Response of Western Mountain Ecosystems to Climatic Variability and Change: The Western Mountain Initiative – Upper Santa Fe Watershed

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and

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Introduction

Forests and woodlands cover vast areas in the southwestern United States, including tens of millions of hectares of piñon-juniper, ponderosa pine, mixed conifer, and spruce-fir ecosystems. Additional scientific information on historical ranges of variability of disturbance regimes and associated ecosystem changes (Swetnam et al. 1999) are needed to guide the substantial backlog of ecological restoration work in Southwestern forests (Allen et al. 2002). Also, ongoing climate changes are expected to produce large shifts in vegetation distributions, largely due to mortality from fires, insect outbreaks, and direct dieback (Westerling et al. 2006, Breshears et al. 2006); information on past fire-climate relationships will help assessments of climate change risks to local forests. This project will study the sensitivity of mountain ecosystems to climate-induced variability and change through determination of long-term relationships between climate and fire events in northern New Mexico.

The increased vegetation stress and mortality caused by predicted climate changes are particularly expected to lead to increasing impacts from fire in the Southwest. Fire is a keystone ecological process in most Southwestern ecosystems (Swetnam & Baisan 1996, Allen 2002). Historic and prehistoric fire activity in the Southwest is known to be related to both drought episodes (Swetnam & Betancourt 1998) and warmer temperatures (Westerling et al. 2006), and any increase in drought stress in this region can be expected to result in more extreme fire events, with associated major effects on ecosystems and watersheds. Even without global change impacts, the Southwest has been experiencing increases in severe fire activity due to the increased fuel buildups associated with fire suppression efforts this century (Swetnam & Betancourt 1998, Allen et al. 2002).

However, most of our knowledge of prehistoric fire events in the Southwest comes from sampling fire scars that recorded low-intensity, high frequency fires (see review by Swetnam & Baisan 1996), although it is apparent that extensive mixed-severity and high severity crown fires also occurred in some higher-elevation Southwestern forests in the mid to late 1800s. Little is known about the frequency, extent, and climatic conditions associated with these pre-1900 mixed-severity and crown fires (but see Margolis 2003, 2007, Margolis et al. 2007), even though it is the severe fire activity that is becoming increasingly prevalent today and that will become an even more pressing issue in coming decades as expected climate changes stress Southwestern vegetation.

Much research exists for Southwestern fire regimes (Touchan et al. 1996, Allen 2002), including fire-climate relationships (Swetnam & Baisan 1996, Swetnam & Betancourt 1998, Swetnam et al. 1999). Significant variability in past fire regimes is evident, depending upon such local factors as vegetation/fuel type, topography, and land-use history. This fire regime research has explicitly worked to develop information at multiple spatial scales, ranging from individual tree samples up to 10-ha sites, watersheds, mountain ranges, and ultimately the entire Southwest region (Swetnam et al. 1999, see graphics at: http://biology.usgs.gov/luhna/chap9.html). In northern New Mexico, perhaps the largest spatial gap in the fire scar record is the Sangre de Cristo Mountains. This project will use dendrochronological approaches to reconstruct fire histories in a key area in the Sangre de Cristos – the *upper* Santa Fe River Watershed Wilderness Area, which is vitally important to the city of Santa Fe. Most of this watershed above Santa Fe is US Forest Service land (Espanola District), where they are

engaged in collaborative efforts with the City of Santa Fe and others to reduce fire risk and restore forest health, including low severity fire.

Recent fire history research in the middle-elevation ponderosa pine forests of the Santa Fe watershed (Balmat et al. 2005) has provided support for the ongoing fire hazard reduction and forest restoration project. Tree-ring analysis revealed that low intensity surface fire was an important process in these pine and xeric mixed conifer forests of the watershed for at least 700 years. Exclusion of fire by grazing and fire suppression dramatically altered these forests and increased the risk of a watershed-scale catastrophic crown fire. The ongoing fuels treatment project has begun to reduce the fire hazard in the overgrown pine forests. This consequently reduces the risk of a post-fire flood or debris flow that would jeopardize ~ 40% of the city's water supply (Grant 2002). However, the current treatment only covers approximately 60% of the watershed at high risk of crown fire.

