A stand-replacing fire history in upper montane forests of the southern Rocky Mountains

Ellis Q. Margolis, Thomas W. Swetnam, and Craig D. Allen

Abstract: Dendroecological techniques were applied to reconstruct stand-replacing fire history in upper montane forests in northern New Mexico and southern Colorado. Fourteen stand-replacing fires were dated to 8 unique fire years (1842–1901) using four lines of evidence at each of 12 sites within the upper Rio Grande Basin. The four lines of evidence were (*i*) quaking aspen (*Populus tremuloides* Michx.) inner-ring dates, (*ii*) fire-killed conifer bark-ring dates, (*iii*) tree-ring width changes or other morphological indicators of injury, and (*iv*) fire scars. The annual precision of dating allowed the identification of synchronous stand-replacing fire years among the sites, and co-occurrence with regional surface fire events previously reconstructed from a network of fire scar collections in lower elevation pine forests across the southwestern United States. Nearly all of the synchronous stand-replacing and surface fire years coincided with severe droughts, because climate variability created regional conditions where stand-replacing fires and surface fires burned across ecosystems. Reconstructed stand-replacing fires that predate substantial Anglo-American settlement in this region provide direct evidence that stand-replacing fires were a feature of high-elevation forests before extensive and intensive land-use practices (e.g., logging, railroad, and mining) began in the late 19th century.

Résumé : Des techniques dendroécologiques ont été utilisées pour reconstituer l'historique des incendies qui ont entraîné le remplacement des peuplements dans les forêts de haute montagne du nord du Nouveau-Mexique et du sud du Colorado. Huit années particulières (1842–1901), durant lesquelles sont survenus quatorze incendies qui ont entraîné le remplacement des peuplements, ont été identifiées en utilisant quatre genres d'indices dans chacune de 12 stations dans le bassin supérieur du Rio Grande. Les quatre genres d'indices étaient : (*i*) la date correspondant au premier cerne annuel chez le peuplier faux-tremble (*Populus tremuloides* Michx.), (*ii*) la date du dernier cerne annuel chez les conifères tués par le feu, (*iii*) les changements dans la largeur des cernes annuels ou autres indices morphologiques de dommages et (*iv*) les cicatrices de feu. La précision à l'année près de la datation a permis d'identifier les années synchrones, celles où des incendies qui entraînent le remplacement des peuplements sont survenus la même année dans les différentes stations et en même temps que des épisodes régionaux de feux de surface reconstitués antérieurement à partir d'un réseau de collection de cicatrices de feu dans les forêts de pin situées à plus faible altitude partout dans le sud-ouest des États-Unis. Presque toutes les années durant lesquelles sont survenus en même temps des incendies qui ont entraîné le remplacement des peuplements et des feux de surface ont coïncidé avec des sécheresses sévères alors que les variations du climat ont engendré des conditions régionales telles que les incendies qui entraînent le remplacement des peuplements et les feux de surface ont brûlé l'ensemble des écosystèmes. La reconstitution des incendies qui ont entraîné le remplacement des peuplements antérieurement à une colonisation anglo-américaine substantielle dans cette région fournit une preuve directe que ces incendies étaient caractéristiques des forêts situées à haute altitude avant que débute l'utilisation généralisée et intensive des terres (coupe de bois, chemin de fer et activité minière) à la fin du 19^{e} siècle.

[Traduit par la Rédaction]

Introduction

The recent occurrence of extensive severe forest fires in the southwestern United States (Arizona, New Mexico, and proximate areas) has highlighted the need to improve our understanding of the historical role of stand-replacing fire in this region. Wildfires with multiple, high-severity burn patches (total or near-total canopy mortality) within larger burned perimeters include the Cerro Grande fire (2000, Jemez Mountains, New Mexico, 19 425 ha total area burned), the Rodeo-Chedeski fire (2002, White Mountains, Arizona, 187 220 ha), and the Bullock and Aspen fires (2002 and 2003, Santa Catalina Mountains, 46 667 ha). Although pre-20th century surface-fire regimes of southwestern United States ponderosa pine (*Pinus ponderosa* Dougl. ex Laws.) are well documented by historical accounts and numerous tree-ring studies (e.g., Bahre 1985; Baisan and Swetnam 1990; Swetnam and Baisan 1996; Fule et al. 1997; Allen 2002; Allen et al. 2002), relatively little research has been conducted on stand-replacing fires in the upper elevation spruce–fir and mixed conifer forests of the region (e.g., Touchan et al. 1996; Abolt 1997).

Extensive quaking aspen (*Populus tremuloides* Michx.) stands in the upper montane forests of the southwestern United States are known to represent a legacy of past stand-

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Fig. 1. View of seral aspen stands in the Sangre de Cristo Mountains of northern New Mexico. This view to the north shows patches of even-aged aspen stands on the south slopes of Santa Fe Baldy, with similar aspen stands in the distance (upper left). It is known from documentary sources (deBuys 1985) that a fire (or fires) burned in these elevations in the late 19th century, and our tree-ring sampling confirms this event in adjoining stands (SKI). Historical photos indicate that mixed conifer and spruce–fir stands existed on these slopes prior to the 19th century fire(s), and these conifer species are currently regenerating within and overtopping the aspen in parts of these stands, in accord with a paradigm of conifer–aspen–conifer succession in the region (Jones 1974; Dick-Peddie 1993).

replacing fires (Debyle and Winokur 1985; Jones and DeByle 1985*a*; Dick-Peddie 1993; Romme et al. 2001). Large even-aged aspen stands embedded within mixed-conifer and spruce–fir forests in the Sangre de Cristo Mountains, for example (Fig. 1), are considered by forest managers, environmental historians, and ecologists working in this region to be the seral stage of a conifer–aspen–conifer successional pathway (Dick-Peddie 1993). However, other successional pathways (i.e., nonseral), and uneven-age characteristics are also possible in quaking aspen. In parts of the Rocky Mountains, for example, aspen sometimes occurs as multiaged stands that appear to be “persistent” or self-replacing (Bartos 2001). In some circumstances aspen may encroach into upper tree-line niches (Elliott and Baker 2004) or into montane grasslands (Allen 1989). In contrast, aspen stands in upper montane forests of the southwestern United States have generally been described as “seral,” indicating a stand-replacing successional pathway with a single-tiered canopy, even-aged stand structure, and prominent, multiaged conifer regeneration in the understory (Jones and DeByle 1985*b*).

Quaking aspen fuel types have relatively low flammability, and stand-replacing crown fires do not carry well through the canopies of aspen-dominated forests, which enables fire managers to use aspen strategically as fire breaks (Jones and DeByle 1985*a*). Conifers regenerating within late-successional stage seral aspen stands provide the fuel that carries stand-replacing crown fires in forests containing aspen. Conifers are more likely to have dominated seral, postfire aspen stands at the time of the last stand-replacing fire than nonseral stands (Kulokowski et al. 2004, 2006). Thus, stand-replacing fires reconstructed in seral aspen stands likely represent fires burning in late successional stage conifer-dominant forest types (i.e., mesic mixed-conifer/aspen or spruce–fir/aspen).

The general successional pathway of these seral aspen stands in the southwestern United States is thought to proceed from: (*i*) mature conifer-dominated spruce–fir/aspen or mixed-conifer/aspen forests burned by stand-replacing crown fire, to (*ii*) rapid sprouting of aspen stems in large portions of the burned areas from aspen clonal root stock (and rarely from seed blown in from surviving mature aspen), to (*iii*) recolonization by conifer seedlings in the understory of the seral aspen stands from bird- or wind-transported seed, followed by (*iv*) the eventual overtopping of aspen by mature conifer trees, and (*v*) returning to a mature conifer forest with remnant old-age aspens persisting as scattered individual stems, often with younger aspen dispersed throughout the conifer forest in small canopy gaps that allow aspen clones to survive conifer dominance until the next stand-replacing fire (Jones 1974; Dick-Peddie 1993).

