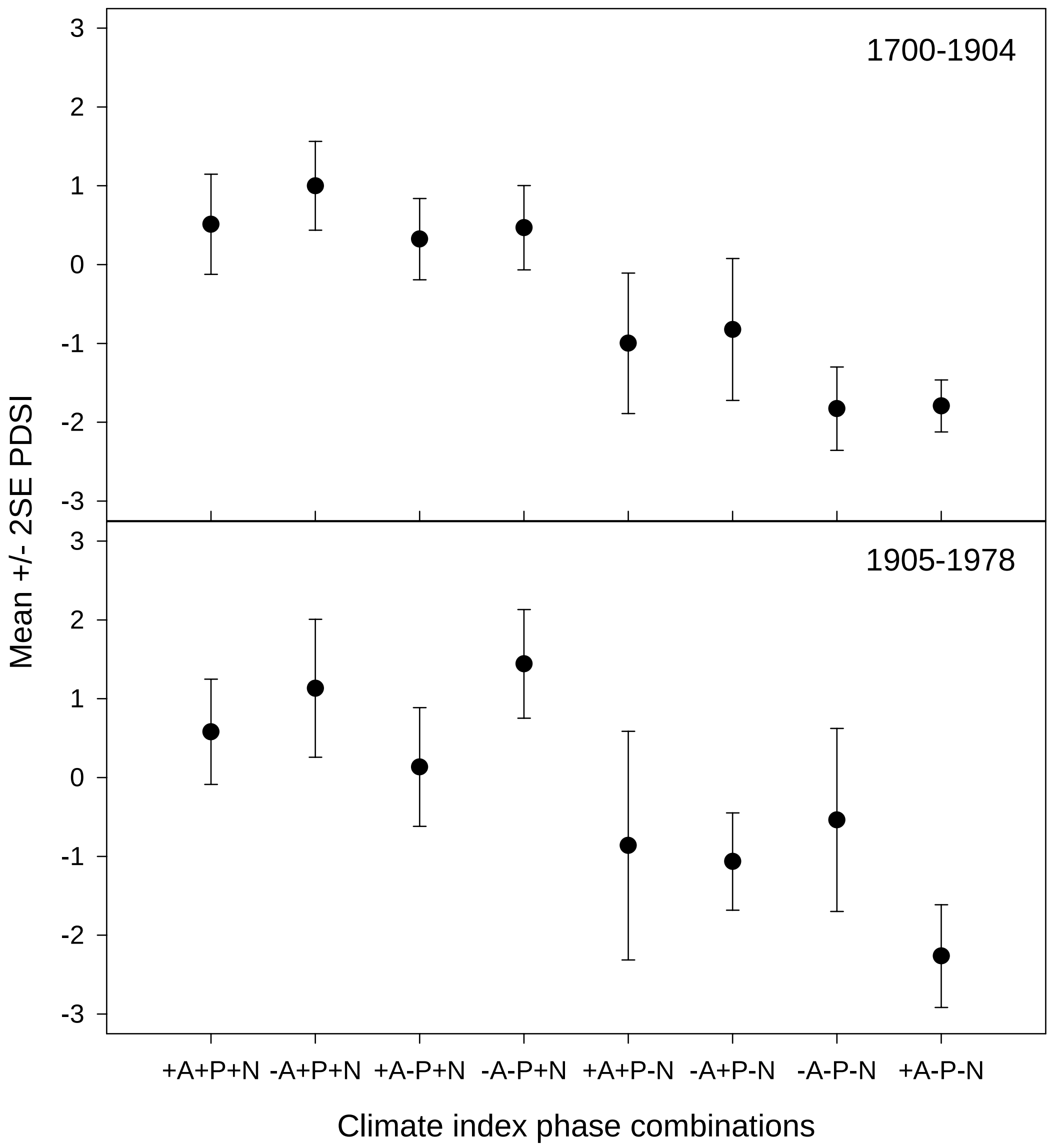

Figure 2. Mean and two standard errors of tree-ring reconstructed PDSI for all eight possible phase combinations of tree-ring reconstructed AMO, PDO and Niño3 climate indices for the reconstructed fire period (top – 1700-1904) and the fire exclusion period (bottom - 1905-1978).

