Research Article

Historical Stand-Replacing Fire in Upper Montane Forests of the Madrean Sky Islands and Mogollon Plateau, Southwestern USA

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ABSTRACT

The recent occurrence of large fires with a substantial stand-replacing component in the southwestern United States (e.g., Cerro Grande, 2000; Rodeo-Chedeski, 2002; Aspen, 2003; Horseshoe 2, Las Conchas, and Wallow, 2011) has raised questions about the historical role of stand-replacing fire in the region. We reconstructed fire dates and stand-replacing fire patch sizes using four lines of tree-ring evidence at four upper montane forest sites (>2600 m) in the Madrean Sky Islands and Mogollon Plateau of Arizona and New Mexico, USA. The four lines of tree-ring evidence include: (1) quaking aspen (*Populus tremuloides*) and spruce-fir age structure, (2) conifer death dates, (3) traumatic resin ducts and ring-width changes, and (4) conifer fire scars. Pre-1905 fire regimes in the upper montane forest sites were variable, with drier, south-facing portions of some sites recording frequent, low-severity fire (mean fire interval of all fires ranging from 5 yr to 11 yr among sites), others burning with stand-replacing severity, and others with no evidence of fire for >300 yr. Reconstructed fires at three of the four sites (Pinaleño Mountains, San Francisco Peaks, and Gila Wilderness) had stand-replacing fire patches >200 ha, with maximum patch sizes ranging from 286 ha in mixed conifer-aspen forests to 521 ha in spruce-fir forests. These data suggest that recent stand-replacing fire patches as large as 200 ha to 500 ha burning in upper elevation (>2600 m) mixed conifer-aspen and spruce-fir forests may be within the historical range of variability.

Keywords: fire history, mixed conifer, quaking aspen, spruce-fir, tree ring

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INTRODUCTION

The number and duration of large fires in the western United States has increased in recent decades due in part to increasing temperatures (Westerling *et al.* 2006). In the southwestern US (Arizona, New Mexico, and proximate areas), many of the recent large fires included large (100 ha to >1000 ha) high-severity fire patches, which raises questions about the historical role of stand-replacing fire in the region. Many of the recent stand-replacing fire patches in the southwestern US have occurred in the overstocked, mid-elevation ponderosa pine (*Pinus ponderosa* C. Lawson) and dry mixed conifer forests, where extensive stand-replacing fires are unreported in the documentary records prior to *circa* 1950 (Cooper 1960, Allen *et al.* 2002). However, in the upper elevation (>2600 m) mixed conifer-aspen and spruce-fir forests, historical photographs and tree-ring data from seral quaking aspen (*Populus tremuloides* Michx.) stands provide direct evidence that fires with large (100 ha to >1000 ha) stand-replacing patches occurred in parts of the region as recently as the early twentieth century (Abolt 1997, Romme *et al.* 2001, Margolis *et al.* 2007).

Relatively little is known about pre-EuroAmerican settlement fire regimes (size, severity, frequency, and seasonality) of upper elevation forests in the southwestern US (Grissino-Mayer *et al.* 1995, Fulé *et al.* 2003, Margolis *et al.* 2007, Margolis and Balmat 2009). Extensive fire histories from upper montane and subalpine forests of southern Wyoming, Colorado, and northern New Mexico indicate that infrequent (>100 yr intervals) stand-replacing fire is a dominant disturbance in upper elevation forests of the southern Rocky Mountains (Kipfmueller and Baker 2000, Sibold *et al.* 2006, Margolis *et al.* 2007). Thus, it is logical to hypothesize that upper elevation mixed conifer-aspen and spruce-fir forests of the southwestern US outside of the southern Rocky Mountains potentially had a historical fire regime that included infrequent, relatively large (>100 ha) patches of stand-replacing fire.

Reconstructing Stand-Replacing Fire

Age-structure-based methods for reconstructing fire history were developed in coniferous subalpine and boreal forests of North America where stand-replacing fire regimes are dominant (Clements 1910, Heinselman 1973, Agee 1993, Johnson and Gutsell 1994). By definition, stand-replacing fires leave few or no surviving trees to record direct evidence of those fires within the highest burn severity patches (but note that fire-scarred survivors can sometimes be found on the edges of such patches; e.g., Margolis *et al.* 2007). Post-fire tree cohorts, assumed to have established soon after the fire, are the most common type of evidence used to date and map stand-replacing burns. In the Rocky Mountains, the assumption that there is typically rapid recruitment of a post-fire cohort (i.e., <5 yr) within stand-replacing burn patches is well supported in the case of quaking aspen, because it has evolved mechanisms for rapid regeneration, and has been commonly observed to do so following fires (Clements 1910, Patton and Avant 1970). Post-fire cohort evidence (dates and mapped perimeters) can be combined with the relatively rare direct conifer evidence of fire (e.g., fire scars, tree death dates, ring-width changes or traumatic resin ducts) to reconstruct annually resolved stand-replacing fire dates (Johnson and Gutsell 1994, Margolis *et al.* 2007).

In the current study, we separate the upper elevation forest into mixed conifer-aspen (2600 m to 3100 m) and spruce-fir (>3100 m) because of differing fire ecology, and potentially different fire regimes and use of differing fire history methods. Age-structure-based fire history methods in mixed conifer-aspen forests have been applied in a few studies in the southwestern US, primarily focusing on quaking aspen regeneration dates as a proxy for stand-replacing fire (Abolt 1997, Romme *et al.* 2001, Margolis *et al.* 2007). Romme *et al.* (2001) reconstructed a 140-year stand-replacing fire rotation period from aspen stand age in the La Plata Mountains of southwestern Colorado. They noted that the lack of fire-scarred trees in aspen stands was a limitation to dating past fires. Abolt (1997) used coincident aspen pith dates and conifer fire scars from lower elevations to date stand-replacing fire patches in mixed conifer forests of the Mogollon Mountains of southwestern New Mexico. Margolis *et al.* (2007) combined four lines of tree-ring evidence (aspen age structure, conifer fire scars, conifer death dates, and conifer injury dates) to reconstruct synchronous, drought-related stand-replacing fire dates and patch sizes from aspen stands embedded in upper montane mixed conifer and spruce-fir forests at a network of twelve sites in the upper Rio Grande Basin (New Mexico and Colorado). These studies indicate that, because of the unique fire ecology of quaking aspen (i.e., high sensitivity to being killed by fire and ability to re-sprout), the age structure from seral aspen stands is a potential indicator of historical stand-replacing fire in upper elevation forests in the southwestern US.

Fewer studies have evaluated the effectiveness of age-structure-based fire history methods in southwestern US spruce-fir forests. In the Pinaleño Mountains, Arizona, Grissino-Mayer *et al.* (1995) used intensive, but spatially limited, age structure sampling in spruce-fir forests, combined with lower elevation fire scars, to hypothesize that the spruce-fir zone regenerated following a stand-replacing fire. Due to limited spatial coverage of the sampling, stand-replacing fire area was not estimated. Fulé *et al.* (2003) used fire scars, tree age and species, and spatial patterns of forest stands to reconstruct fire-initiated tree groups at the plot scale (20 m × 50 m), which likely originated after severe eighteenth century fires in high-elevation forests (including aspen and spruce-fir) on the north rim of the Grand Canyon, Arizona. They were not able to identify distinct fire-created stands in the study area from aerial photos or satellite data, which differs from the stand-replacing fire history methods used in the Rocky Mountains. In the Santa Fe Watershed, New Mexico, Margolis and Balmat (2009) combined a systematic spatial grid sampling of spruce-fir age structure with conifer ring-width growth changes and conifer fire scars to conclude that approximately 90% of the spruce-fir zone (1200 ha) regenerated following stand-replacing fire. These studies provide evidence of past stand-replacing fires in spruce-fir forests in the southwestern US, but leave questions about patch sizes, variability between sites, and the ability to apply fire history methods from other regions and forest types.