Treatments in the remainder of the upper watershed may be necessary to ensure the future of the city's water supply and reduce the risk of post-fire flooding. The fire history of the remaining upper 40% (~ 2500 hectares) of the Santa Fe watershed is unknown, and these higher elevation mixed-conifer and spruce-fir forests almost certainly have a different historical fire regime than the middle-elevation forests studied to date. Fire history research in the adjacent Tesuque watershed and other sites in the upper Rio Grande Basin indicate that climate-driven, stand-replacing crown fire is part of the natural disturbance regime in the upper montane forests of the region (Margolis et al. 2007). Still, fire suppression in the past may have led to substantial increases in forest

density in at least portions of the upper watershed and thereby increased the risk of extensive crown fire, but details of this fire history are not yet known.

Project Goals

Our research goals were to reconstruct fire history and fire-climate relationships for the upper elevation forests of the upper Santa Fe Watershed, providing essential information to support management of these and similar nearby forests, including those of the upper Frijoles and Alamo watersheds in Bandelier National Monument. The complex topography of the upper Santa Fe watershed supports various vegetation types from xeric mixed conifer to mesic spruce-fir forests. This mosaic of vegetation types likely has a complex fire history and subsequently variability in fire hazard. Due to the restrictions of the Forest Service Wilderness Area designation of the upper watershed, mechanical fuels treatment is not permitted and prescribed fire would likely be the management tool of choice. This situation is similar to that of the high-elevation forests found in the Cerro Grande area of the upper Frijoles watershed in Bandelier National Monument, where the park's revamped fire management program is working to reintroduce fire in a similarly difficult landscape setting. Improved understanding of fire history in the upper Santa Fe River watershed is needed to determine fire regime patterns, including climate drivers, over the past several centuries in this area. Knowledge of the extent and frequency of past surface fires or crown fires would be valuable to help determine what types of prescribed fire treatments during a restoration phase could be appropriate (and in what areas), and what types of future "natural" fires or "maintenance" prescribed fires would be appropriate. More generally, it is widely recognized that knowledge of past fire history is a fundamental starting point for developing wilderness

fire plans, regardless of whether naturalness, resource utilization, or other objectives are primary considerations (Parsons et al. 1986, Agee 1993, Swetnam et al. 1999).

High quality data and graphical information on the fire and vegetation history of this watershed will benefit ongoing and future hazard fuel reduction efforts in the local area (including at Bandelier National Monument), helping to garner additional public and project financial support. The information developed by this research on fire-climate relationships, spatial patterns of fire activity across topographic and elevational gradients, and little-known histories of mixed-severity fire events will also help support the objectives of the new fire management plan at Bandelier to reintroduce fire to the park's high elevation forests. This information will also be valuable for all fire and land managers in northern New Mexico.

Study area:

The study area (2669 ha) was located in the upper Santa Fe River Watershed, defined by the Pecos Wilderness Area and natural watershed boundaries (Figure 1). The watershed is located on the west slope of the Sangre de Cristo Mountains northeast of the city of Santa Fe, NM, near the southern extent of the range. Vegetation types transitioned from mesic, spruce-fir forests (>3000m) in the upper half of the study area to more arid pine and mixed conifer forests (<3000m) on south aspects in the lower half.

<u>Methods</u>

Due to the complexity of vegetation types and associated fire regimes in the upper watershed a combination of tree-ring methods were necessary to reconstruct the fire history. Fire scar-based methods were used to reconstruct surface fire frequency, seasonality, and extent for the more xeric, mixed-confer portions of the watershed.

However, fire-scarred trees are rare or non-existent in upper elevation spruce-fir forests for two reasons: 1) high severity, high intensity, stand-replacing crown fires destroy (kill and burn) direct tree-ring evidence of past fires and 2) the thin bark of spruce and fir species is more susceptible to being fatally girdled by even low-intensity fire, thus leaving no evidence of the most recent fire (e.g. fire scars).

In forest types where fire scars are not abundant, age structure-based fire history methods are commonly applied (Heinselman 1973; Agee 1993; Johnson & Gutsell 1994, Margolis et al. 2007). This method dates the origin of tree cohorts that regenerated following the stand-replacing fire event. We used labor-intensive age structure sampling to determine the age of forest patches that potentially regenerated after the last standreplacing fire. Satellite imagery, aerial photography, and field observations were used to predetermine potential post-fire forest patches. We used dendroecological methods to determine the age of the oldest trees, thereby estimating the time since the last fire. Age structure data alone is often not sufficient to determine if the forest patch was a poststand-replacing fire cohort and ultimately date the fire. This is because spruce and fir trees may take years to decades to regenerate following a fire. Due to the long return intervals (100 yrs to > 400 yrs) of crown fire regimes (Turner & Romme 1994), decadal precision of fire dates is still valuable. However, annually-precise fire dates may be determined if fire scars, fire-killed trees or injured trees are present in adjacent areas, unburned patches or lower on the landscape (Johnson & Gutsell 1994, Margolis et al. 2007).