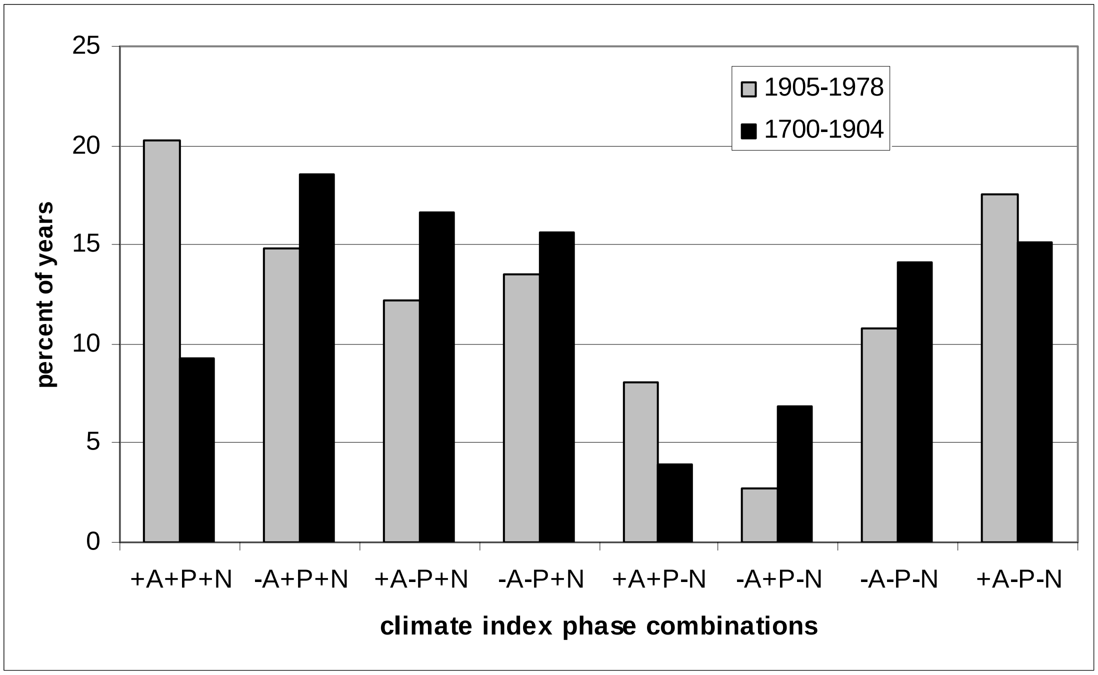

Figure 3. The percent of years in each of eight phase combinations of reconstructed AMO, PDO, and Niño3 indices during the fire exclusion period (1905-1978) and reconstructed fire period (1700-1904).