Fire Patch Size and Severity

Fire patch size and severity have strong influences on the ecological effects of fire on terrestrial and aquatic systems. Stand-replacing fire patch size is a key determinant of post-fire vegetation composition and structure (Agee 1993, Turner *et al.* 1994, Turner and Romme 1994). Following the extensive (>250 000 ha) fires in Yellowstone National Park, Wyoming, in 1988, the size and severity of burn patches were shown to affect overall plant cover, tree seedling recruitment, and herbaceous recruitment (Turner *et al.* 1994). High-severity 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). The size of high-severity fire patches is important in determining the probability of fire-induced flooding or debris flows (Pearthree and Wohl 1991, Cannon and Reneau 2000). Recent, large stand-replacing fires in the southwestern US have produced runoff and erosion events as much as two orders of magnitude greater than pre-fire conditions (Veenhuis 2002).

High-severity (stand-replacing) fire patches are usually part of a "mosaic" of burn severities, within fire perimeters that include moderate- and low-severity surface fire patches, as well as unburned patches (Turner and Romme 1994). For example, less than half of the 1988 Yellowstone fires burned with high severity (Turner *et al.* 1994). Reconstructing the complex spatial patterns and wide range of burn severities of pre-twentieth century fires at high resolution (i.e., less than a few hectares) is not possible. However, the largest stand-replacing fire patches often leave a persistent and identifiable legacy in the form of tree ages and, less commonly, as conifer death dates, conifer fire scars, and tree-ring growth patterns in conifers injured by the fire. From these legacies, stand-replacing fire patch sizes and dates can be reconstructed and compared with recent fires even if overall size (extent) of the entire fire is unknown.

Research Objectives

Our primary objective was to use dendroecological methods to expand the upper elevation stand-replacing fire history network of Margolis *et al.* (2007) to four new sites in mixed conifer-aspen forests (2600 m to 3100 m elevation) in the Mogollon Plateau and Madrean Sky Island regions of the southwestern US, focusing on quaking aspen as a potential indicator of the dating and patch size of past stand-replacing fires. The secondary objective was to test the utility of using spruce-fir forest age structure to expand the reconstruction of stand-replacing fires above the local elevation range of quaking aspen (>3100 m) at two test sites. We did not attempt to reconstruct a complete inventory of all historical stand-replacing fire patches at these four sites; rather, we mapped and dated the largest and potentially most ecologically significant patches.

METHODS

Study Area

To expand the existing southwestern US network of upper elevation stand-replacing fire history sites of Margolis *et al.* (2007) beyond the upper Rio Grande Basin, we selected two sites on the Mogollon Plateau and two sites from the Madrean Sky Islands (Figure 1, Table 1). The sites were selected based on the presence of the largest seral aspen stands, which potentially represented historical stand-replacing fire patches. We used the regional gap analysis program vegetation map, USDA National Forest vegetation maps, black and white and color infrared digital ortho-rectified quarter-quadrangle photographs (DOQQs) and field surveys to map and verify the largest aspen patches on the Mogollon Plateau and Madrean Sky Islands on US Forest Service land. We set the minimum aspen patch size threshold at 5 ha to eliminate smaller patches. We targeted seral aspen stands embedded within conifers to eliminate self-replacing aspen and aspen within high-elevation parklands that likely experienced frequent surface fires (Jones and DeByle 1985).

The largest potential post-stand-replacing fire aspen patches on the Mogollon Plateau were in the San Francisco Peaks (SFP) and the Mogollon Mountains (Gila Wilderness, GIL; Table 1 and Figure 2). On the Mogollon Plateau, we chose GIL as our test site for age-structure-based fire history methods in spruce-fir (>3100 m) because the patches were smaller than at SFP and required less sampling. In the Sky Islands, the Chiricahua Mountains (CHI) and the Pinaleño Mountains (PIN) had the largest potential historical post-stand-replacing fire aspen patches (Figure 2). At PIN, aspen was not present in homogeneous patches; rather, aspen stems were scattered throughout the mixed conifer forest, potentially representing older stand-replacing fire patches that had infilled with conifers. The PIN contains the only spruce-fir forest in the Sky Islands, which we used as the second test site for spruce-fir fire history methods.

Mean elevation of the study sites was 2982 m and tree-ring samples were collected between 2694 m and 3257 m (Table 1). All sites are managed as US Forest Service wilderness areas except PIN, which is closed to the public to protect the endangered Mount Graham red squirrel (*Tamiasciurus hudsonicus grahamensis*). We did not see evidence of logging (e.g.,

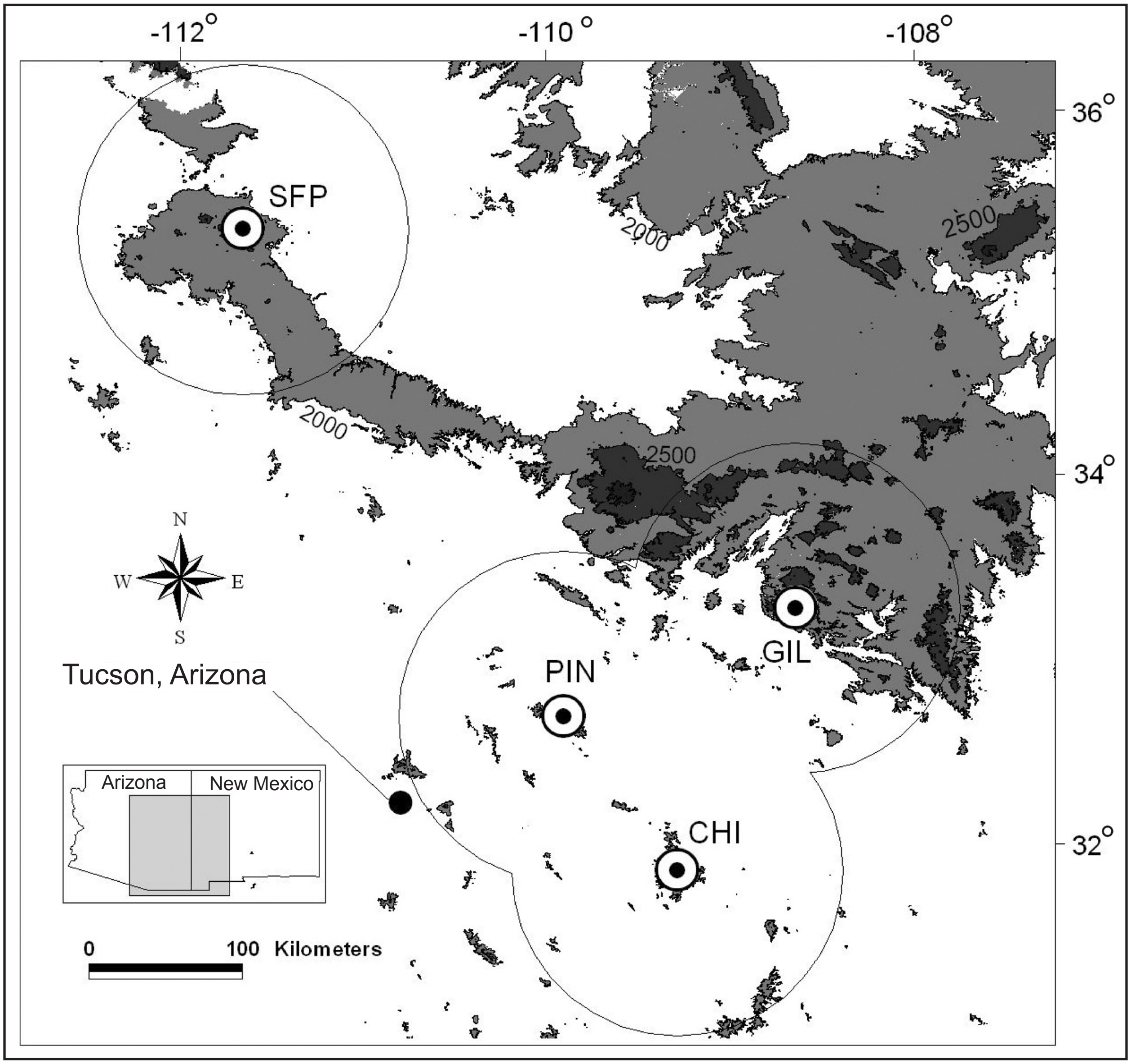

Figure 1. Map of site locations (e.g., SFP) in the Mogollon Plateau and the Madrean Sky Islands of Arizona and New Mexico, USA. Shading indicates major topographic features >2000 m in elevation at 500 m intervals. Large circles indicate the 100 km search radius around the fire history sites used to select recent fires (1984 to 2008) to quantify the size of recent stand-replacing fire patches.