The successional process of rapid resprouting of aspen following stand-replacing fires in mixed conifer and spruce–fir forests, as described in the literature, is supported by contemporary observations of abundant aspen regeneration within recent high-severity burn patches in upper montane coniferous forests throughout the southwestern United States (e.g., Patton and Avant 1970 and portions of the Aspen fire 2003, Viveash fire 2000, Cerro Grande fire 2000, Clarke Peak fire 1996; personal observations of all authors). Conifer re-establishment within postfire seral aspen stands and eventual overtopping of the aspen are also supported by repeated observations of this circumstance in the southwestern United States (e.g., Fig. 1; Dick-Peddie 1993; Johnson 1994;

Bartos 2001). Moreover, this typical successional pattern of conifer replacing aspen has been the source of some concern regarding an observed decline of the aspen cover type in the region in the late 20th century (Johnson 1994; Bartos 2001). Given the recent large fires in this region and prolific aspen regeneration in these burns, this trend may now be reversing.

Quaking aspen is the classic early seral, clonal species that resprouts prolifically from extensive interconnected root networks and stem bases following stand-replacing fires in forests with aspen as a prefire component (Barnes 1966; Patton and Avant 1970). Aspen seedling establishment (from wind-dispersed seed) has been documented following recent fires but is considered rare (Romme et al. 1997; Quinn and Wu 2001). The aboveground mortality of aspen stems from fire alters the hormonally controlled apical dominance mechanism and stimulates vigorous vegetative regeneration, often referred to as “suckers” (Farmer 1962; Wan et al. 2006). The shade-intolerant aspen sprouts use resources from the prefire root systems to grow rapidly in dense thickets, providing an initial competitive advantage over other tree species (Farmer et al. 1988). Aspen suckers can reach heights >1 m in the first year of growth (Jones 1975; Crouch 1981). However, ungulate browsing may significantly reduce sucker growth (Romme et al. 1995) and inhibit successful recruitment into the canopy (Binkley et al. 2006).

The immediate suckering response of quaking aspen following stand-replacing fires in conifer-dominant forests provides an opportunity to reconstruct accurate, annually resolved fire dates using dendroecological techniques. The ages of postfire aspen regeneration can be a good indicator of the number of years since the stand-replacing fire. However, previous attempts to reconstruct annually resolved fire dates with aspen age structure based fire-history methods have proved to be challenging. Inability to always obtain aspen pith dates and lagged sprouting following some fires, seems to have resulted in difficulties in identifying the specific year of past stand-replacing fires from aspen age structure alone. For example, Romme et al. (2001) reconstructed stand-replacing fires with decadal resolution from aspen stands in the San Juan Mountains, Colorado, and they emphasized the lack of fire-scarred trees in aspen forests as a limitation to determining annually resolved fire dates. Touchan et al. (1996) encountered a range of aspen ages when sampling small, patchy, aspen groups in mixed-conifer stands of the Jemez Mountains, New Mexico, likely reflecting a mixed-severity fire regime and a fine-scale mosaic pattern of fire severity in these stands.

Abolt (1997) successfully dated stand-replacing fire events in the Gila Wilderness, New Mexico, by combining aspen age structure from large, seral, even-aged stands; fire scars from adjacent conifers; and documentary records. Combining multiple lines of tree-ring evidence from large, seral, aspen patches seems to be the best approach for reconstructing stand-replacing fire history in the upper montane forests of the southwestern United States. This multiple lines of evidence approach is an adaptation of stand-replacing fire history methods applied in boreal and subalpine forests of North America, where both age structures and fire scar evidence was used (Heinselman 1973; Agee 1993; Johnson and Gutsell 1994; Kipfmueller and Baker 1998).

Fire history site networks are extremely valuable for investigating the relationship between interannual climate variability and fire in time and space. Annually resolved fire dates are essential for identifying patterns of climate-induced fire synchrony and asynchrony across multiple sites in the network (e.g., Swetnam and Baisan 1996, 2003; Veblen et al. 2000). These studies indicate that surface fire occurrence is strongly related to drought during the fire year. A similar, but more pronounced, relationship between stand-replacing fire and drought during the fire year exists in the subalpine forests of the southern Rockies (Kipfmueller and Baker 2000; Sibold and Veblen 2006). Lagging relationships between fire occurrence and antecedent moisture conditions that drive fine fuel production have also been identified for some surface fire regimes in the southwestern United States in both fire scar studies (Swetnam and Baisan 1996) and in modern (20th century) fire statistics studies (Westerling et al. 2003; Crimmins and Comrie 2004). Variability of fire occurrence in the southwestern United States has been shown to be synchronous with synoptic-scale oscillations in the climate system. The wet and dry phases of the El Niño – Southern Oscillation (ENSO) significantly influence and synchronize fire occurrence in the southwestern United States (Swetnam and Betancourt 1990, 1998).

The primary objective of our research was to apply dendroecological techniques to reconstruct an annual-resolution, stand-replacing fire history network in upper montane (>2700 m) forests of the upper Rio Grande Basin. Our approach combined multiple lines of evidence, including quaking aspen age structure, conifer tree death dates, fire scars, and postfire growth responses to obtain annually resolved fire dates. The secondary objective was to use the fire history network to evaluate the role of interannual climate variability in stand-replacing fire occurrence and fire synchrony over large areas.

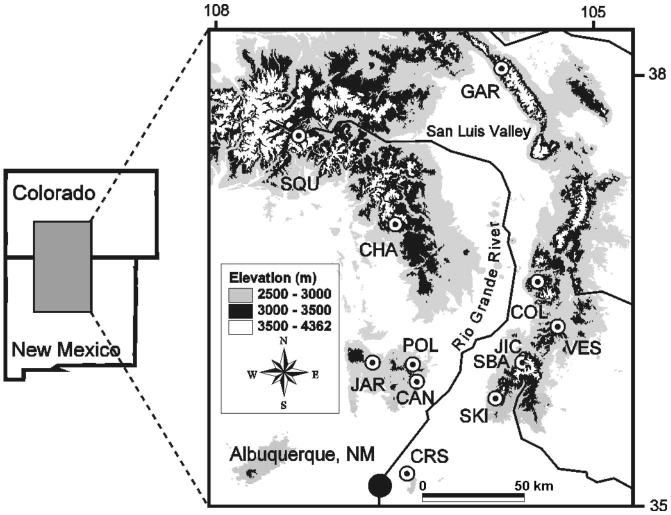
Methods

Study area

The study area is located in the upper Rio Grande Basin of northern New Mexico and southern Colorado in the southwestern United States (Fig. 2). The basin, at the southern limit of the Rocky Mountains, is encompassed by the four large mountain ranges we sampled: (*i*) Sandia, (*ii*) Jemez, (*iii*) Sangre de Cristo, and (*iv*) San Juan. The general elevation ranges from 1500 m at the Rio Grande River in Albuquerque, New Mexico, to >4200 m on the peaks of the San Juan and Sangre de Cristo Mountains. Mean elevation of the study sites ranges from 2794 to 3251 m, with samples collected between 2695 and 3479 m (Table 1).