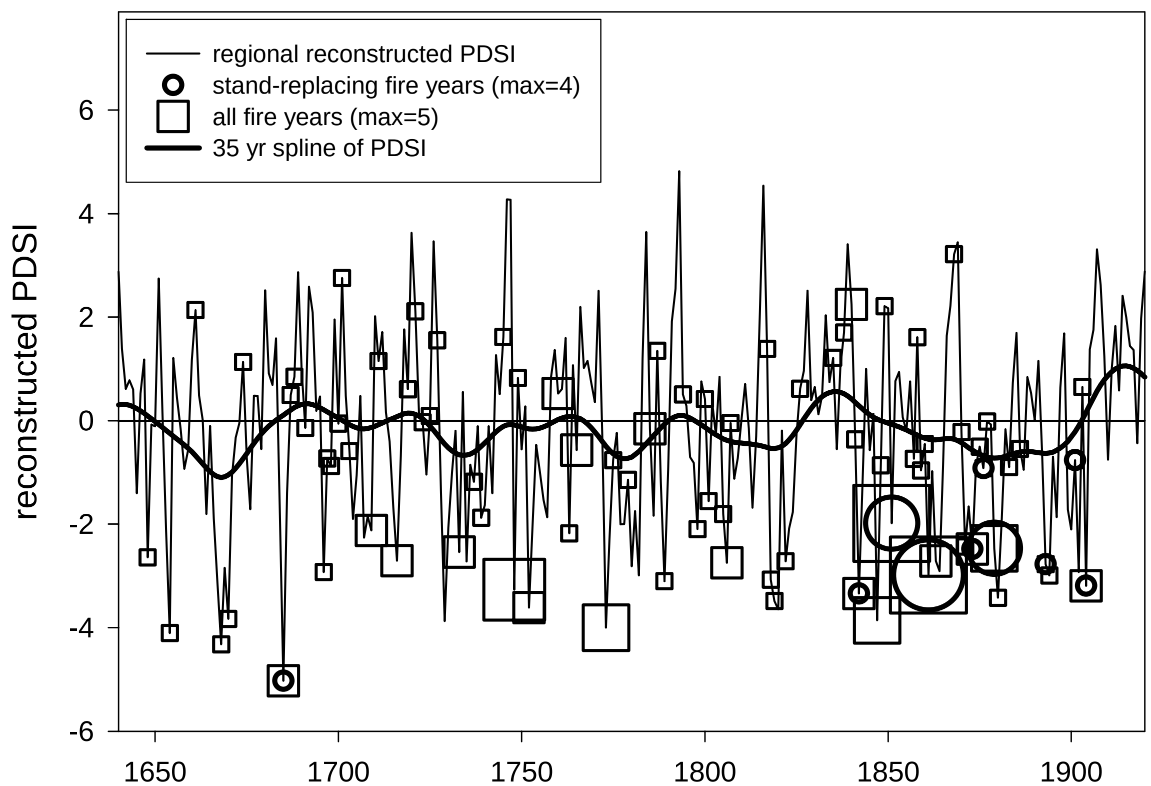

Figure 4. All upper elevation fires (>2700m) and stand-replacing fires plotted on the regional tree-ring reconstructed PDSI time series. The size of the symbol indicates the number of sites recording fire on synchronous fires years (maximum number of sites recording synchronous stand-replacing fires = 4, all fires maximum = 5).