Sampling design

We designed a sampling scheme to test for relationships between forest age in the upper elevation (>3000m) spruce-fir forests and annually resolved historic fire dates. Historic fire dates were derived from direct tree-ring evidence of fire (e.g., fire scars) and indirect evidence of fire (e.g., resin ducts and growth changes in the rings of trees that survived the fire). To estimate forest age we used a systematic, gridded sampling design (Figure 1). We generated a 1 km grid beginning with a random location in the study area. The grid was oriented along cardinal directions to facilitate navigation in the field. Two grid points (24 and 28) initially fell within unforested vegetation types and were relocated 50 km inside the nearest forested area.

In the topographically complex mountains of the semi-arid southwest U.S., aspect can be an important variable in determining vegetation and fire regimes through effects on moisture availability. To ensure that the distribution of aspect class (N,S,E,W) at our sample points was proportional to the relative abundance of aspect classes in the study area we stratified the sampling grid by aspect class. The percent of sample points in the four primary aspect classes was distributed similar to the percent of land area in each aspect (Figure 2), with a slight over (under) sampling of east (south) facing slopes compared to relative presence in the study area.

To determine stand age at each grid point we collected increment cores from the 20 largest (diameter at breast height (dbh)) trees along a 100m by 20m belt transect. The transect was centered on the grid point and the long axis was oriented parallel to the contour of the slope (i.e., sideslope). The location of the sampled trees along the transect was recorded. To determine tree age increment cores were collected as close to the base of the tree as possible (<0.3m). We angled the borer down to intersect the root crown in

an attempt to sample all the years of tree growth. To further increase the accuracy of tree age we re-sampled trees until we extracted a core containing rings estimated to be within 10 years of the pith ring.

In the lower elevation (<3000m) pine and mixed conifer forest portion of the study areas we did not collect age structure as described above. In contrast to the upper elevation forests, fire-scarred trees were present in these drier forest types and were determined to be the best evidence of the fire history. Although present, fire scarred trees were not abundant, even in the drier, lower elevations of the upper watershed. We did not locate any fire-scarred trees within 50 m of the low elevation gridpoints we visited (1, 2, 6, and 7). Because of the relative scarcity of fire scars we used a targeted sampling approach. Fire scarred trees were most abundant on ridges, apparently because fire intensity was lower and allowed trees to survive fires that were otherwise stand-replacing on the adjacent steep slopes. We searched and sampled ridges with the gloal of obtaining a relatively even distribution of fire scar plot locations and to maximize the length of the fire history record. The final spatial distribution of the fire scar sample plots was ultimately determined by the distribution of the samples and therefore is not evenly distributed.

Where fire-scarred trees and remnant wood were present we used a plot-based sampling approach. Samples from multiple trees were collected within a 50 m search radius that defined the plot. Collecting multiple trees within a plot increased the probability of recording all fires that actually occurred in that area. This is necessary because trees are imperfect recorders of fire and individual trees may not record all fires (as fire scars) that burned around the tree. Wedges and cross-sections were collected

with a cross-cut saw from fire scarred logs, stumps and rarely from live trees using standard procedures for fire scar collection in wilderness areas (e.g. Baisan & Swetnam 1990).

Lab methods

All tree-ring samples were prepared and cross-dated using standard dendrochronological procedures (Stokes & Smiley 1968). The date of the first year of growth was estimated for increment cores that did not contain the pith ring using the concentric circle technique (Applequist 1958). Cores that were estimated to be greater than 30 years from the pith ring were not included in the age structure data. The error associated with the age to core height was assumed to be minimal and not estimated, because cores were collected at a downward angle to intercept the root crown. For fire scar samples the approximate season of fire occurrence was determined by analyzing the relative position of each scar within the annual growth ring (Baisan & Swetnam 1990).

A qualitative description of the initial growth of cored trees (i.e., Open, Moderate, Suppressed) was recorded to provide information regarding the growth environment when trees were established. Although spruce and fir species are shade tolerant and are able to survive in low light conditions under canopies, the growth rates in these conditions are very slow (i.e., suppressed). Growing conditions for trees germinating in open forest, such as following a stand-replacing fire, would be more favorable and should be indicated as relatively large initial ring growth (i.e., Open). This information was used in conjunction with tree age and fire dates to determine if trees were likely part of post stand-replacing fire cohorts.