Table 1. Site information for four upper elevation fire history sites from the Mogollon Plateau and Madrean Sky Islands, USA.

Site ID	Site name	Vegetation type[a]	Sampled aspen area (ha)	Sampled spruce-fir area (ha)[b]	Number of plots	Mean sample elevation (m)
CHI	Chiricahua Mountains	MC/S	139	--	26	2856
GIL	Mogollon Mountains	MC/SF	744	1639	32	3060
PIN	Pinaleño Mountains	MC/SF	0*	521	33	3057
SFP	San Francisco Peaks	MC/SF	990	--	25	2954

[a] MC = mixed conifer-aspen, SF = spruce-fir, S = spruce
[b] Spruce-fir was only mapped and sampled at two test sites (GIL and PIN).
* Distinctive seral aspen patches greater than 5 ha were not present.

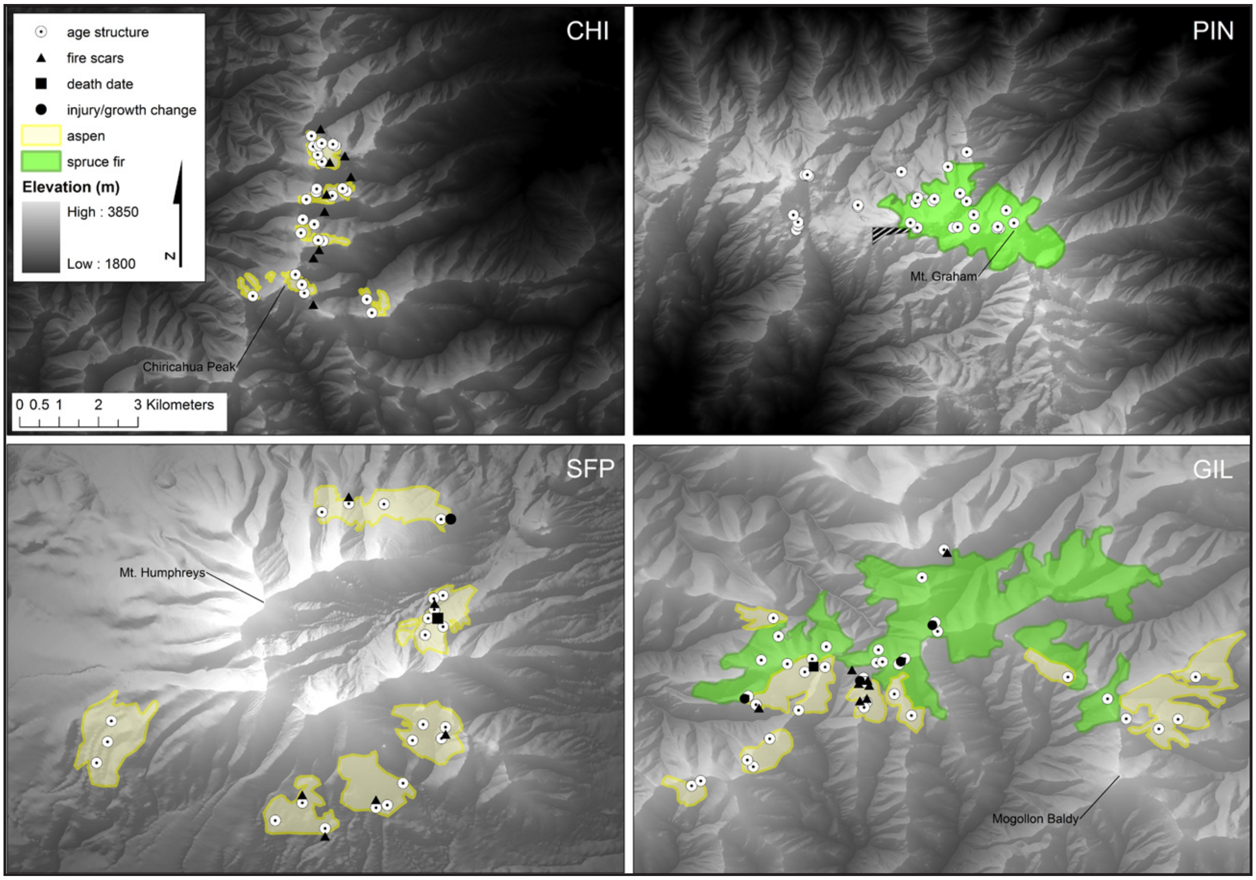

Figure 2. Tree-ring sample locations and analyzed aspen and spruce-fir stands at the study sites in the Chiricahua Mountains (CHI), Pinaleño Mountains (PIN), San Francisco Peaks (SFP), and Gila Wilderness (GIL) of the Mogollon Mountains. Hatched polygon at PIN indicates fire scar sample area from Grissino-Mayer *et al.* (1995).

stumps or skid trails) within the sampled stands. Fire exclusion resulting from late nineteenth century grazing followed by twentieth century fire suppression occurred at all sites, similar to most montane forests in the southwestern US (Dieterich 1980, Bahre 1985, Swetnam and Baisan 1996, Allen *et al.* 2002).

The general climate of the study area is continental with a bimodal precipitation regime. All sites receive an average of 40% to 50% of annual precipitation from summer (July to September) monsoon convective thunderstorms (1910 to 2009; http://www.prism.oregonstate.edu/). Average annual precipitation was similar amongst sites, ranging from 800 mm to 950 mm. Average annual maximum temperature ranged from 12.5°C to 17°C and minimum temperature ranged from 0°C to −4.5°C (1910 to 2009; http://www.prism.oregonstate.edu/). All sites receive winter snow, but snowpack varies widely from year to year depending on the winter storm track. The majority of area that burns in the study area occurs during a consistently dry and warm pre-monsoon period that begins in April or May and lasts through June (Barrows 1978). The potential severity and length of the fire season in the high-elevation forests of the region is largely a function of the snowpack and residual moisture that persists into the early summer pre-monsoon period.

The sampled seral quaking aspen stands at all four sites were located adjacent to mixed conifer or spruce-fir forests. The following conifer tree species were observed within and adjacent to the aspen stands, listed in descending order of occurrence: Engelmann spruce (*Picea engelmannii* Parry ex Engelm.), Douglas-fir (*Pseudotsuga menziesii* [Mirb.] Franco), southwestern white pine (*Pinus strobiformis* Engelm.), white fir (*Abies concolor* [Gord. & Glend.] Lindl. Ex Hildebr.), subalpine fir (*Abies lasiocarpa* [Hook.] Nutt.), ponderosa pine, and Rocky Mountain bristlecone pine (*Pinus aristata* Engelm.).

Although all sites contained quaking aspen, there were differences between and within sites. Aspen patches in the two Sky Island sites were smaller than on the Mogollon Plateau (Table 1, Figure 2). This pattern can be partially explained by less land area in the aspen zone (2600 m to 3100 m) at the Sky Island sites (2927 ha in CHI, and 5945 ha in PIN) compared to Mogollon sites (7088 ha in SFP, and 7645 ha in GIL). Within-site differences in vegetation that could affect fire regimes were driven by aspect, with south-facing slopes containing drier, more open forests, and north-facing slopes generally supporting more mesic, denser forests.