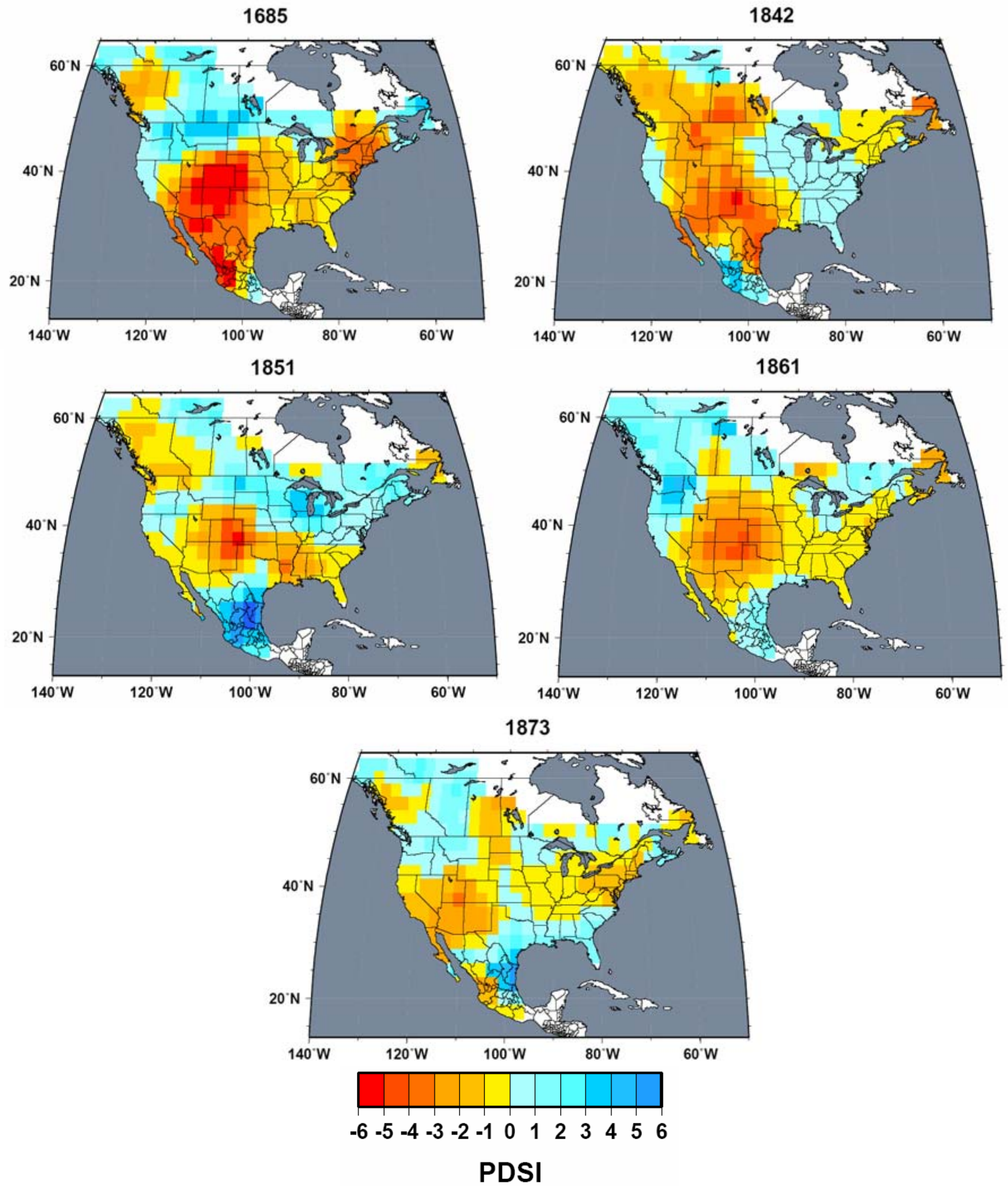

Figure 5a. Tree-ring reconstructed PDSI maps for stand-replacing fire years (1685-1873; Cook et al 2004).