The study sites are typical of the mesic high elevations of the southwestern United States that experience continental climate with a bimodal precipitation regime. Winter snowpack is common, except during exceptionally dry years (e.g., 2002). In the southwestern United States, a dry foresummer (April, May, and June) typically precedes the onset of a monsoon pattern in July. Fire hazard is most extreme in the premonsoon period, coinciding with dry, lightning-producing convective storms. Area burned on USDA National Forest land of Arizona and New Mexico peaks in this premonsoon period (June), although peak lightning ignition occurs in July with the full onset of the monsoon

Fig. 2. Location of study area and 12 study sites in the upper Rio Grande Basin of northern New Mexico and southern Colorado. See Table 1 for site abbreviations.



rains (Barrows 1978; Allen 2002, pp. 146–150). The severity of the late-spring, premonsoon fire season is influenced by the amount and timing of winter precipitation and snowpack that ultimately affects fuel moisture. Mean annual precipitation decreases with latitude and elevation within the study area, ranging from 1180 (1971–2000; Wolf Creek Pass, Colorado; elevation 3243 m) to 635 mm (1971–2000, <20 km from the CRS site, New Mexico; elevation 3258 m). Mean annual temperature at the same climate stations range from 0.8 to 3.0 °C (Western Regional Climate Center).[2]

The latitudinal and elevational gradients within the study area encompass a range of vegetation types. All study sites were selected based on the presence of large, contiguous, seral (i.e., containing conifer regeneration in the understory) aspen stands that were likely dominated by mixed-conifer or spruce–fir vegetation at the time of the last stand-replacing disturbance. The vegetation adjacent to, and regenerating within, the aspen stands ranged from pure spruce–fir to mixed-conifer (Table 1). Vegetation association was determined by current conifer regeneration within and adjacent to the stand and the remnant stumps, snags, and logs from the predisturbance forest. The tree species observed within and adjacent to the aspen stands included Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco.), white fir (*Abies concolor* (Gord. & Glend.) Lindl. ex Hildebr.), Englemann spruce (*Picea engelmannii* Parry), subalpine fir (*Abies lasiocarpa* (Hook) Nutt.), bristlecone pine (*Pinus aristata* Engelm.), and occasionally ponderosa pine. Soils were generally mollisols in the aspen stands or inceptisols at the higher elevations of the San Juan and Sangre de Cristo Mountains (Maker and Daugherty 1986).

Evidence of human presence in the Rio Grande Basin dates back to the Paleo-Indian cultures (e.g., Clovis), over 10 000 years B.P. The Oshara culture occupied the valley 3000 years B.P., followed by the most recent indigenous groups, the Puebloans in the south and the Utes and Comanches in the north (Wolf 1995). In 1540, Francisco Coronado led the Spanish into the basin from the south, and settlers arrived in the San Luis Valley, Colorado, by 1598

Table 1. Site information and number of dated tree-ring samples (sorted by ascending mean elevation).

Site identification	Site name	Vegetation type*	Mean elevation (m)	Aspen area (ha)	No. of sample points	No. of aspen inner-ring dates	No. of conifer fire scars	No. of conifer bark-ring dates	No. of conifer growth changes or injuries	Total dated tree-ring samples
JAR	Jarosa Springs	MC	2794	30	8	14	9	0	0	23
CHA	Chama River	MC	2841	1142	12	20	1	2	0	23
CAN	Quemazon Canyon	MC	2929	66	20	31	2	2	1	36
SBA	Santa Barbara River	MC/SF	2954	1173	19	38	0	8	2	48
COL	Columbine Creek	MC/SF	2963	274	14	25	0	4	0	29
VES	Valle Escondido	MC/SF	2984	163	21	27	8	6	6	47
CRS	Sandia Crest	SF	3033	30	15	31	0	6	1	38
SQU	Squaw Creek	SF	3097	219	11	20	0	0	2	22
JIC	Jicarita Creek	SF	3111	243	10	12	0	3	0	15
SKI	Santa Fe Ski Basin	SF	3124	823	26	64	1	4	1	70
POL	Polvadera Peak	SF	3242	59	15	22	1	0	4	27
GAR	Garner Creek	SF	3251	285	11	20	0	0	0	20

*MC, mixed conifer; SF, spruce–fir.

(deBuys 1985, p. 46). Widespread Anglo-American settlement in the San Luis Valley began in 1870, following the discovery of gold near Summitville, Colorado, and the ensuing mining boom (Agee and Cuenin 1924; Wolf 1995; USDA Forest Service 1999). Mining activity in the southern Sangre de Cristo Mountains of New Mexico increased dramatically between 1865 and 1870, following the end of the American Civil War (deBuys 1985; Pearson 1986). There are reports of fires resulting from railroad, mining, grazing, and Ute activity in the San Luis Valley, Colorado, where some aspen stands (fires) are reported to date to the post-1870 mining era (Agee and Cuenin 1924; USDA Forest Service 1999). However, a report issued by the forest supervisor of the former Cochetopa National Forest states "the source of most of these fires will never be known" (Agee and Cuenin 1924).

Field methods

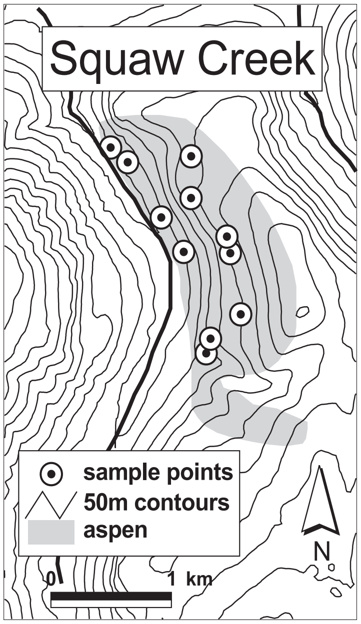
Study sites were selected to include 12 of the largest, seral aspen stands dispersed throughout the upper Rio Grande Basin (Fig. 2; Table 1) to reconstruct the dates of significant stand-replacing fires. Although this is a small number of sample sites for such a large area, these 12 largest extant aspen stands are widely distributed across the basin on a variety of landforms in the largest mountain ranges (i.e., Jemez, Sandia, Sangre de Cristo, and San Juan). Therefore, this network of sites provides the broadest historical perspective currently available of fire history in upper montane forests and of large stand-replacing fires at these elevations in the southwestern United States.

Two geographic information system data layers, a gap analysis program vegetation map for the region, and the Rio Grande National Forest vegetation map were used to help locate the largest aspen stands in the basin. Preliminary field reconnaissance identified misclassified stands and apparent multiaged, potentially self-replacing aspen stands adjacent to grasslands that were unlikely to be evidence of stand-replacing fires. Lack of accessibility, land ownership, and prior anthropogenic disturbance history (e.g., logging and mining) prevented sampling of some of the largest aspen stands.

Many of the largest aspen stands identified (>5000 ha) were located in the San Juan Mountains, Colorado, but were not selected, because they were in areas known to have extensive mining activity and because historical documents indicate that some stands resulted from fires used for land clearing by prospectors or railroad activity (USDA Forest Service 1999). By excluding these stands, our sample included only aspen stands (fires) that had an unknown cause (human or lightning). How the exclusion of these sites might affect our results and interpretations is addressed in the discussion section. Only two sites, Jarosa Springs and Chama River, had minor evidence of selective logging dating to the late 20th century within the stand.

Dendroecological sampling was conducted to obtain multiple lines of tree-ring evidence to determine stand-replacing fire dates at each of the 12 sites. The four lines of evidence included: (*i*) aspen inner-ring dates, (*ii*) fire-killed conifer bark-ring dates, (*iii*) conifer growth changes or other morphological tree-ring indications of injury (e.g., traumatic resin ducts), and (*iv*) conifer fire scars. Digital orthophotographic quarter quads were used to digitize aspen stand boundaries and systematically locate sample points to provide dispersed spatial coverage of the aspen stands.

Fig. 3. Location of tree-ring sample points within an aspen stand digitized from a digital orthophotographic quarter quad at Squaw Creek, Colorado, study site.



A minimum of 10 predetermined sample points were located within each aspen stand. The points were distributed throughout the stand on multiple transects following topographic contours to ensure broad and approximately even spatial sampling of the stand (e.g., Fig. 3). Less than 10% of the original sample point locations were altered in the field when necessary due to topography (i.e., inaccessible or unsafe places), weather, decayed aspen heartwood, and time constraints. Additional points were added to include unmapped areas and to ensure adequate density to date the aspen patch. Extensive searching among the original sample points was necessary to locate all three lines of conifer evidence (i.e., fire-killed conifers, fire scars, and traumatic resin ducts or growth releases — see further description below), because this material is relatively rare in upper montane forests of this region (especially fire scars). All sample locations were mapped using a global positioning system transponder, which reported a maximum error of 15 m.