Stand-Replacing Fire History Methods—Mixed Conifer-Aspen Forest

Our general sampling methods follow Margolis *et al.* (2007), in which large quaking aspen patches embedded in mesic mixed conifer and spruce-fir forests of the upper Rio Grande Basin were mapped and tree-ring dated with multiple lines of evidence to reconstruct stand-replacing fire patch sizes and dates. The four lines of evidence included 1) quaking aspen age structure, 2) conifer death dates, 3) conifer traumatic resin ducts or ring-width changes, and 4) conifer fire scars. All conifer death dates were bark-ring dates. Bark-ring dates indicate that either bark or other evidence of an intact outer ring (e.g., insect galleries) was present on the samples—this ensures that the outer ring dates are actual tree death dates.

Age structure plots were randomly located within each mapped aspen patch at a minimum density of three to four plots per 100 ha (e.g., SFP in Figure 2). Aspen patches were visually surveyed in the field to ensure plot locations were representative of the stand. Additional plots were added in the field at locations with conifer evidence of fire to verify stand boundaries, or to age potentially older trees (fire survivors) indicated by anomalously large diameter.

Aspen age structure plots had a 10 m fixed radius. Within the plots, we cored the two aspen stems with the greatest diameter at breast height (dbh). Trees were cored at <0.3 m core height until the pith was present in one sample at the plot. In a post-stand-replacing fire aspen stand, sampling two stems per plots at multiple plots within a patch has been shown to be sufficient to determine stand age (Margolis *et al.* 2007). This is because of the immediate asexual regeneration response of aspen following aboveground stem mortality, which creates a distinct recruitment pulse and a single-tiered, even-aged stand (Barnes 1966, Patton and Avant 1970). In upper montane seral aspen stands, subsequent regeneration is relatively rare and the dominant post-fire cohort is easily identified as the stems with largest dbh (Margolis *et al.* 2007). A more intensive sampling design would be necessary to fully describe a multi-cohort age structure, but this was not our goal. Post-fire quaking aspen regeneration can grow up to 1 m in the first year of growth (Jones 1975); thus, <0.3 m core height seems adequate to capture the first year of the aspen regeneration pulse (Margolis *et al.* 2007).

We searched within aspen patches and along the patch boundaries for conifers with potential direct evidence of fire (e.g., fire scars, conifer death dates, and ring-width changes and injuries). Cross sections and partial cross sections were collected with handsaws from remnant conifer logs, living trees, and standing dead snags with intact outer rings. Increment cores were collected from potentially injured live conifers without basal scars. Potential evidence of fire injury included char, scars on the undersides of branches, elevated crown base height, and unilateral loss of branches. Fire scars were not collected at PIN due to the existing fire scar collection located within our study site (Grissino-Mayer *et al.* 1995).

All tree-ring samples were prepared and crossdated according to standard dendrochronological procedure (Stokes and Smiley 1968). To estimate the date of the first year of growth (pith) for age structure increment cores that did not contain the pith ring, we used a concentric circle pith estimator (Applequist 1958). Dates from the four lines of tree-ring evidence were plotted together to determine fire dates (from conifer fire scars, death dates, and tree-ring growth changes and injuries) and stand-replacing fire patches (from age structure of aspen patches).

A mapped aspen patch was determined to represent the minimum extent of a previous stand-replacing burn patch if: 1) the oldest aspen estimated pith dates were associated with (≤5 years following) a fire event recorded by conifer death dates from within the patch or fire scars on surviving trees along the periphery of the patch, and 2) estimated aspen pith dates were part of a site-level (i.e., multi-patch) aspen recruitment pulse. The rarity and poor spatial coverage of fire-scarred trees at some sites (e.g., $n = 6$) prevented the use of percent-scarred filters to categorize and compare relatively widespread versus local fires between sites (Swetnam and Baisan 2003). Instead, we categorized fires recorded by ≥5 conifer samples at a site (e.g., conifer death dates, growth changes or traumatic resin ducts, and fire scars) as likely being more widespread than fires recorded by fewer trees.

Testing Fire History Methods in Spruce-Fir Forest

Within our study area, potential post-stand-replacing fire quaking aspen patches were generally found between 2600 m and 3100 m, and forests above 3100 m were generally dominated by spruce and fir. Pure spruce-fir forests with no living aspen stems would not be expected to contain quaking aspen regeneration following fire, so above 3100 m in this region, past stand-replacing fire patch size and dates cannot be estimated using post-fire aspen patches. We tested the utility of age structure fire history methods in spruce-fir forests at two sites, PIN and GIL. These sites were chosen because the relatively small size of the spruce-fir patches was more manageable for testing the efficacy of the methods. Therefore, the extensive spruce-fir stands at SFP were not sampled.

Aerial photographs and field observations were used to map spruce-fir patches and identify differences in texture, density, color, or differences in tree height, potentially representing fire boundaries (Johnson and Larsen 1991, Agee 1993, Johnson and Gutsell 1994). We were not able to identify any evidence of potential fire boundaries (e.g., discrete changes in canopy height) within the spruce-fir stands at PIN or GIL. Therefore, we treated each spruce-fir stand as a single potential stand-replacing fire patch.

In contrast to the predominance of asexual reproduction in aspen, spruce and fir trees recruit from seed, so the initial post-fire cohort can lag behind the fire date and may be distributed over decades (e.g., Antos and 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 in spruce-fir more difficult to identify with age or size structure data. We collected age structure samples using similar methods for dating aspen patches (see above), but with two differences to account for the differing fire ecology. First, we doubled the number of trees cored at each plot to include the four trees of largest dbh in order to account for the potentially complex age structure. Conifers were cored as low on the bole as possible and angled down to intersect the root crown and capture the earliest years of growth.

The second difference from the aspen age structure methodology was in the criterion to qualify as a stand-replacing fire patch. A spruce-fir patch was determined to be a post-stand-replacing fire patch if the oldest estimated conifer pith dates were ≤10 years following a fire recorded by conifer death dates from within the patch or by fire scars on the periphery of the patch. We increased the cut-off criteria to 10 yr (compared to 5 yr for aspen) to account for potentially lagged seedling recruitment (compared to immediate asexual regeneration in aspen). A 10-year lag window is likely conservative, given reports of greater than 50-year lags for subalpine forest regeneration following stand-replacing fire (Stahelin 1943). Because of relatively high fire frequency recorded by fire scars in some of the mixed conifer forests immediately below the spruce-fir stands, we determined that a 10-year lag would help to avoid spurious matches between fire scar dates and age structure that could be interpreted as stand-replacing fire dates. All tree-ring samples were collected in 2003 and 2004.

Historical Stand-Replacing Fire Patch Size

The aspen and spruce-fir patches that were dated to historical stand-replacing fires were used to derive minimum estimates of historical stand-replacing fire patch sizes. Patch area was calculated with a geographic information system (GIS). This data set provides the first estimate of historical stand-replacing burn patch sizes within two elevation and vegetation ranges at our study sites, including: 1) the aspen zone (2600 m to 3100 m) and 2) the spruce-fir zone (>3100 m).

RESULTS

Tree-ring dates from 178 aspen stems and 139 conifers were used to reconstruct upper montane fire history, including stand-replacing fire patch dates and sizes (Tables 2 and 3, Figures 3-6). Annually dated, direct conifer evidence of fire (e.g., fire scars and tree death dates) was used to reconstruct 77 new fires in addition to the existing fire dates (from Grissino-Mayer *et al.* 1995) for PIN. Across the four sites, 100 fires occurring on 87 unique fire dates were analyzed (1623 to 1904; Table 3). Twenty five percent of the fires (n = 25) were recorded by ≥5 conifers (including fire scars) at a site. An average of 59% of all sampled aspen regenerated within five years after fire, ranging from 27% to 89% among sites. Three fires (1685 in PIN, 1879 in SFP, and 1904 in GIL) met our criteria for stand-replacing fire within mapped aspen or spruce-fir patches (Figures 4-6). Evidence of stand-replacing fire included aspen and conifer recruitment pulses, coincident conifer death and fire scar dates, and a lack of trees that survived (pre-date) the fire.

Table 2. Number of trees with crossdated tree-ring samples used to reconstruct fire history in the Mogollon Plateau and Madrean Sky Islands, USA.