Data Analysis

The fire scar data was entered into a fire history database developed by Richmond (2004) and analyzed using FHX2 software (Grissino-Mayer 2001). Because fire scar data are rarely normally distributed and more commonly fit a Weibull distribution (Grissino-Mayer 1999), FHX2 tests for the fit of this model and estimates fire interval parameters from the model. Central tendency parameters (mean, median and Weibull median) of fire frequency were calculated for multiple filtered subsets of the composite fire history data (e.g., minimum of 2 trees scarred, 20% of recording trees scarred). "Recording trees" refers to fire scarred trees that have intact wood (i.e., not burned away or missing pieces) and an open wound (not covered by bark) during the time period in question. Many montane conifers have thick bark that protects trees from damage to the cambium by fire. These full-bark trees may not record fires as fire scars, while the same fire is recorded on adjacent trees with an open "cat face" fire scar wound.

Filtering the fire scar data by the percent of recording trees scarred is used to infer widespread fires, versus small fires that only scar a relatively small number (percent) of trees. Widespread fires are thought to be more ecologically important because of the extent of the effects. Too few fire-scarred trees were present on the landscape and/or collected to enable plot-based fire frequency analyses. This approach has benefits compared to a full site composite analysis because it provides a better description of spatial variability within a site. Future field sampling at this site will be aimed at increasing the fire scar sample size so that a plot-based analysis will be possible. Because fire intervals vary over time with fuels and climate, central tendency statistics (e.g., mean fire interval) can oversimplify historic fire regimes. We also report additional statistics (e.g., minimum and maximum fire intervals) and interpret these data in terms of

fire management to provide a better understanding of the historic range of variability of the fire regime.

We used superposed epoch analysis (SEA)(Baisan & Swetnam 1990) to test for relationships between fire occurrence and four climate variables. Palmer Drought Severity Index (PDSI) is a commonly used measure of available moisture in North America (Palmer 1965). Summer (June – August) PDSI is a good indicator of premonsoon moisture conditions that determine fire risk in the Southwest. A 2.5° gridded tree-ring reconstruction of PDSI exists for much of North America and in the Southwest it extends hundreds of years prior to the 20th century instrumental climate data (Cook et al. 2004). PDSI gridpoint 133 is nearest to our study site and is used in the SEA analysis. A tree-ring based precipitation reconstruction from El Malpais, NM (Grissino-Mayer 1996) was also used as a sub-regional climate variable.

Indices of Pacific Ocean-atmosphere oscillations (e.g., El Niño/Southern Oscillation (ENSO) and the Pacific Decadal Osciallation (PDO)) that have been shown to affect climate variability in both the instrumental and paleo-climatic record in the Southwest were also used as variables in the SEA analysis. As a proxy index for 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). 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).

Results

Fire scars

In the lower elevation (<3000m) pine and mixed conifer forests we collected 25 fire scar samples from 23 conifers at 12 locations (Figure 3). This is in addition to samples previously collected within the Wilderness area by Balmat et al. (2005). We were able to cross-date and analyze fire scar samples from 31 trees. A total of 69 fire scars in 25 unique fire years were identified (Table 1). The full tree-ring chronology covers 595 years (1412-2006) and the oldest cross-dated fire scar was 1495 and the most recent was 1879 (Figure 4). The period from 1595 to 2006 was chosen for fire interval analysis based on sample size and the number of recorded fires.

The season of fire occurrence was determined for 41 (60%) of the fire scars (Table 2). The remaining fire scars were in poor condition or were in rings too narrow to accurately determine the season. The dominant ring position of the fire scars when the season could be determined was dormant (i.e., between ring boundaries). All remaining fire scars were in the earlywood portion of the ring and the majority of those were in the first third of the earlywood (early earlywood). All fire years recorded in the dormant season in one tree and within the growing season in a separate tree were earlywood fires. This indicates that most fires were burning in May or June, at the beginning of the growing season. Predominant occurrence of spring or early summer fires is widely supported by fire seasonality data from observed 20th century fires (Barrows 1978) and from many tree-ring reconstructed fires in the southwest U.S. (Swetnam & Baisan 1996).

Based on our observations and conventional season of montane fire occurrence in the region, all fire scars only recorded in the dormant season were assigned to the spring/summer of the next year (ring) instead of late summer/fall of the previous year (ring).