Quaking aspen inner-ring dates

A minimum of 15 aspen stems per site were cored to adequately characterize postfire regeneration. The minimum sample size was adapted from methods used to date postfire lodgepole pine (*Pinus contorta* Dougl. ex Loud.) cohorts (Kipfmueller and Baker 1998). The two largest (diameter at breast height; DBH) aspen stems within 10 m of the predetermined sample points were cored. Two or more increment cores were extracted from each stem at ≤0.3 m core height

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[2] Historical climate data are available from Western Regional Climate Center, Reno, Nevada: www.wrcc.dri.edu/Climsum.html.

until at least one core from the sample point contained the pith ring.

Given that aspen suckers often achieve heights of 1 m or taller within the first year of growth (Jones 1975; Crouch 1981), it is likely that cores containing the pith ring at the <0.3 m level should usually contain all of the years (rings) of growth. It is possible that repeatedly browsed aspen suckers may require multiple years to attain heights of 0.3 m (Romme et al. 1995), adding "noise" to dates of postfire recruitment. If inner rings were not attainable because of decayed heartwood, then the search radius was extended up to 20 m to obtain two solid aspen stems.

Conifer evidence of fire

Three additional types of tree-ring evidence of past fires were obtained by searching for and collecting conifer samples to determine (*i*) fire-killed conifer bark-ring dates, (*ii*) fire scar dates, and (*iii*) dates of growth changes or injuries. These specimens were found by searching systematically (i.e., walking transects through the aspen stands and around the stand perimeters). These three forms of evidence were relatively rare and usually required extensive searching to locate intact specimens within and adjacent (<100 m) to the sampled aspen stands. More information on the nature of these lines of evidence is described below.

Fire-killed conifer bark-ring dates

Fire-killed conifers within the aspen stands typically appeared as broken, standing stems with no branches. We targeted samples that retained relatively intact bark and (or) sapwood on portions of the bole (Fig. 4). Char was always present on the bark and the branch stubs. Char was generally not present on the woody part of the bole, because the tree was apparently killed by fire and, thus, would have been protected by full bark. Extensive charring of the bole may indicate a tree that had died an undetermined number of years before the fire and had lost its protective bark; in such cases, the outer ring may not be reliably used to date the stand-replacing fire event.

Fire-killed conifers (Douglas-fir and (or) Engelmann spruce) were present at all sites and very abundant in some locations. However, because of extensive (>100 years) exposure in these mesic, upper elevation environments, all samples were decomposed, and many did not have intact sapwood. Because of the relatively poor condition of the samples, none of the Engelmann spruce and only some of the Douglas-fir samples could be successfully cross-dated out to the bark ring. By "bark-ring" dates, we mean that intact bark was present on the outermost dated ring, and (or) it was evident from the outermost wood and ring surface (e.g., presence of intact, solid sapwood or beetle galleries) that the final ring indicates the actual death date of the tree (Bannister 1962). Only samples with bark-ring dates were used in the reconstructions ("death dates" in Figs. 5 and 6).

Fig. 4. Photograph from Santa Barbara River, New Mexico, study site of a remnant fire-killed Douglas-fir with intact bark (left) among an even-aged, postfire quaking aspen stand.

The presence of bark and intact sapwood on these trees was quite remarkable, considering that some of these snags persisted on the landscape for >160 years after death. The DBH of many of the fire-killed Douglas-fir trees was >100 cm with the remaining bark measuring up to 20 cm in thickness. The intact sapwood beneath the bark was often discolored because of the presence of resin that was seemingly "cooked" into the sapwood during the fire event. The resin apparently prevented portions of the wood from deteriorating, allowing the sapwood to be preserved and all rings out to the bark-ring to be clearly visible and dateable with the cross-dating technique.

Although fire-killed conifers were present at all sites, we were not able to cross-date and, thus, did not include samples from three (25%) of the study sites becuase of poor sample preservation and lack of interannual ring variability. In all cases, we considered the possibility that sampled conifer snags died from other causes (e.g., drought or beetles) and were subsequently burned. However, we interpreted the coincidence of the bark-ring dates (on dated snags) with the inner-ring dates (piths) of aspen, along with physical characteristics of the snags (char on bark and branch stubs), to constitute multiple lines of evidence confirming our interpretation that they were mostly likely killed by these fire events.

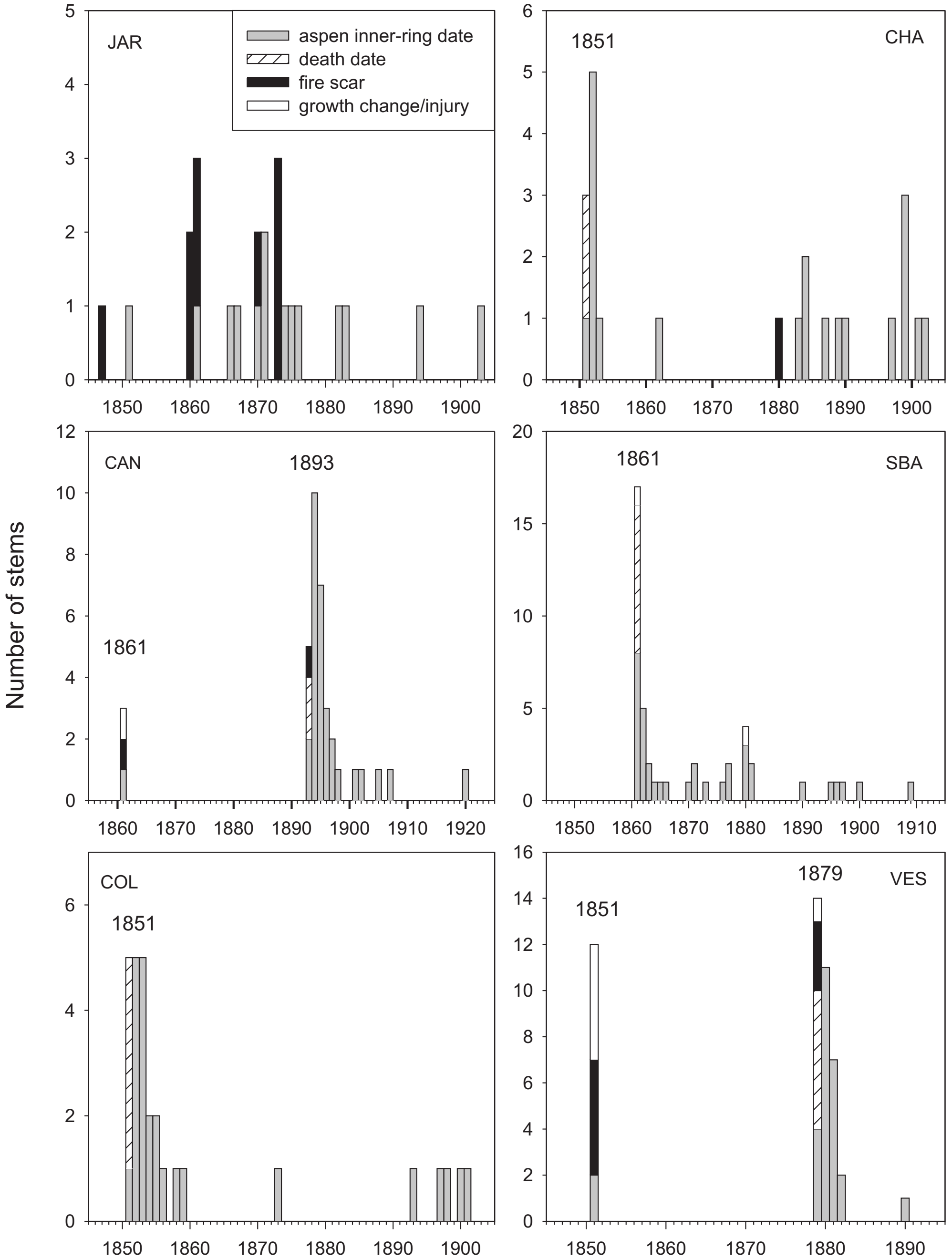
Conifer fire scars

Partial cross sections were collected with chainsaws from fire-scarred trees using standard procedures where easily accessible (Arno and Sneck 1977). Seventy-five percent (eight) of the sites were in wilderness areas and (or) were too remote to carry chainsaws, so hand saws were used to collect samples in these cases. Fire-scarred trees were very rare, and most were found on south-facing slopes at the lower ecotone of the aspen stands, around the perimeters of the aspen stands where old-growth conifers survived the reconstructed stand-replacing fire, or in fire-protected sites (e.g., near or within rock outcrops).