Site ID	Aspen age structure	Conifer age structure	Conifer fire scar	Conifer death date	Conifer growth change or injury	Total
CHI	44	0	26	0	6	76
GIL	58	44	10	1	6	119
PIN	31	25	12*	0	0	68
SFP	45	0	6	1	2	54
Total	178	69	54	2	14	317

* Data from Grissino-Mayer *et al.* 1995 (PIN).

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	1904, 1748, 1773	1716, 1765
PIN*	1685	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	1879	1752, 1773, 1809, 1818, 1836, 1840, 1847, 1851, 1855, 1857, 1860, 1863, 1876

* Fire scar data from Grissino-Mayer *et al.* 1995 (PIN).

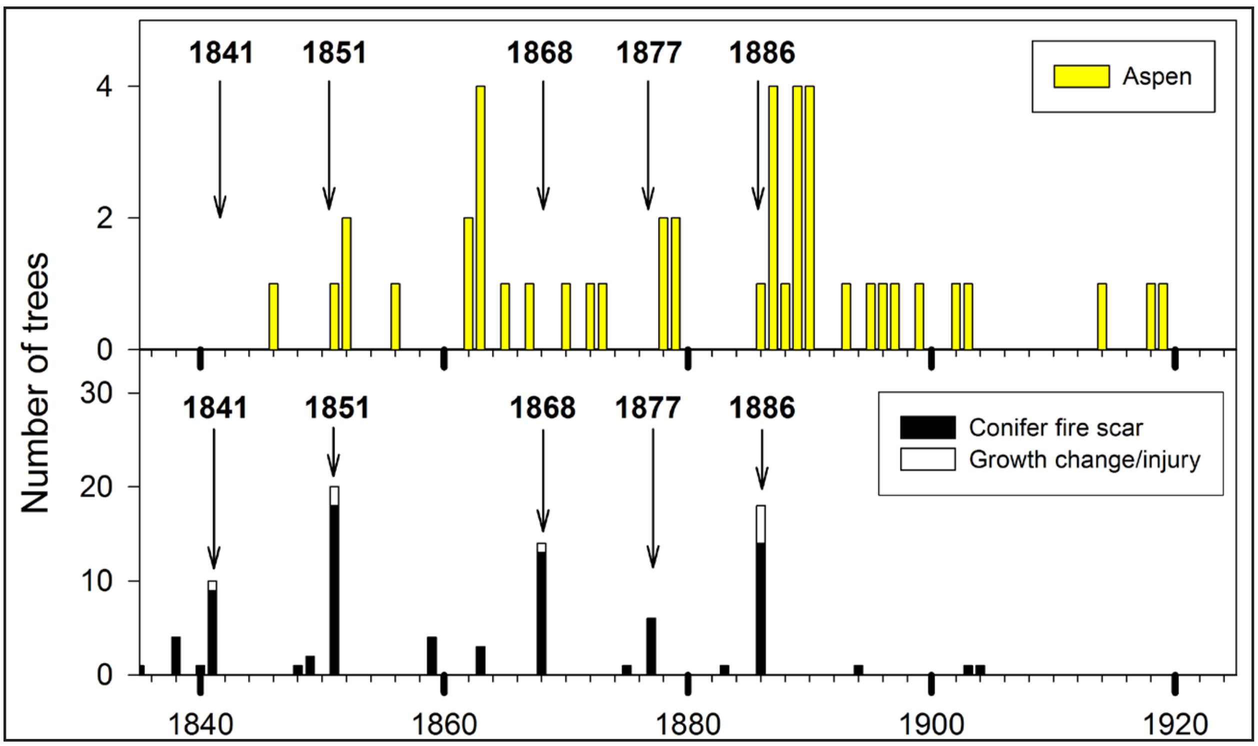

Figure 3. Chiricahua Mountains (CHI) estimated aspen pith dates (top) and direct conifer evidence of fire (bottom) in 1-year classes used to reconstruct fire history in the upper elevation forests. Years (e.g., 1886) indicate annually dated fire events recorded by ≥5 conifer trees, including fire scars.

Chiricahua Mountains

Eight small quaking aspen patches were mapped at CHI, totaling 139 ha (Table 1, Figure 2). No single post-stand-replacing fire quaking aspen cohort was present at CHI, but 89% of the aspen stems regenerated within five years after a fire (Figure 3). Surface fires recorded by conifers on south-facing slopes adjacent to the aspen stands were relatively

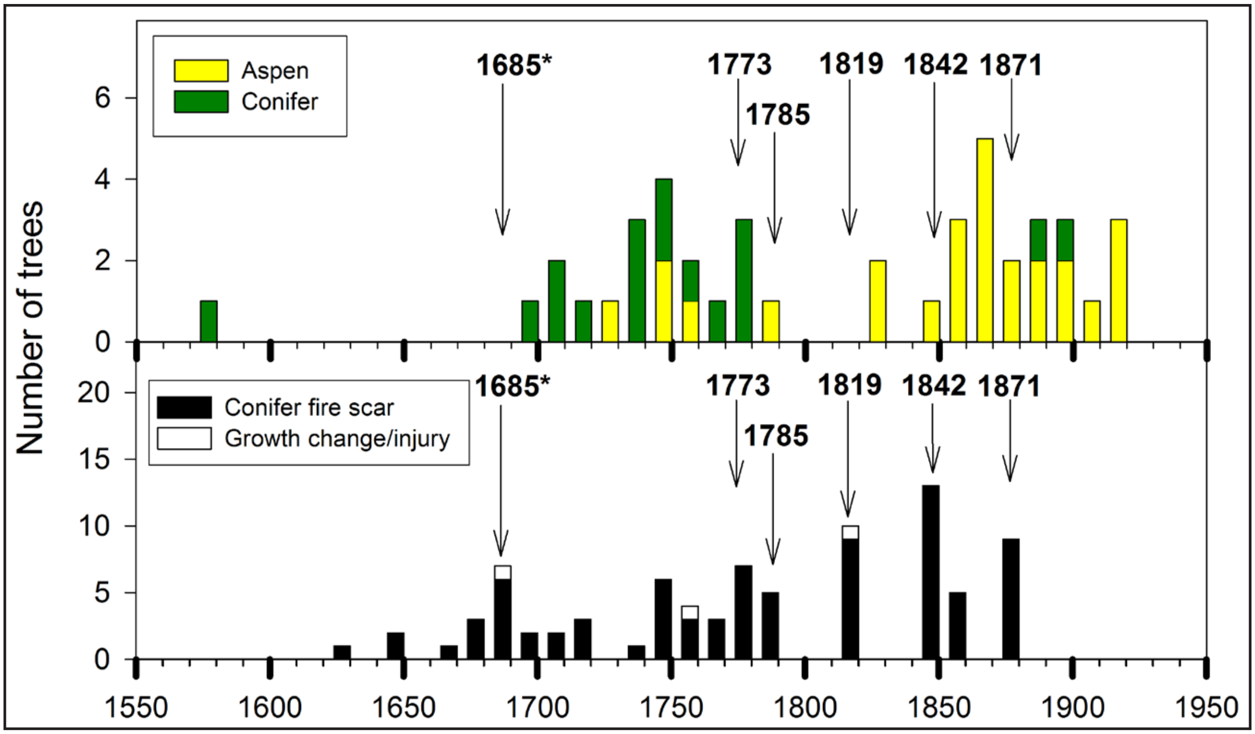

Figure 4. Pinaleño Mountains (PIN) estimated pith dates (top) and direct conifer evidence of fire (bottom) in 10-year classes used to reconstruct fire history in the upper elevation forests. Years (e.g., 1685) indicate annually dated fire events recorded by ≥5 conifer trees, including fire scars. * Indicates stand-replacing fire date. Fire scar data from Grissino-Mayer *et al.* (1995).