Fire interval statistics were calculated for 5 sets of the Wilderness Area composite fire history data: 1) all fires, 2) fires recorded by a minimum of 2 trees, 3) fires recorded by a minimum of 2 trees and 10 percent of recording trees, 4) fires recorded by a minimum of 2 trees and 20 percent of recording trees and 5) fires recorded by a minimum of 2 trees and 25 percent of recording trees (Table 3). Because of relatively small sample size (e.g., 18 fire intervals for all fires) the fire intervals statistics for fires recorded by 10 percent and at least 2 trees was identical. The Weibull model adequately fit the fire scar data, but the differences between the arithmetic mean, median and the Weibull median fire intervals are minimal. As expected, increasingly exclusive filters increased the values of all statistics such that the Weibull median fire interval increased from 15 years (all fires) to 40 years (fires recorded by 25 percent of the trees). Minimum (maximum) fire intervals increased from 1 to 16 years (31 to 94 years) for the same data sets. The differences between fire intervals among the 5 data sets are discussed later in the paper.

Age structure

We collected 240 cores from 188 trees at 9 age structure transects and 3 additional locations containing quaking aspen (Figure 3). All of the age structure transects were located in the upper half of the study area (>3000m), in forest types dominated by Engelmann spruce and sub-alpine fir with no *Pinus spp* present. Direct evidence of fire

(e.g., fire scars or charred wood) was not present within or between the upper elevation age structure plots we sampled (9 of 14 total upper elevation grid points).

We were able to estimate pith dates for 168 (90%) of the 188 trees sampled. Cores from the remaining 10% of the trees had no curvature in the inner rings or were estimated to be greater than 30 years from the pith so the number of rings to pith could not be estimated. The collective age structure data, presented as both inner-ring dates and estimated pith dates, are similar graphically (Figure 5). Estimated pith dates are presented and discussed in the remainder of the paper because these data are better estimates of the cohort establishment dates and potentially of time since fire.

The collective age structure from all 9 transects indicates that the majority of the establishment of the dominant trees in upper portion of the Wilderness area occurred between circa 1700 and the mid-1800's (Figure 5b). Very few of the dominant trees established prior to circa 1650 and after circa 1900. The small number of living trees (3) pre-dating 1650 suggests that a disturbance (e.g., drought, fire, or insect outbreak) may have truncated the age structure, since both Engelmann spruce and Douglass fir are capable of living for at least 400 years and in many cases much longer.

Evidence of stand-replacing fire

The age structure of dominant trees at the individual transects illustrates spatial variability and the possibility of stand-replacing disturbance in multiple locations within the upper half of the Wilderness area (Figure 6). Five transects (11 and 20-23) had no living trees that pre-date 1685, a reconstructed fire year. Three of the four transects with trees that pre-date 1685 (15, 24, and 29) show growth changes or injuries in the tree-rings in 1685 (e.g., Figure 7). The 1685 fire was recorded as fire scars at two locations in the

lower half of the Wilderness area and at all 12 recording fire scar plots in the watershed below the Wilderness boundary (Balmat et al. 2005). The combination of age structure, growth changes/injuries, and widespread fire scar evidence suggests that the 1685 fire was relatively large and stand replacing in parts of the upper watershed.

Other fires that were widespread throughout the watershed (i.e., recorded by > 50% of fire scar plots above and below the wilderness boundary; 1842 and 1748) showed no clear evidence of stand-replacement in the upper portion of the Wilderness area. Age structure transects with many trees that pre-date these fires suggests that these widespread fires in the mid-elevation mixed-conifer and pine forests did not burn in the upper elevations.

Fire-climate

The results of the SEA indicate that all four sets of fire scar data (all fires, 10%, 20%, and 25% scarred) were significantly associated with negative (dry) departures during the fire year from mean summer PDSI and El Malpais, NM precipitation (Figure 8). All four sets of fire scar data were also associated with positive (wet) departures two to three years prior to the fire year from mean summer PDSI and El Malpais, NM precipitation. All sets of fire scar data were associated with negative (cool ocean phase – La Niña) SST departures from the mean Niño3 index during the fire year and positive (warm ocean phase – El Niño) SST departures three to four years prior to the fire year. Fire occurrence was not associated with inter-annual variations in PDO (results not shown), but low sample size (n = 11, 6, 5 and 3 fire years) makes these results less robust.