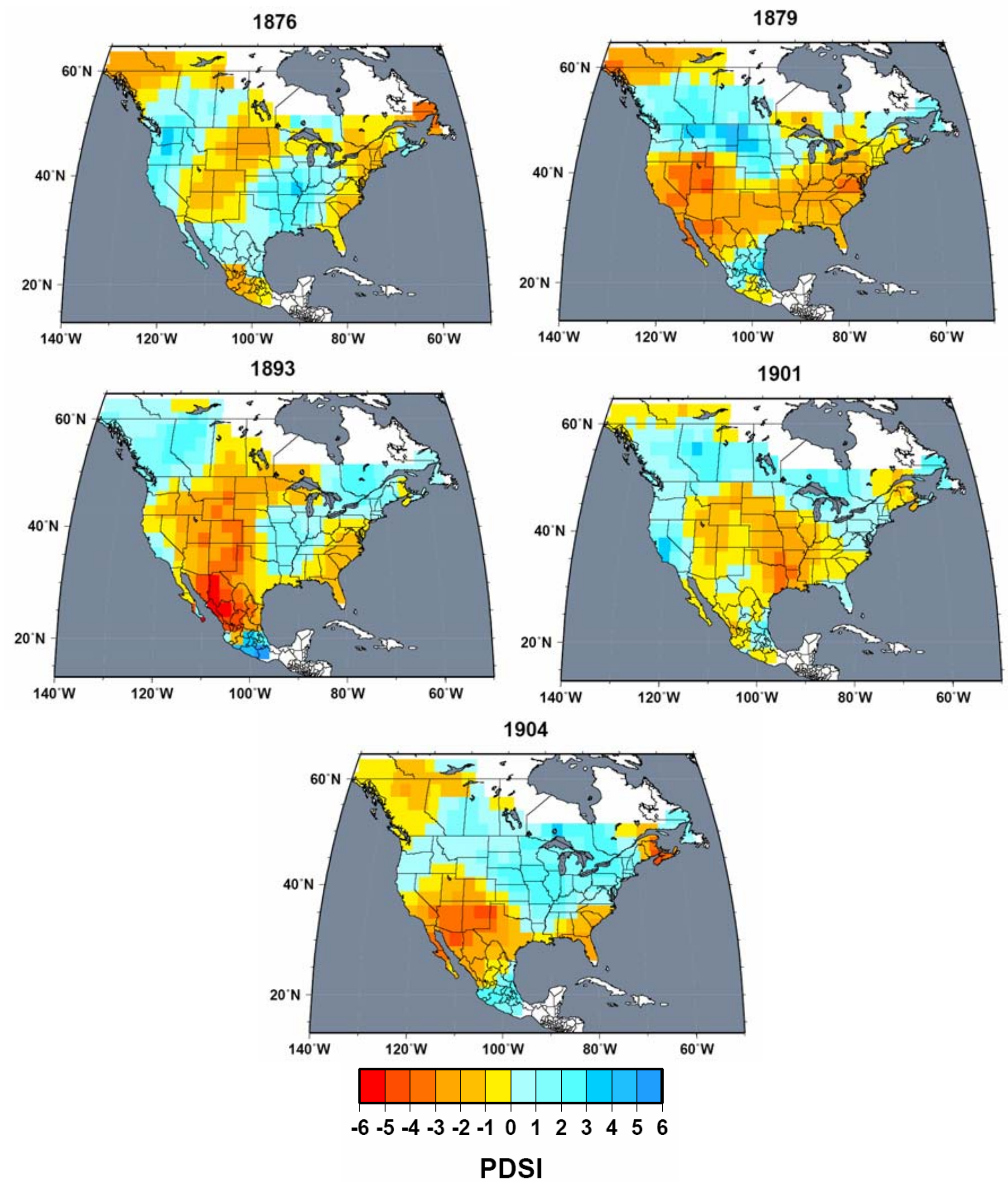

Figure 5b. Tree-ring reconstructed PDSI maps for stand-replacing fire years (1876-1904; Cook et al 2004).