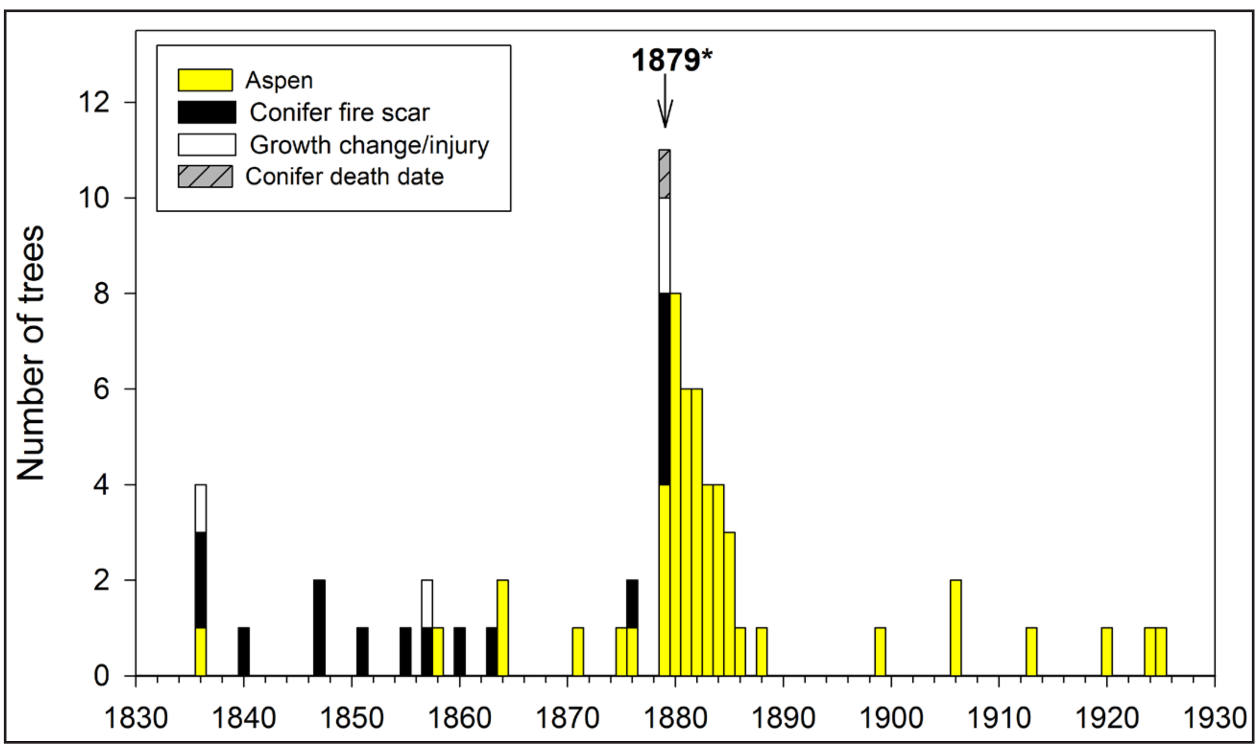

Figure 5. San Francisco Peaks (SFP) estimated aspen pith dates and direct conifer evidence of fire in 1-year classes used to reconstruct fire history in the upper montane forests. Years (e.g., 1879) indicate annually dated fire events recorded by ≥5 conifer trees, including fire scars. * Indicates stand-replacing fire date.

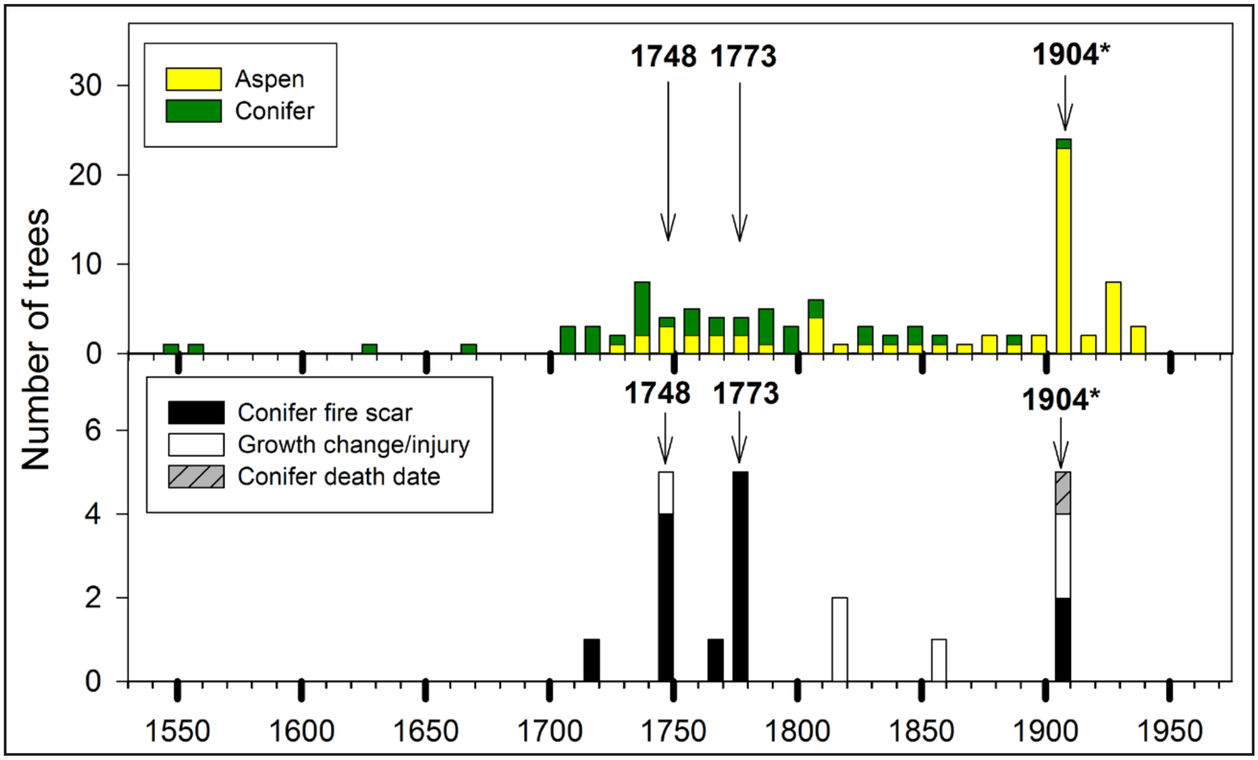

Figure 6. Mogollon Mountains (GIL) estimated pith dates (top) and direct conifer evidence of fire (bottom) in 10-year classes used to reconstruct fire history in the upper montane forests. Years (e.g., 1904) indicate annually dated fire events recorded by ≥5 trees, including fire scars. * Indicates stand-replacing fire dates.

frequent prior to *circa* 1900 (mean fire interval from 1654 to 1904 for all fires was 4.5 yr; Table 3).

The mapped aspen patches at CHI were not post-stand-replacing fire patches based on our criteria. The age structure of the dominant aspen within each patch was multi-aged, with some trees surviving (pre-dating) multiple fire events. For example, aspen from the 1886 post-fire cohort were scattered throughout multiple patches, but were often located adjacent to older aspen stems (e.g., 1851 post-fire regeneration) that survived the 1886 fire.

Pinaleño Mountains

The combined age structure of the multiple, small aspen groups (5 to 10 stems) scattered throughout the mixed conifer forest showed no evidence of a single, widespread, post-fire cohort (Figure 4). Only 27% of the dominant aspen at PIN regenerated within 5 years after a fire. Many aspen pre-dated (survived) fires recorded by multiple conifers as fire scars (e.g., 1871 fire), with the oldest living aspen dating to 1724 (estimated pith date).

Without post-fire aspen cohorts or large contiguous patches of seral, post-fire quaking aspen at PIN, the spruce-fir stand was the best potential evidence of past stand-replacing fire. The oldest tree (Engelmann spruce; 1692 estimated pith date) in the spruce-fir stand regenerated within 10 years after the 1685 fire that scarred all recording trees in the adjacent mixed conifer-aspen zone (Figure 4). The one tree that pre-dated the 1685 fire was a Douglas-fir located on the edge of the spruce-fir zone. These data met our criteria for stand-replacing fire in the spruce-fir zone at PIN in 1685.