Conifer growth changes or morphological indicators of injury

Potentially injured, fire-survivor trees were identified by

Fig. 5. Aspen age structure and conifer tree-ring evidence used to reconstruct stand-replacing fire events (e.g., 1851) at sites with mean elevation <3000 m. The high number of fire scars and lack of an aspen recruitment pulse at the lowest elevation site, JAR, suggest a higher frequency surface fire regime that was not stand replacing. See Table 1 for site abbreviations.



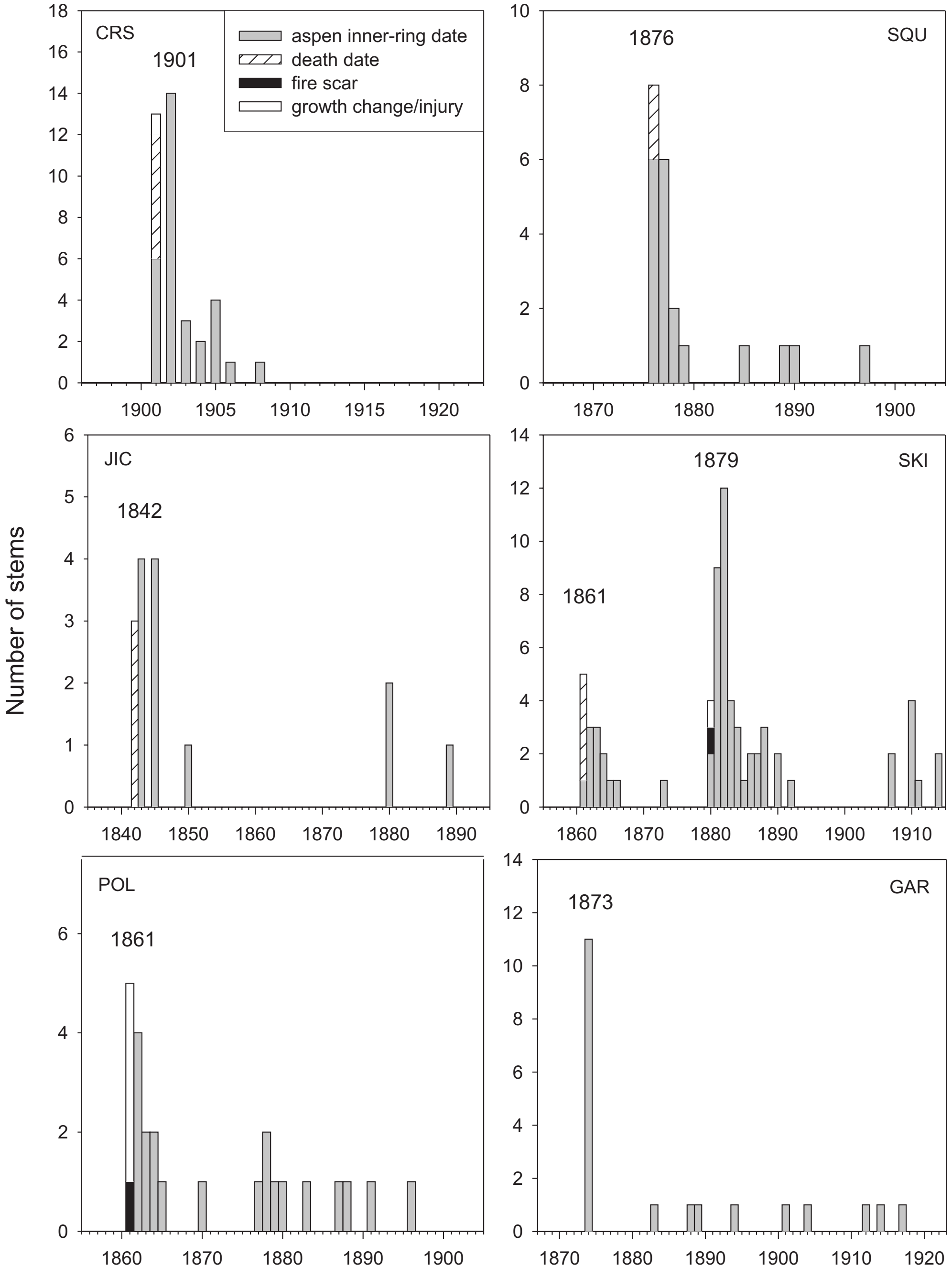
relatively large DBH (compared with most surrounding trees), elevated crown base height, unilateral loss of branches, charred bark, or scarring on the underside of lower branches. In the rare case that fire survivors were present within or immediately adjacent to the aspen stand, they were most often large Douglas-fir trees. It seems likely that the thick fire-resistant bark of older Douglas-fir trees, and chance, allowed some of these trees to survive high-severity fire in the near vicinity.

Increment cores were collected from potential fire-surviving conifers at a height of approximately 1.5 m. Increment cores from some injured trees contained morphological indicators of injury (e.g., traumatic resin ducts) or growth change in the year of the fire (as dated by fire scars and (or) conifer bark-ring dates) and, sometimes, in the following year. In some cases, the growth change (dramatic, multiyear suppression or release) occurred in the ring containing the resin ducts. Growth changes or resin ducts in rings of injured trees that lagged fire dates were not included in the plots, because we could not be sure of the cause of the injury.

Laboratory methods

All conifer samples were prepared and cross-dated according to standard dendrochronological procedures (Stokes

Fig. 6. Aspen age structure and conifer tree-ring evidence used to reconstruct stand-replacing fire events. Mean elevation of sites is >3000 m, with spruce–fir vegetation dominantly associated with the aspen. See Table 1 for site abbreviations.



and Smiley 1968). Diffuse porous ring structure of aspen and growth suppressions from possible tent caterpillar outbreaks in some samples required special surfacing methods to ensure proper viewing of annual ring patterns. The cores were first cut with a razor and then hand sanded with progressively finer grit sandpaper, finishing with 15 μm paper. Cross-dated inner-ring dates were determined for all aspen samples. Dormant season fires, indicated by fire scars on conifers, were assigned to the subsequent year, based on the dominant occurrence of spring and early summer fires in the region (Barrows 1978; Swetnam and Baisan 1996). All fire-killed conifer bark-ring dates were in the earlywood, enabling the year of tree death to be determined without interpretations relating to dormant season death.

Dates from the four lines of tree-ring evidence and associated spatial data were compiled for each site to determine fire dates. A reconstructed fire was considered to be stand-replacing if an aspen recruitment pulse initiated within 2 years after a fire scar date or a fire-killed conifer bark-ring date. Postfire aspen regeneration density typically peaks within 3 years postfire (Patton and Avant 1970; Romme et al. 1995). We considered all aspen with inner rings dating ≤5 years after conifer fire evidence to be part of the postfire recruitment cohort. We used this 5 year window to include

Table 2. Stand-replacing fires and "other" fire dates reconstructed from multiple lines of tree-ring evidence in the upper Rio Grande Basin.

Site	Stand-replacing fire dates	Other fire dates*
CAN	1861, 1893	
CHA	1851	1880
COL	1851	
CRS	1901	
GAR	1873	
JAR	—	1847, 1860, 1861, 1870, 1873
JIC	1842	
POL	1861	
SBA	1861	
SKI	1861, 1879	1806
SQU	1876	
VES	1851, 1879	1748

Note: See Table 1 for site abbreviations.