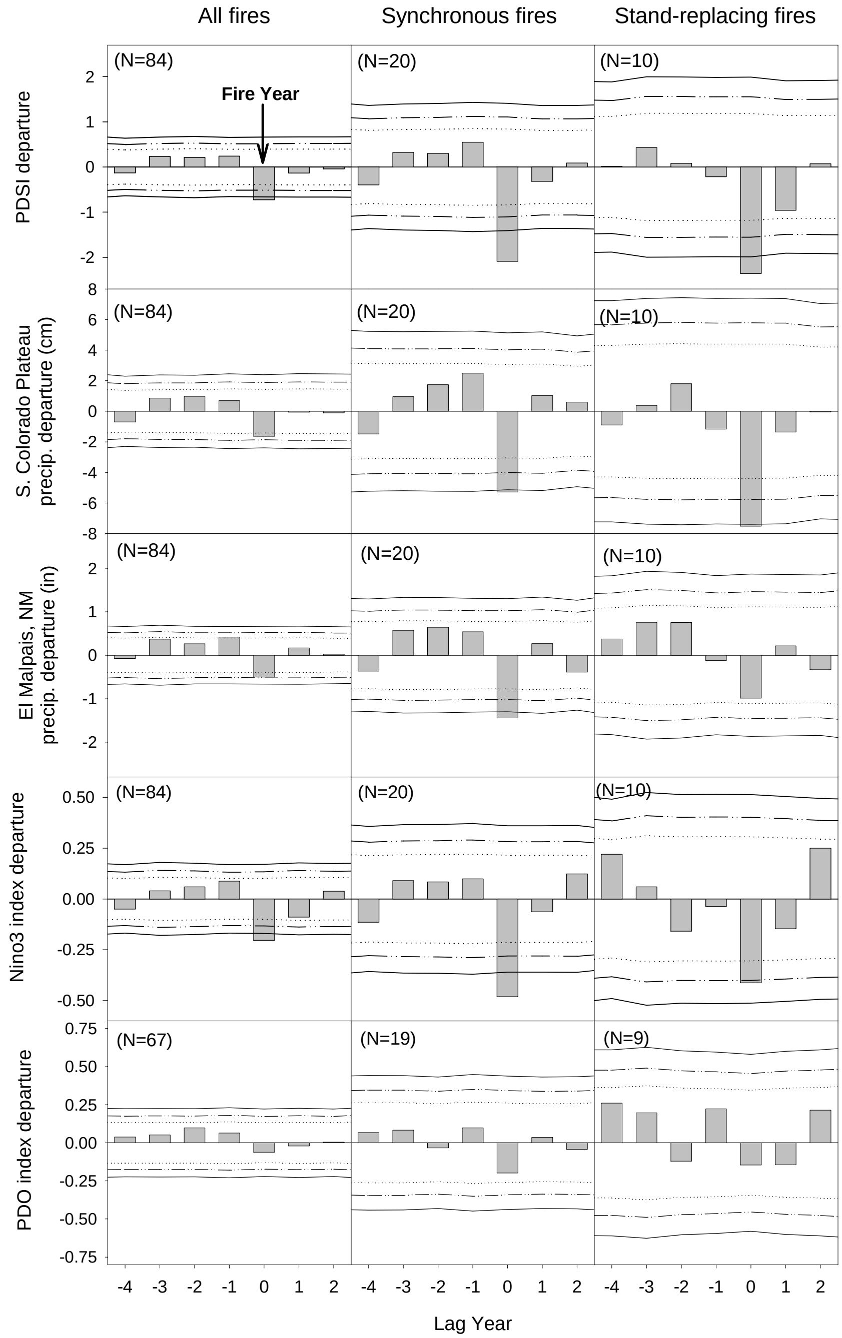

Figure 6. Superposed epoch analysis illustrating departure from the mean reconstructed climate indices (regional PDSI, Southern Colorado Plateau precipitation, El Malpais, NM precipitation Niño3 index, PDO index,) for all fire years (left), synchronous fire years (middle), and stand-replacing fire years (right). Period of analysis; all fires (1619-1906), synchronous and stand-replacing fires (1681-1906), except for PDO index analysis; all fires (1702-1906), synchronous fires (1705-1906), and stand-replacing fires (1838-1906). Dotted, dashed and solid lines represent 95, 99, and 99.9% confidence intervals derived from 1000 Monte Carlo simulations; n, number of fire years.