San Francisco Peaks

Seventy-one percent of the dominant aspen at SFP regenerated within five years after a fire. Multiple lines of tree-ring evidence indicate that the 1879 fire was stand-replacing in some of the mapped patches (Figure 5). A distinct and immediate aspen recruitment pulse began in 1879, accounting for 63% of the sampled aspen. This site-level aspen age structure, dominated by a single post-fire aspen cohort, was different from the two Sky Island sites that had no dominant aspen cohort (CHI and PIN, Figures 3 and 4). The few aspen at SFP that pre-date 1879 were from the southeastern part of the site where there was no fire-scar evidence of the 1879 fire (Figures 2 and 5). In total, tree-ring evidence of the 1879 fire was present in all but one aspen patch.

The seral, post-stand-replacing fire aspen patches at SFP were located on the north-facing slopes and had the largest mean reconstructed stand-replacing fire patch size of all of the sites (145 ha). The drier, south-facing slopes contained conifers with multiple fire scars within the aspen stands. The ten fires recorded between 1836 and 1879 were all recorded by fire-scarred conifers on the south slope (Figures 2 and 5). This frequent fire regime ($MFI_{All\ fires}$ = 4.8 yr) that scarred, but did not kill, conifers within the south-facing aspen stands differed from the post-stand-replacing fire aspen patches, with no surviving conifers, on the north-facing slopes at SFP.

Mogollon Mountains (Gila Wilderness)

The aspen age structure at GIL was dominated by a post-1904 fire recruitment pulse (Figure 6). No sampled trees from within the mapped aspen patches survived the 1904 fire. These homogenous, even-aged aspen patches contained fire-killed Douglas-fir that died in 1904. Based on this evidence, all mapped aspen patches at GIL (totaling 744 ha) were determined to be stand-replacing fire patches from the 1904 fire. The aspen stems that predated the 1904 fire were located in the spruce-fir stands as scattered, co-dominant stems, some of which were >250 years old. A synchronous recruitment pulse was not evident from these old aspen. Overall, 42% of the sampled aspen at GIL regenerated within five years after a fire.

No direct evidence of fire (e.g., charred wood or fire scars) was observed within the spruce-fir stands at GIL. Relatively continuous conifer regeneration was recorded in the decades from 1700 to 1910, and the oldest individual (Engelmann spruce) in the spruce-fir patches dated to 1707. Multiple spruce trees were older than the oldest crossdated fire scar (1716) recorded adjacent to the spruce-fir patches (Figure 6). Therefore, the sampled age structure did not meet our criteria to be a post-fire recruitment cohort. There was no evidence that the 1904 fire, which our results suggest burned with stand-replacing severity in adjacent mixed conifer-aspen forests, burned into the spruce-fir zone.

Historical Stand-Replacing Fire Patch Size

We derived historical stand-replacing fire patch size estimates from the 10 tree-ring dated post-stand-replacing fire aspen patches (1879 to 1904) and the one post-stand-replacing fire spruce-fir patch (1685 fire; Table 4). Fires at three of the four sites (GIL, PIN, and SFP) had stand-replacing fire patches >200 ha. The maximum reconstructed historical stand-replacing fire patch size was 286 ha in the mixed conifer-aspen zone (2600 m to 3100 m) and 521 ha in the spruce-fir zone (>3100 m; Table 4).

DISCUSSION

Historical Stand-Replacing Fire

We found evidence of historical stand-replacing fire in upper elevation forests

Table 4. Historical and recent stand-replacing fire patch area statistics. Historical burn patch areas derived from combined tree-ring reconstructed aspen and spruce-fir stand-replacing fire patches. Recent burn patch area derived from fire severity maps (1984 to 2008, *n* = 352 fires). The conservative estimate of recent stand-replacing fire patch size includes only high-severity patches (H), and a more inclusive estimate includes high- and moderate-severity patches (H+M). Recent data only include patches >30 ha, equal to the smallest reconstructed historical stand-replacing fire patch.

	Historical burn patches		Recent burn patches					
	2600 m to 3100 m	>3100 m	2600 m to 3100 m		>3100 m		All elevations	
	Aspen	Spruce-fir	H	H+M	H	H+M	H	H+M
Count	10	1	64	85	1	2	204	675
Mean (ha)	110	521	129	206	33	110	136	233
Median (ha)	63	521	80	86	33	110	65	74
Standard deviation (ha)	89	--	134	300	--	70	204	500
Minimum (ha)	30	521	32	31	33	60	32	31
Maximum (ha)	286	521	637	1 540	33	159	1 929	5 136
Sum (ha)	1 104	521	8 251	17 507	33	219	27 810	157 482

(>2600 m) at three of the four sites. Fires with multiple large (>100 ha) stand-replacing fire patches were tree-ring dated at the two Mogollon Plateau sites using quaking aspen age structure and associated direct conifer evidence of fire (1904 in GIL and 1879 in SFP). Aldo Leopold (1922), while on a fire assignment in the Gila Wilderness, referenced a 1904 fire in the Mogollon Mountains. Abolt (1997) identified a widespread fire with a stand-replacing component in 1904 in the Mogollon Mountains from tree-rings and historical documents. In the San Francisco Peaks, Heinlein *et al.* (2005) recorded a fire in 1879 in lower elevation ponderosa pine-mixed conifer forests using fire scars, but does not report evidence of stand replacement. Historical photographs taken in 1910 at SFP show standing dead and downed trees in the spruce-fir and mixed conifer-aspen zones that likely resulted from a fire with large (estimated >500 ha) stand-replacing patches in the late nineteenth century (http://www.rmrs.nau.edu/imagedb/viewrec.shtml?id=22141&colid=fv).

We were able to associate spruce-fir age structure with direct conifer evidence of fire (i.e., fire scars) at one of the spruce-fir fire history test sites (PIN). The age structure data we collected, and prior 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.* 2009, but see Stromberg and Patten 1991). Margolis and Balmat (2009) reconstructed a 1200 ha stand-replacing fire patch in the spruce-fir forests of the Santa Fe Watershed, New Mexico, also in 1685. This year was extremely dry (−5.0 reconstructed Palmer Drought Severity Index: Cook *et al.* 2004) and a common fire year throughout the southwestern US (Swetnam and Baisan 2003). Thus, it is plausible that the typically mesic spruce-fir zone at PIN could have been dry enough in 1685 to burn.

Frequent Fire and Quaking Aspen

We did not find evidence of past stand-replacing fire in the sampled aspen stands at CHI. Although 89 % of the aspen stems at this site regenerated within five years after reconstructed fires, the mapped aspen patches were multi-aged. This indicates that some aspen stems survived multiple fires, while other aspen in the same patch were top-killed by the same fires and then regenerated by sprouting.

We found direct evidence of repeated low-severity fire (e.g., conifers with multiple fire scars) adjacent to aspen stands at CHI and within the mixed conifer-aspen forests of PIN. Frequent fire occurred at these two upper montane Sky Island sites prior to *circa* 1900: MFI-$PIN_{All\ fires}$ = 10.9 yr (1685 to 1871), approximately 150 ha sample area (Grissino-Mayer *et al.* 1995), and MFI-$CHI_{All\ fires}$ = 4.4 yr (1654 to 1904), approximately 250 ha sample area. This history of frequent fire may have prevented sufficient fuel accumulation to sustain stand-replacing fire. This suggests that the cessation of fire for over 120 years due to late nineteenth century grazing and twentieth century fire suppression may be a cause of fuel structure changes and buildup that contributed to the recent occurrence of stand-replacing fires in the mixed conifer-aspen forests at these Sky Island sites (Swetnam *et al.* 2009).