Discussion

Very little age structure and/or fire history data exist for old-growth spruce-fir forests of Arizona and New Mexico, so comparisons are limited. Age structure data do exist for the spruce-fir in the Pinaleño Mountains in southeastern Arizona (Grissino-Mayer et al. 1995, Stromberg & Patten 1991, Margolis 2007) and the Mogollon Mountains in the Gila Wilderness Area of southwestern New Mexico (Margolis 2007). These forests types have not experienced significant stand-replacing disturbance in at least 300 years (excluding recent fires), similar to the upper Santa Fe Watershed. The data in the Gila were insufficient to date the stands to a fire event, but the Pinaleño spruce-fir stand regenerated after a stand-replacing fire in 1685, the same year as the stand-replacing fire in the upper Santa Fe Watershed. 1685 was a remarkably widespread and severe drought year throughout the Southwest (Cook et al. 2004) (Figure 9). This climate event synchronized these rare stand-replacing fire events hundreds of kilometers apart.

The watershed north of the study area, the Tesuque watershed, last burned in a crown fire in 1879, with evidence of prior fires in some areas (Margolis et al. 2007). We collected fire scar evidence from two locations in the mixed conifer forest on the northwest side of the Santa Fe watershed indicating that the 1879 fire crossed the ridge that divides the two watersheds. There is no evidence from the age structure data that this fire, which was extensive and severe in the high elevation forests of the adjacent watershed, burned with stand-replacing severity in the upper Santa Fe Watershed. Age structure data from the lower half of the Wilderness area, near where the 1879 fire scars were collected, would be necessary to determine if this fire or other fires were stand-

replacing in the mixed-conifer forests of the watershed. Although the adjacent watershed and multiple other high elevation forests in the upper Rio Grande Basin burned in high severity fires in the 19th century (Margolis et al. 2007), the Santa Fe Watershed has not had a widespread stand-replacing fire for over three hundred years.

Interpreting fire interval statistics

Interpretations of fire-scar based fire history data can be difficult and have been the topic of much debate (Baker & Ehle 2001). Recent studies have compared fire-scar based reconstructions and mapped 20th century fire atlas data (Farris in prep.) as well as different sampling strategies (e.g., gridded versus targeted) (Van Horne & Fule 2006). The results indicate that fire scars, regardless of the sampling approach, are remarkably accurate at detecting the "widespread" fires that are arguably the most ecologically significant. While it is true that a fire occurs every year in many mountain ranges of the southwest U.S. (e.g., Sky Island ranges of southern Arizona and New Mexico), most of these fires are very small, hard to reconstruct with fire scars, and are not an important ecological process at the landscape scale. The fires that ecologist and natural resource managers are concerned about are the widespread fires that burn large portions of the landscape and affect vegetation, wildlife, and watersheds. These fires are recorded remarkably well by fire-scarred trees.

Information regarding the strength of the fire scar record is vital to consider when interpreting reconstructed fire return interval data. Fire intervals statistics based on "all fires," without filtering, include many small fires and should be interpreted with caution. For example, the mean fire interval in our study area, calculated using all fire scars (15 years), does not indicate that a fire burned the entire study area every 15 years. It means

that based on our sampling a fire occurred somewhere in the lower half of the study area on average every 15 years and many of these fires were likely small since they were only recorded by a single tree. Another flaw of the composite mean fire interval based on all fire scars is that it is dependent on the size of the study area and on the intensity of the sampling effort (Falk 2004). Increasing the number of fire scars collected increases the number of fires that will be recorded, until theoretically the mean fire interval will reach 1 year for a large enough study area (e.g., a fire burns somewhere every year in the southern Sangre de Cristos). An additional problem with the *mean* fire interval is that it implies periodicity or regularity of fire occurrence, which is not supported by tree-ring reconstructed fire histories or modern data. For example, the fire return intervals calculated from all fires ranged from 1 year up to 31 years, approximately twice the *mean* fire interval (15 yrs).

To avoid the problems associated with interpretations of fire interval data generated from all fires, we filter the fire scar record as a percent of trees recording a fire. This highlights the widespread fires that are recorded by multiple trees at multiple points across the landscape, which are the fires of interest. In the lower half of the Santa Fe Watershed Wilderness Area fires scarring between 10% and 25% of recording trees occurred on average every 30 to 40 years. A fire gap of 74 years (10% scarred) to 91 years (25% scarred) occurred in the late 18th-early 19th centuries and the minimum time between widespread fires was 16 years (10% scarred).

All fire interval statistics for the 10% to 25% scarred filter classes in the mixed conifer forests were approximately twice that of the adjacent pine-dominant midelevation forest below the Santa Fe Watershed Wilderness boundary (Balmat et al. 2005).