*"Other" fire dates derived from fire scars without an associated post-fire aspen recruitment pulse (e.g., JAR).

cores that were very near to, but did not include, the pith ring and additional suckers that lagged the fire by up to 5 years. Various pith date estimation techniques have been used in dendroecology studies when the actual pith is not obtained in an increment core. However, we chose not to estimate pith ring dates in this study to eliminate associated errors (e.g., overestimated number of years to pith resulting in erroneously dating aspen recruitment occurring before the fire event). Instead, we relied on our collection of the pith ring in ≈50% of the aspen stems (one of every two aspen stems sampled at a sample point) to adequately capture the timing of the actual postfire recruitment pulse.

Data analysis

The composite, stand-replacing fire history from the 12 sampled sites was analyzed for interannual fire–climate relationships and synchrony with regional surface fire occurrence. The reconstructed summer (June, July, and August) Palmer drought severity indices (PDSI) (Cook et al. 1999) for the grid points (50 and 51) centrally located within the study area were averaged to derive a regional PDSI time series for the fire–climate analyses. Because of the general lack of spring precipitation in the southwestern United States and the lagging nature of PDSI (Palmer 1965), summer PDSI largely reflects prior winter precipitation and snowpack. The regional PDSI time series was used to quantify drought conditions during years of stand-replacing fire occurrence. Superposed epoch analysis (SEA) (Baisan and Swetnam 1990) was used to test for relationships between stand-replacing fire occurrence and reconstructed summer PDSI, including antecedent conditions. SEA was also used to test for interannual relationships between stand-replacing fire occurrence and ENSO phase and strength using a tree-ring reconstruction of the Southern Oscillation index (SOI) (Stahle and Cleaveland 1993).

To test for co-occurrence of stand-replacing fire years and "regional" surface fire years (i.e., >20% of sites recording fire) from a southwestern United States fire history network (Swetnam and Baisan 1996) we used a 2 × 2 contingency table. The contingency table was initially evaluated with a χ^2 goodness-of-fit test, but small sample sizes resulted in expected values less than five. Because of this limitation, a Fisher's exact test was used to test for independence among the data sets (Milton 1999). We tested the null hypothesis that stand-replacing fire years and regional surface fire years were independent (i.e., the number of coincident fire dates of the two types was no more frequent than might occur by chance). We set an a priori probability level of $p < 0.05$ to reject the null hypothesis.

Results

Stand-replacing fire dating

A total of 850 increment cores and partial cross sections were collected from 329 aspen stems and 99 conifers at 12 study sites. Ninety-three percent of the samples were successfully cross-dated and used to reconstruct fire dates (Table 1). The remaining samples were excluded, because annual dates could not be assigned to the tree rings. Accurate crossdating in these cases was not possible because of low interannual ring variability, too few rings present, decayed wood structure, or severe growth suppressions.

Seventy-five percent of the aspen regenerated within 5 years following fires recorded by conifer samples. The aspen regeneration pulses were associated with conifer evidence of fire at 11 of 12 sites (Figs. 5 and 6). The one exception was Garner Creek, where fire-killed conifer evidence was present but not dateable because of poor sample preservation and complacent (low-variance) tree-ring growth.

All aspen inner-ring dates that were synchronous with conifer evidence of fire were pith dates, confirming our dating of the fire event. Distinct, aspen regeneration peaks were observed at all sites, clearly identifying a dominant cohort with no fire survivors. Multiple peaks of aspen regeneration were found at three sites (e.g., Santa Fe Ski Basin; see Fig. 6) and represented two stand-replacing fires. At these sites, tree-ring evidence of the two fires was separated geographically within the site. There was rarely evidence of multiple fires at any particular point within a sampled site (21 of 172 sample points) and almost half (nine) were from Jarosa Springs.

Twenty-two fires (1748–1901) were reconstructed with annual accuracy (Table 2). Fourteen fires from eight unique fire years were interpreted to be stand replacing, based on the synchrony of conifer evidence of fire and the immediate postfire aspen recruitment pulse. The stand-replacing fire dates ranged from 1842 to 1901, with up to four sites recording fires during the same year (1861). The remaining, nonstand-replacing ("other") fire dates were identified by fire-scarred trees with no associated aspen recruitment pulse. The majority of the nonstand-replacing fire dates were from the smallest aspen stand at the driest and lowest elevation site (Jarosa Springs; see Fig. 5), which was also unique among these study sites in that it contained a relatively high proportion of ponderosa pine and no spruce–fir vegetation.

Fire–climate analysis

All reconstructed stand-replacing fire dates occurred during drought years (Fig. 7). The PDSI value during all but

Fig. 7. Stand-replacing fire years plotted on reconstructed Palmer drought severity index (PDSI) time series (1835–1915), indicating severe drought during fire year. A 35 year spline of the PDSI data indicates prolonged, reduced PDSI coinciding with the period of reconstructed stand-replacing fires (1840–1900).

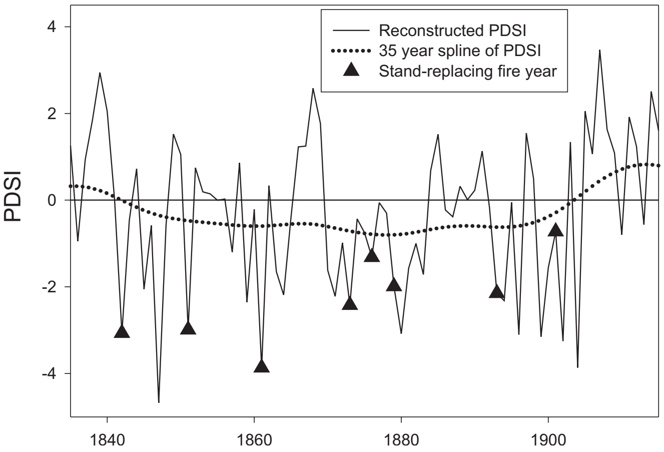
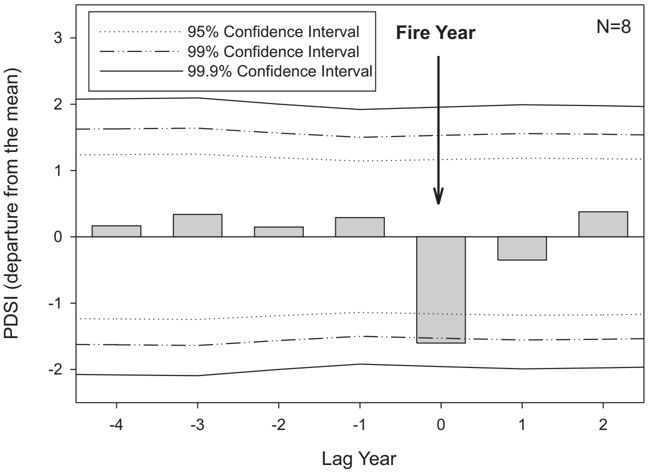


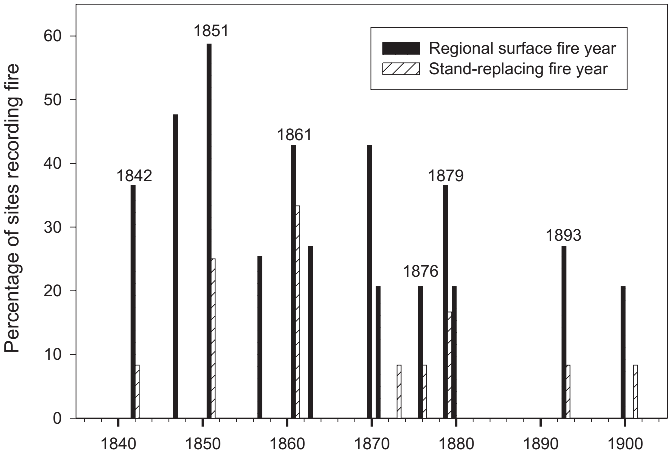
Fig. 8. Superposed epoch analyses (SEA) illustrating negative (dry) departure of reconstructed summer Palmer drought severity index during stand-replacing fire years ($N = 8$) from the mean (1838–1903). Confidence intervals indicate a significantly dry fire year with no antecedent relationship with climate.



one stand-replacing fire year was <–1.0, and the mean value was –2.78, indicating moderate to severe regional drought. Stand-replacing fire years were significantly ($p < 0.01$) related to negative (dry) departures from the mean summer PDSI (1838–1903) (Fig. 8) but not antecedent PDSI. No significant relationships were found between stand-replacing fire dates and SOI (results not shown).