Similar evidence of frequent low-severity fire (i.e., logs and living conifers with multiple scars) was present within and adjacent to the aspen stands on the south slope of SFP (Figures 2 and 5). The lower borders of these aspen stands are connected with ponderosa pine-mixed conifer forests that historically burned with frequent low-severity fire (e.g., Heinlein *et al.* 2005). Based on this evidence of repeated surface fire in aspen on south aspects at SFP, it is likely that the present stand structure, dominated by >20 m tall, mature aspen stems (>120 years old) may be in part an artifact of fire exclusion. These fire-sensitive aspen stems would have been historically exposed to frequent fire, thus the same stands likely looked very different in the nineteenth century. One hypothesis is that they were smaller diameter aspen "thickets" that were top-killed and regenerated after each fire (Maini 1960, Allen 1989). Alternatively, some larger diameter stems at the center of the stand may have been protected from being girdled by fire, creating a multi-cohort age and stand structure. Binkley *et al.* (2006) proposed a similar hypothesis of altered quaking aspen stand-structure in response to twentieth century fire exclusion on the Kaibab Plateau in north-central Arizona. The following hypothesis should be tested with future research: the age and stand structures of quaking aspen that historically experienced frequent fire have shifted from young or multi-aged, dense stands, to the current open structure dominated by a single mature cohort, largely due to >120 years of fire exclusion.

Spruce-Fir Fire History Challenges

The lack of burn boundaries within the spruce-fir stands at our two test sites (PIN and GIL) differs from higher latitude, Rocky Mountain landscapes where old stand-replacing fire patch boundaries are visible as obvious stand-height and structural differences that are used to map and date historical crown fires (e.g., Kipfmueller and Baker 2000, Sibold *et al.* 2006). Fulé *et al.* (2003) reported a similar lack of fire-related patch boundaries identifiable with remote sensing data in mixed conifer, aspen, and spruce-fir forests of the north rim of the Grand Canyon, Arizona. The lack of old fire boundaries within the spruce-fir zone of the current study, and on the north rim of the Grand Canyon may suggest that, in these spruce-fir forests, large crown fire patches were not as common within recent centuries as they were in the Rocky Mountains.

The inconclusive evidence of stand-replacing fire in the spruce-fir zone at GIL was possibly due to an insufficient number of tree ages to determine the complex and relatively old (>300 yr) age structure, and the relative scarcity of old (pre-1700 AD) fire scar material in this high-elevation forest type (Figure 6). Age-structure transects with a higher density of samples may be necessary to determine patch age in old (>300 years old) southwestern US spruce-fir forests. Repeated, sample-intensive age structure transects distributed throughout the mapped stands may be the best method to confidently evaluate the age structure of old spruce-fir forests in this region (e.g., Margolis and Balmat 2009). The number of trees sampled for age structure could be adjusted based on the estimated age of the stand (e.g., <150 yr old, > 250 yr 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 sub-alpine forests of the upper Rio Grande Basin or at SFP could be used to select test sites because there are large spruce-fir stands adjacent to large, post-fire aspen patches from historically documented nineteenth century fires (e. g., Santa Fe Ski Basin, New Mexico). 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 highest elevations (>3100 m) in the southwestern US. These data are necessary to estimate 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 spruce-fir forests of the region.

Historical Stand-Replacing Burn Patch Size

The occurrence of historical stand-replacing fire patches >200 ha at three of the four upper elevation sites suggest that recent large (200 ha to 500 ha) stand-replacing patches are within the historical range of variability in upper elevation forests (>2600 m) of the southwestern US outside of the southern Rocky Mountains. Based on our reconstructions, stand-replacing fire patches as large as 286 ha historically occurred in the mixed conifer-aspen zone, and patches as large as 521 ha historically occurred in the spruce-fir zone. Within these upper elevation forests, it is possible that older, larger stand-replacing fire patches were burned over by the late nineteenth century fires, or that such patches were re-colonized by mixed conifer species instead of aspen. We did not observe obvious even-aged mixed conifer stands with abundant fire-killed, remnant conifer logs or snags at our study sites that might indicate evidence of past stand-replacing fire. However, extensive (>500 ha) mixed conifer and spruce-fir patches exist in the region and could be systematically sampled to determine whether they regenerated following stand-replacing fire.

The largest historical stand-replacing fire patch we reconstructed was in the spruce-fir zone at PIN (521 ha). Historical photographs at SFP, discovered after our sampling was completed, illustrate large late-nineteenth century stand-replacing fire patches (estimated >500 ha) in the spruce-fir zone (http://www.rmrs.nau.edu/imagedb/viewrec.shtml?id=22141&colid=fv). In the southern Rocky Mountains of New Mexico, Margolis and Balmat (2009) reconstructed a 1200 ha stand-replacing fire patch in spruce-fir forest. Thus, documentary and tree-ring evidence at multiple sites in the southwestern US indicates the potential for large (500 ha to >1000 ha) stand-replacing fire patches in spruce-fir forest.

Recent Stand-Replacing Burn Patch Size

All four of our study sites have recently burned with high-severity patches. As an ancillary investigation to summarize the recent (1984 to 2008) fires, we quantified patch sizes of 352 fires >404 ha with high- or moderate-severity patches within 100 km of the four fire history study sites (Figure 1, http://www.mtbs.gov/index.html). We stratified the recent burn severity patch size data by elevation and vegetation type and fire severity to produce six subsets: 1) high severity with no elevation limit, 2) high plus moderate severity with no elevation limit, 3) high severity 2600 m to 3100 m, 4) high plus moderate severity 2600 m to 3100 m, 5) high severity >3100 m, and 6) high plus moderate severity >3100 m. The elevation ranges are the same used to categorize the upper elevation fire reconstructions. The subset with no elevation limit includes lower elevation, pine-dominant oak or shrub vegetation. Recent patch sizes were limited to ≥30 ha, equal to the minimum reconstructed stand-replacing fire patch size. Data from all sites were pooled. We were most interested in the largest patches since they arguably have the greatest ecological effects.

Significant direct and delayed mortality from crown scorch and insect attack has been documented in moderate-severity burn patches in recent fires (McHugh and Kolb 2003). Based on an assumption that a substantial percentage of the trees in moderate-severity burn patches die, high- and moderate-severity patches were combined in one subset of the data. We posit that the actual area of fire-related tree mortality (i.e., stand replacement) was probably somewhere between the "high severity" and "high plus moderate severity" patch size estimates.

The largest recent stand-replacing fire patch size with no elevation limit was 1929 ha (high severity) and 5136 ha (high plus moderate severity), with 37 patches >1000 ha (2 high severity and 35 high plus moderate severity; Table 4). In the mixed conifer-aspen zone (2600 m to 3100 m), the largest recent high-severity patch was 637 ha, and the largest high- plus moderate-severity patch was 1540 ha. Above 3100 m, in the spruce-fir zone, the largest recent high-severity patch was 33 ha, and the largest high- plus moderate-severity patch was 159 ha.

Direct comparison between recent and historical stand-replacing fire patch sizes are challenging. Due to reasons discussed above, our historical estimates are likely conservative estimates of stand-replacing patch size. Thus, we cannot confidently test whether the largest recent high- or moderate-severity patches are larger than have occurred in past fires. However, given these limitations, the data suggest that recent high- (or moderate-) severity patches that are smaller than the historical estimates (maximum reconstructed patch size, 286 ha in mixed conifer-aspen forest and 521 ha in spruce-fir forest) are likely within the historic range of variability.

In summary, historical fire regimes at multiple upper elevation (>2600 m) mixed conifer-aspen and spruce-fir sites on the Mogollon Plateau and Madrean Sky Islands included large (>200 ha) stand-replacing fire patches. Aspen recruitment was historically associated with fire, with an average of 59 % of the dominant aspen stems regenerating within five years after fire (ranging from 27 % to 89 % among sites). In the drier portions of the mixed conifer-aspen sites, the cessation of historically frequent fires for the last 130 years has likely altered the current aspen age and stand structures. Tree-ring and photographic evidence of historical stand-replacing fire in the spruce-fir zone indicates that recent fires that burned with high severity in this forest type at the study sites (e.g., 2004 Nuttall Fire at PIN) are rare events, but not unprecedented. Based on the reconstructed estimate, recent stand-replacing fire patches as large as 286 ha in the mixed conifer-aspen zone and 521 ha in the spruce-fir zone may be within the historic range of variability and should be expected in future fires, particularly when considering predictions of a warmer and drier climate in the southwestern US (e.g., Seager *et al.* 2007).

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