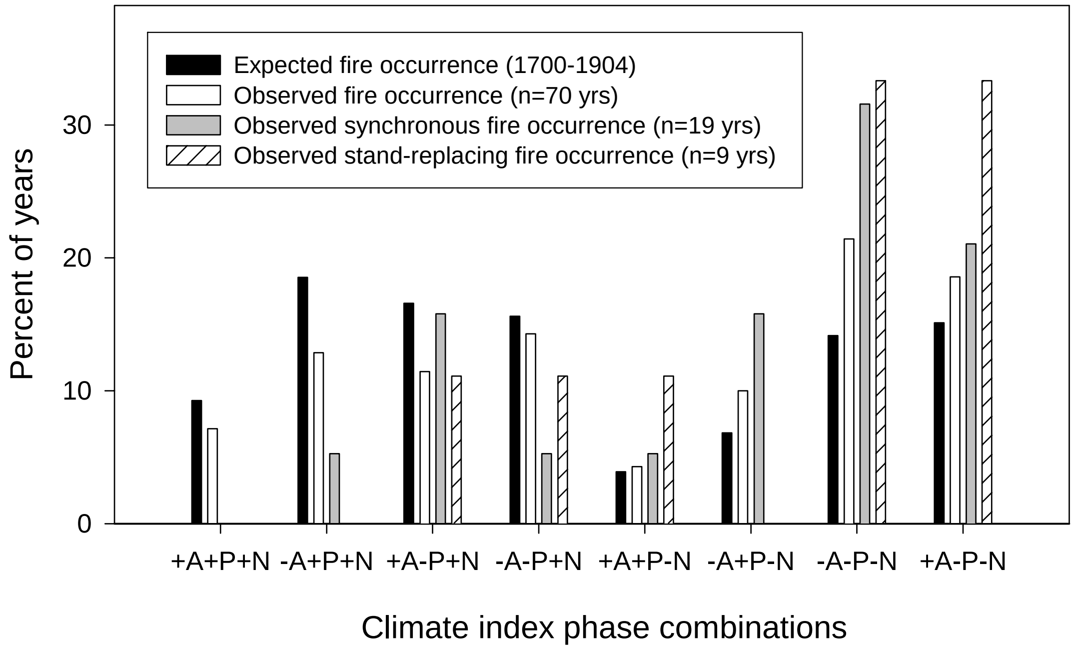

Figure 7. The percent of expected and observed number of all fire years, synchronous upper elevation fire years (i.e., fires occurring at multiple sites) and stand-replacing fire years during each of eight possible phase combinations of the Atlantic Multidecadal Oscillation (A; Gray et al., 2004), the Pacific Decadal Oscillation (P; D'Arrigo et al. 2001) and Niño3 (N; Cook et al. 2000). Expected fire occurrence was derived from the frequency occurrence of the climate phase combinations for the entire period (1700-1904).

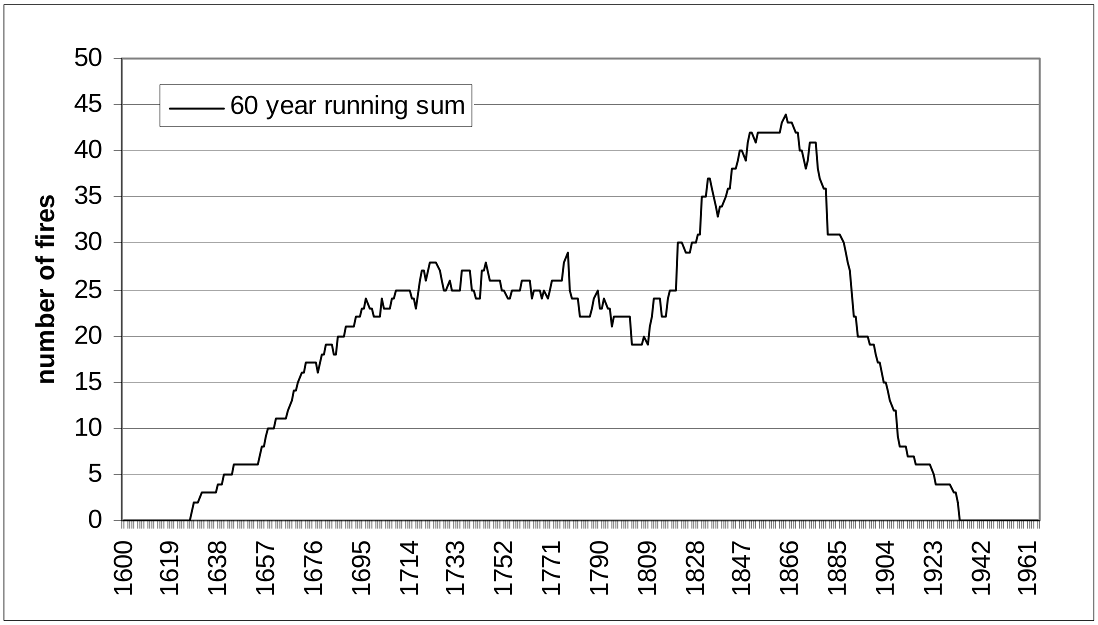

Figure 8. Sixty year running sum (plotted on yr 30) of all upper elevation fires (1600-1978). A local minimum number of upper elevation fires occurs near circa 1800, coincident with a multi-decadal negative AMO phase (Gray et al. 2004). The decline in number of fires in the early part of the record (pre-1700) is likely due to the "fading record" of tree-ring evidence of fire. The decline to zero in number of fires in the latter part of the record is not attributed to sampling, but is interpreted as a real feature of the record.