Seventy-five percent of stand-replacing fire years occurred during regional surface fire years (Fig. 9). The null hypothesis of independence between stand-replacing fire occurrence and regional surface fire occurrence was rejected (Fisher's exact test; $p < 0.001$). Stand-replacing fires were not recorded during all regional surface fire years (e.g., 1847).

Fig. 9. Southwestern United States regional surface fire years (>20% of sites recording; total sites = 63) compared with stand-replacing fire years (all: total sites = 12). Observed synchrony between regional surface fires and stand-replacing fires was significantly greater than expected by chance ($p < 0.001$, Fisher's exact test).



Discussion

This study demonstrates that stand-replacing fires occurred in multiple locations across the upper Rio Grande Basin in the later half of the 19th century, and climatic variability was a primary driver of fire occurrence in these upper montane forests. The legacy of these fires is clearly indicated by the large, even-aged seral quaking aspen stands we sampled. Extensive, even-aged seral aspen stands in other regions of Colorado are the result of large 19th century stand-replacing fires in what were primarily conifer-dominated subalpine forests (Kulokowski et al. 2004, 2006). Our observations support the importance of stand-replacing disturbance in the general successional model described for the persistence of seral quaking aspen in upper montane conifer-dominated forest types of the southwestern United States (Jones 1974; Dick-Peddie 1993).

Mid to late 19th century stand-replacing fire occurrence

The short, relatively recent period of stand-replacing fire occurrence (1842–1901) we reconstructed with our sample is interesting given the much longer history of fire and the relatively old age of midelevation pine forests throughout the region. Many fire scar chronologies and ponderosa pine tree ages extend back to the early 1600s in the southwestern United States, for example (Swetnam and Baisan 2003). There are some historical accounts of late 19th century stand-replacing fires in northern New Mexico, including areas where we reconstructed fires in the Sangre de Cristo mountains (deBuys 1985). A high incidence of stand-replacing fire in the southern Rocky Mountains and Colorado Front Range during the late 1800s was attributed to a combination of land-use practices, such as railroads, logging, and mining activities; conversion of forest to sheep pastures; and climatic conditions suitable for large, severe fires (Veblen et al. 2000; Donnegan et al. 2001; Allen 2002, pp. 170–176; Sibold et al. 2006).

Interestingly, individual years of synchronous occurrence of stand-replacing fire in the upper Rio Grande Basin and regional surface fire throughout the southwestern United States (e.g., 1851 and 1879) were also years of widespread and stand-replacing fire occurrence in other regions of the southern Rockies. Donnegan et al. (2001) report 1851 as a "synchronous fire year," when multiple, distant stands recorded fire in the Pike National forest of central Colorado. Sibold et al. (2006) reconstructed stand-replacing fires in multiple watersheds of subalpine forests in northern Colorado in 1851 and 1879. The co-occurrence of fires during specific years across ecosystem types from the southwestern United States to northern Colorado suggests that climate variability was likely the synchronizing factor. The relative roles of climate and anthropogenic effects on middle to late 19th century fire occurrence are addressed below.

The earliest reconstructed stand-replacing fire date was 1842, and the latest was 1901. Does this represent a period of relatively high fire occurrence, or is it just the period of record that we were able to reconstruct because we were limited by our methods or the nature of the tree-ring record? The concentration of fire dates in this period has multiple potential explanations. One explanation is a phenomenon we call the "burning record" problem. By definition, stand-replacing fires "erase" or burn evidence of prior fires (i.e., postfire cohorts and rare, remaining fire-killed or fire-scarred trees). This is a major hurdle to overcome when reconstructing stand-replacing fire regimes (Johnson and Gutsell 1994). It is possible that the 19th century fires we reconstructed consumed all evidence of prior fires within the patches that we sampled. However, age structure based stand-replacing fire-history studies commonly extend back for hundreds of years (e.g., Heinselman 1973; Kipfmueller and Baker 2000; Sibold et al. 2006). Thus, at the landscape scale, it seems unlikely that more recent fires completely erased all evidence of postfire cohorts prior to 1842.

A second possibility is that we were limited as to how far back in time we could reconstruct fires by the longevity of aspen stems. Traditionally, aspen stands were classified as mature or "overmature" at 120 years (Jones and Schier 1985). However, very old aspens (i.e., >280 years old) have been found in multiple mountain ranges in the southwestern United States, where they can persist as codominants in conifer stands (e.g., Abolt 1997).

The third (and we think the primary) explanation for the lack of postfire aspen cohorts predating 1842 was an unintended bias in our site selection toward younger stands. Older, seral aspen stands are less conspicuous and smaller than younger stands because of infilling and overtopping by shade-tolerant conifers as postfire succession proceeds. Therefore, older aspen stands are less likely to be included in the set of the largest stands in the region that we identified for our original sample sites. This probably biased our reconstruction toward more recent fires. With additional searching, mapping and sampling of smaller stands and groups of old aspen trees and cohorts, it should be possible to extend the record of stand-replacing fire dates. A systematic sample of larger numbers of aspen stands of varying sizes across a series of upper montane landscapes might be used to capture the full age range of aspen cohorts (fires) (e.g., Romme et al. 2001) and, thereby, determine whether the late 19th century temporal cluster of stand-replacing fire events is unusual or not.

We suspect our sampling strategy may have truncated the early record of stand-replacing fires in the region, but it seems unlikely that the lack of stand-replacing fire dates after 1901 in our data set was due to a sampling bias. We preferentially targeted the largest aspen stands in the region, but we did not select against 20th century stands. The well-documented reduction of fire in the southwestern United States since ca. 1900 is coincident with a dramatic decline in aspen cover (i.e., 95% reduction in Arizona and 88% in New Mexico) (Johnson 1994; Bartos 2001) and, consequently, the lack of large aspen stands dating to the 20th century. However, a number of very recent high severity crown fires, (e.g., 1996 Hondo fire near Taos, N.M., the 2000 Cerro Grande fire near Los Alamos, N.M., and the 2000 Viveash fire, near Pecos, N.M.) burned across elevation gradients, including ponderosa pine to spruce–fir forests, and have induced aspen regeneration in fairly large patches (personal observations of all authors).

Effects of Anglo-American settlement and climate variability on stand-replacing fire occurrence

The middle to late 19th century was a period of greatly increased Anglo-American settlement in the western United States, and northern New Mexico and southern Colorado were not exceptions to this historical pattern. Changing human land-use patterns, leading to increased ignitions, have been shown to increase fire occurrence in localized areas of the southwestern United States and Colorado (Baisan and Swetnam 1997; Veblen et al. 2000; Donnegan et al. 2001). Therefore, it is possible that increased human ignitions in high elevation forests influenced the occurrence of stand-replacing fires in the upper Rio Grande Basin (Allen 2002, pp. 170–176). Widespread Anglo-American economic exploitation of, and settlement in, the upper Rio Grande Basin began between 1865 and 1870 with increased mining activity (Agee and Cuenin 1924; deBuys 1985, p. 149; Pearson 1986; Wolf 1995; USDA Forest Service. 1999). However, 57% of the stand-replacing fire events we reconstructed occurred prior to widespread Anglo-American settlement in the study area, including two of the most synchronous years: 1851 and 1861 (Table 2). Synchronous occurrence of large, stand-replacing fires in our study area before extensive Anglo-American settlement suggests that humans (at least Anglo-Americans) were not the primary cause of these events. Further, given the correspondence of these fire events with regional drought and regional surface fire dates (Figs. 7, 8, and 9), it appears that climate was a primary, and possibly the most important, factor driving the regional synchroneity of the middle to late 19th century stand-replacing fires we reconstructed.