Differences in fire interval statistics could be a function of differences in study area size or sampling intensity, but because we compared widespread fires these problems should be alleviated. Upper elevation mixed-conifer forests in the Southwest generally have longer fire intervals than mid-elevation pine-dominant forests (Swetnam & Baisan 1996), which can be explained by increased moisture at higher elevations and consequently less frequent occurrence of drought conditions severe enough to sustain fire spread.

Fire-climate

The relationship between fire occurrence and dry conditions during the fire year is intuitive and common among fire history reconstructions in Southwest montane forests (Swetnam & Baisan 1996). The lagged relationship with wet conditions is less intuitive, but also well replicated from fire history studies throughout the Southwest pine-dominant forests (Swetnam & Baisan 1996). Wet years increase fine fuels (e.g., grass and pine needles) that carry fire, which are subsequently burned during dry years. This antecedent wet-year relationship is not present in high elevation sub-alpine forests and upper montane seral aspen/mixed conifer forests of the Southern Rockies (e.g., Sibold et al. 2006, Margolis et al. 2007). These mesic forest types are generally not fuel limited, but require extreme drought for fire occurrence. A similar drought-only fire-climate relationship exists at multiple mixed-conifer fire history sites in the region (Swetnam & Baisan 1996). The antecedent wet year fire-climate relationship in the lower half of the Santa Fe Watershed Wilderness Area was somewhat surprising because much of the area is mixed conifer forest. This result suggests that variability in fine fuels may have been important for fire occurrence (i.e., the system was fuel limited).

But how can a fire regime with a 30 to 40-year mean return interval for widespread fires be fuel limited? Thirty years in a mixed-conifer forest should be sufficient to produce enough fuel to sustain fire spread, even in the semi-arid Southwest. It is possible that due to the topographic heterogeneity of the landscape, a wet year followed by drought was needed to produce sufficient fuel on the dry south aspects to connect the more productive forest patches and allow fire to burn across aspect and forest types (i.e., widespread fire).

An alternative explanation invokes anthropogenic influence, which was known to be substantial during the entire period of fire interval analysis (1595-2006). The Spanish colonization period was much earlier in the Rio Grande Valley than in other parts of west due to travel along the Camino Real that connected Santa Fe with the Mexico City. Grazing reduces fine fuels that carry surface fires and can eliminate fire occurrence even in areas with a long history of frequent fire (e.g., Savage & Swetnam 1990). It is possible that due to the proximity of the study area to the city of Santa Fe and a history of grazing in the watershed that sufficient wet periods were necessary to replenish the fuels removed by grazing so that fires could spread, even in these relatively productive, mesic upper elevation mixed-conifer forests.

A third explanation for antecedent wet years being associated with fire occurrence may be an artifact of the oscillatory nature of the climate system. Antecedent El Niño events were associated with historical fire occurrence on La Niña years. The oscillation from warm to cold eastern equatorial pacific SST's and associated wet and dry winter teleconnections in the Southwest are well documented in the instrumental and paleoclimate record, occurring most frequently with a 2 - 7 year periodicity (Diaz & Markgraf

2000). Thus, if dry and wet conditions driven by oscillations in ocean temperature occur on average every two to seven years then it is probable that for any given dry year there was a preceding wet year within a window of two to seven years. Thus, the alternative hypothesis is that fire occurrence is only linked to drought conditions and that antecedent wet years occur regularly before drought years due to the oscillatory nature of the ENSO teleconnection. This hypothesis could be tested by selecting random draws of drought years as "fire event years" and running the SEA. If wet years still precede the artificial fire years more than would be expected by chance then this pattern may be an artifact of the climate system.

Conclusions

Widespread fires (20% scarred) occurred half as frequently in the mixed-conifer forests of the lower half of the Wilderness Area (WMFI = 33yrs) compared to the pinedominant forests below the Wilderness boundary (WMFI = 16 yrs). Multiple lines of tree-ring evidence including 1) spruce-fir forest age structure, 2) growth changes/injuries, and 3) fire scars recorded throughout the lower mixed-conifer and pine-dominant forests indicated that a widespread fire in 1685 was stand-replacing in more than half of the sampled upper elevation spruce-fir forests. Although other widespread fires occurred in the mid-elevation of the watershed (e.g., 1748 and 1842), drought and fire weather conditions were not sufficiently extreme for these fires to burn into the upper elevation spruce-fir forests. Extreme drought presumably combined with extreme fire weather (i.e., high winds) was widespread during 1685 and synchronized crown fires in spruce-fir forests of multiple, distant mountain ranges in the Southwest. Inter-annual fire-climate analyses indicate that widespread fires recorded by fire scars in the mixed-conifer forests

occurred on drought years preceded by wet years and that these wet/dry oscillations may be driven by the El Niño/Southern Oscillation. All conclusions are based on a partial sampling of the Santa Fe Watershed Wilderness Area and completion of the sampling will be necessary to confirm the results and add critical details, particularly regarding historical fire extent, which is vital for fire and forest management applications.