Historical accounts indicate that some of the large aspen stands in the San Luis Valley, Colorado, that we excluded from our sample resulted from fires set during the period after ca. 1865–1870 settlement era (Agee and Cuenin 1924; USDA Forest Service. 1999). We can only speculate about the relative importance of various ignition sources and climate conditions when these fires were burning. We cannot rule out the possibility that the presence of more people in the high elevations provided more ignition sources during relatively dry, low lightning occurrence seasons. The fuels generated by logging, clearing for mining, and other activities could also have contributed to extensive high-severity burns.

We did not find evidence of mining or logging-related fire activity at any of the remaining 10 sites outside of the San Luis Valley, Colorado, and none of the largest aspen stands identified in New Mexico were excluded from the sample. Thus, it is likely that stand-replacing fire activity in the San Luis Valley was affected by increased ignition sources during the period of intensive mining activity. However, the data suggest that, in the remainder of the study area and before ca. 1865–1870, fire occurrence and synchrony were primarily determined by the infrequent occurrence of drought conditions necessary for successful ignition and fire spread in these mesic high-elevation forests, regardless of ignition source.

We interpret the data to indicate that drought conditions likely were of primary importance in driving upper montane forest fire regimes and that ignition frequency or source (human or lightning) were of only secondary importance. This interpretation is also supported by a general argument (and supporting data) that northern New Mexico landscapes have ubiquitous lightning-caused ignitions in almost every year, and hence, it is generally not necessary to invoke additional ignitions by human causes to explain reconstructed fire regimes (Allen 2002). Moreover, it is notable that lightning ignitions are also fairly common in the late spring and summer, and sufficiently dry conditions for fire spread (especially during drought years) may persist in the southwestern United States until September, October, or even later during some years. Consequently, relatively few successful ignitions in dry years could result in very large areas burned over periods of months prior to the fire suppression era.

Fire–climate relationships

The SEA revealed a strong relationship between fire occurrence and drought with no antecedent relationships. Only eight unique fire event years were used in the SEA analyses in this study, which may be fewer than desired for a robust replication of fire–climate patterns. However, the plot of fire years on the PDSI time series confirms the consistent pattern of coincident drought and stand-replacing fire occurrence in the stands we sampled (Fig. 7).

A fire–climate relationship where only severe drought is strongly associated with fire occurrence was also evident in the upper elevation mixed-conifer forests of the Jemez Mountains, New Mexico (Touchan et al. 1996), and in composites of mixed-conifer fire dates in the southwestern United States regional fire scar network (Swetnam and Baisan 1996, 2003). Similar fire–climate relationships exist in subalpine forests of Colorado (Sibold et al. 2006). This contrasts with replicated findings in lower elevation pine-dominant forests, where significantly wet antecedent conditions apparently enhanced fuel production and increased the probability of fire spread in subsequent dry years (e.g., Swetnam and Baisan 1996; Crimmins and Comrie 2004). Results from the current study support the hypothesis that upper elevation forests (mesic mixed-conifer to subalpine spruce–fir) are relatively less fuel limited on interannual time scales than ponderosa pine forests and, therefore, only require sufficient desiccation of the fuels (and an ignition source) for fire occurrence (Swetnam and Baisan 2003).

Our study is the first to identify the synchronous occurrence of upper elevation stand-replacing fire, widespread regional surface fire, and drought at a landscape scale in the southwestern United States. This has potentially important implications for both management and the understanding of disturbance ecology in the forests of the region. The potential for direct linkages (i.e., fire spread) between upper elevation (high-severity) and lower elevation (low-severity) fire regimes needs further investigation. Extensive and continuous sampling of fire-scar and age-structure evidence along elevation gradients would be necessary to test this hypothesis. An important ramification of a hypothesis of fire spread from low to high elevations relates to the potential for effects on upper elevation forests and fire regimes as a result of the late 19th to early 20th century cessation of surface fires in lower elevation pine-dominated forests (Swetnam and Baisan 1996, 2003).

Ecological and management implications

Our results documenting the specific timing of stand-replacing fires in the upper Rio Grande Basin, and associations with past droughts, suggest that such "fire–climate" events are an inherent part of these forest ecosystems, and, therefore, are likely to recur in the future. Recent severe droughts and warming temperatures in the southwestern United States, and western United States as a whole, may be a larger factor in driving increased areas burned and numbers of large forest fires in the past two decades than previously recognized (Westerling et al. 2006). In general, recent large stand-replacing fires in the southwestern United States (such as those listed in the introduction) have occurred predominately in middle elevation, ponderosa pine dominant forests. However, given the clear association between past droughts and stand-replacing fires in the mesic, upper elevation conifer forests where our sampled aspen stands were embedded, we expect that, if future warming occurs as a result of greenhouse gases, more stand-replacing fire events will likely occur in coming decades.

The probability of burning these high-elevation, montane forests is likely also a function of successional stage (i.e., species composition). During the seral stage when aspen dominate a site, there may be lower fire risk, which may increase through time as succession proceeds and conifers invade the site. Both the ephemeral nature of upper montane, seral aspen stands and the paradigm that they often represent past large, stand-replacing fire patches in what were formerly conifer-dominated forests are key points for management of these forest types. Identifying the details of when and how the fire risk and fuel loads change through the successional process should be addressed by future research.

Currently, managers, scientists, and policy-makers are developing and experimenting with restoration treatments (e.g., prescribed fire and (or) forest thinning) in the midelevation ponderosa pine dominated forests of the southwestern United States that were altered by grazing, logging, and fire suppression over the past century (Allen et al. 2002). This is based on the well-established paradigm that many of these forests changed drastically as a consequence of the elimination of successive, low-severity surface fires a century or longer ago (Swetnam and Baisan 1996). Confirming earlier observations of southwestern United States forest ecologists (e.g., Dick-Peddie 1993), our results from higher elevation forest types indicate a very different fire regime. We found that these forests sustained high severity, stand-replacing fire regimes with relatively little evidence of low-severity surface fire. This important difference in natural fire regimes and the range of potential forest density and composition changes through succession should be recognized in developing management strategies for these upper elevation landscapes (Schoennagel et al. 2004; Sibold et al. 2006).

Conclusions and summary

Stand-replacing fire dates were successfully derived from seral quaking aspen stands using multiple lines of dendroecological data. Fire–climate analysis of this new network of fire history sites indicates significant relationships between severe regional drought, regional surface fire occurrence, and stand-replacing fire occurrence in upper montane forests of the upper Rio Grande Basin. Multiple reconstructed fire dates (1851 and 1879) were synchronous within our study area and with sites elsewhere in Colorado. The abundance and synchrony of pre-1865 fires, and the strong fire–drought relationships suggest that 19th century stand-replacing fire occurrence in the study area was not primarily due to increased Anglo-American settlement in the region. Severe drought seems to be an essential factor driving the occurrence of these fire events. The occurrence of stand-replacing fires during regional surface fire years indicates that climate created regional conditions conducive to fire across ecosystems in the southwestern United States.

This study of stand-replacing fire in the upper Rio Grande Basin describes only a small number of historic stand-replacing fires in the region. Increasing the geographic extent of the network is necessary to determine if these results apply to other upper elevation forests in the southwestern United States. A larger network could be used to answer a number of important questions relating to (*i*) sub-regional spatial variability in stand-replacing fire occurrence in upper montane forests throughout the southwestern United States, (*ii*) spatial variability in fire–climate relationships, (*iii*) the potential for fire forecasting through a detailed analysis of climate–fire associations (i.e., antecedent climatic conditions or PDSI thresholds associated with stand-replacing fire occurrence), and (*iv*) the geographic extent of climate forcing for widespread fire years (e.g., 1851).

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