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Century	<1600	1600's	1700's	1800's	1900's
Fire years	1495, 1516, 1542, 1546, 1579, 1587, 1599	1608, 1619, 1622, 1624, 1654, 1685	1700, 1716, 1729, 1748, 1773, 1795	1819, 1820, 1842, 1857, 1860, 1879	

Table 1. Santa Fe Watershed Wilderness Area fire scar dates.

	Number of fire		Percent of samples with
Scar position	scars	Percent of total	season determined
Dormant	20	29.0	48.8
Early earlywood	9	13.0	22.0
Middle earlywood	6	8.7	14.6
Late earlywood	6	8.7	14.6
Latewood	0	0.0	0.0
Undetermined	28	40.6	

Table 2. Fire scar seasonality.

	Number	Mean	Median	Weibull		
Filter	of	fire	fire	median	Minimum	Maximum
	intervals	interval	interval	fire interval	interval	interval
all scars	18	15.56	15.5	13.56	1	31
2 trees	9	31.11	30	29.69	15	71
10%	9	31.11	30	29.69	15	71
20%	7	34.71	30	33.31	16	71
25%	6	40.5	31	37.18	16	94

 Table 3. Fire interval analysis statistics (1595-2006).

	All fires	100/ gaarrad	2004 gaarrad	25% soorrad
	All lifes	10% scalled	20% scalled	25% scalled
El Malpais, NM precipitation	1489 - 1883	1489 - 1883	1489 - 1883	1489 - 1846
Niño 3 index	1602 - 1883	1618 - 1883	1618 - 1833	1618 - 1846
PDO index	1700 - 1883	1700 - 1883	1700 - 1883	1700 - 1846
PDSI gridpoint 133	1489 - 1883	1489 - 1883	1489 - 1883	1489 - 1846

Table 4. Period of analysis for SEA fire-climate analyses.



Figure 1. Sampling grid (1 km grid point spacing) used to sample forest age structure for stand-replacing fire history reconstruction in the upper Santa Fe Watershed, NM. The 3000 m elevation contour approximates the ecotone between the spruce-fir and the mixed conifer forests.



Figure 2. Percent of study area (left) and sample grid points (right) in four aspect classes.



Figure 3. Location of age structure transects (>3000m) and fire scar plots (<3000m) sampled for fire history reconstruction.



Figure 4. Historical fire occurrence in the lower half of the Santa Fe Watershed Wilderness Area. Each horizontal line is a tree and each vertical line is a dated fire scar. The composite fire chart (bottom) indicates only "widespread" fires recorded by two or more trees and at least 20% of the trees recording fire.



Figure 5. Age structure of the dominant trees (largest diameter at breast height) from the upper half of the Santa Fe Watershed Wilderness Area. Data are pooled into 10-year classes (plotted on center) and presented as inner-ring dates (a) and estimated pith dates (b). Data include all trees from all sampled age structure plots (see Figure 3).



Figure 6. Age structure of the dominant trees at individual transects (e.g., 11) from the Santa Fe Watershed Wilderness Area. The lack of trees pre-dating the 1685 fire at five of the nine transects suggests that this fire was stand replacing in parts of the upper watershed. Three of the four transects with older trees (15, 24, and 29) had growth changes or injuries in the tree-rings in 1685 (see Figure 7). Tree age data are pooled into 10-year classes (plotted on the last year of the decade) and presented as estimated pith dates.



Figure 7. Tree ring growth release in a Douglass fir core inferred to be a result of reduced competition following tree mortality from the 1685 fire.



Figure 8. Superposed epoch analysis illustrating departure from the mean of reconstructed climate indices (PDSI, El Malpais, NM precipitation, and Niño3 index) for all fire scars, 10% scarred, 20% scarred, and 25% scarred. See Table 4 for periods of analysis. 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 9. Tree-ring reconstructed Palmer Drought Severity Index map illustrating severe and widespread drought in the southwest United States during 1685, the year of the reconstructed stand-replacing fire in old growth spruce-fir forests of the upper Santa Fe Watershed.