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Paired charcoal and tree-ring records of high-frequency Holocene fire from two New Mexico bog sites

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Abstract. Two primary methods for reconstructing paleofire occurrence include dendrochronological dating of fire scars and stand ages from live or dead trees (extending back centuries into the past) and sedimentary records of charcoal particles from lakes and bogs, providing perspectives on fire history that can extend back for many thousands of years. Studies using both proxies have become more common in regions where lakes are present and fire frequencies are low, but are rare where high-frequency surface fires dominate and sedimentary deposits are primarily bogs and wetlands. Here we investigate sedimentary and fire-scar records of fire in two small watersheds in northern New Mexico, in settings recently characterised by relatively high-frequency fire where bogs and wetlands (Chihuahueños Bog and Alamo Bog) are more common than lakes. Our research demonstrates that: (1) essential features of the sedimentary charcoal record can be reproduced between multiple cores within a bog deposit; (2) evidence from both fire-scarred trees and charcoal deposits documents an anomalous lack of fire since ~1900, compared with the remainder of the Holocene; (3) sedimentary charcoal records probably underestimate the recurrence of fire events at these high-frequency fire sites; and (4) the sedimentary records from these bogs are complicated by factors such as burning and oxidation of these organic deposits, diversity of vegetation patterns within watersheds, and potential bioturbation by ungulates. We consider a suite of particular challenges in developing and interpreting fire histories from bog and wetland settings in the Southwest. The identification of these issues and constraints with interpretation of sedimentary charcoal fire records does not diminish their essential utility in assessing millennial-scale patterns of fire activity in this dry part of North America.

Additional keywords: Alamo Bog, CHAPS, Chihuahueños Bog, fire scars, Jemez Mountains, replicated charcoal records.

Introduction

Fire is widely recognised as a keystone disturbance process in forests of the south-western United States (Swetnam and Baisan 1996), driving a myriad of ecological patterns and other processes (Bogan *et al*. 1998). Fire activity is sensitive to climatic conditions, in that fire regimes change through time in response to climatic variability (Swetnam and Betancourt 1998; Grissino-Mayer and Swetnam 2000; Swetnam and Baisan 2003; Westerling *et al*. 2006; Kitzberger *et al*. 2007). As climate reconstructions for the Southwest indicate substantial variability at all time scales (Grissino-Mayer 1996), fire activity almost certainly has also varied markedly through time. However, quantitative documentary records of fire activity in the Southwest only extend back about a century (Westerling *et al*. 2006). Thus reconstruction of prehistoric fire regimes requires use of paleoenvironmental methods, each with particular strengths, weaknesses, and uncertainties (Swetnam *et al*. 1999).

Two primary methods for reconstructing paleofire occurrence are: (i) dendrochronological dating of fire scars and stand ages from live or dead trees (Swetnam and Baisan 1996; Margolis *et al*. 2007), which in the Southwest can typically push back regional fire histories up to 500 years before present (BP); and (ii) the development of sedimentary records of charcoal particles from lakes and bogs (Patterson *et al*. 1987; Whitlock and Anderson 2003), providing perspectives on fire history that can extend back for many thousands of years. Each of these techniques has unique strengths as well as weaknesses. Used in conjunction, the two proxies can provide complementary information on past fire activity (Whitlock *et al*. 2003). To deduce long-term patterns of forest fire, dendrochronological approaches can be used to calibrate sedimentary reconstructions, such as has been done in fire history studies from Alberta (MacDonald *et al*. 1991; Laird and Campbell 2000), the Klamath-Siskiyou region (Mohr *et al*. 2000; Briles *et al*. 2005), northern Rockies (Brunelle and Whitlock 2003; Brunelle *et al*. 2005), western Washington (Higuera *et al*. 2005), and Finland (Pitkänen *et al*. 1999). Similarly, studies comparing forest stand ages (to estimate long-interval stand-replacing

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fire histories) with sedimentary charcoal fire dates come from British Columbia (Hallett and Walker 2000; Gavin *et al*. 2003, 2006; Hallett *et al*. 2003; Hallett and Hills 2006), Yellowstone (Millspaugh and Whitlock 1995), and Alaska (Anderson *et al*. 2006). Research that combines both charcoal and tree-ring fire history methods has been particularly rare in settings where high-frequency surface fires were dominant, and from bogs and wetlands, as most charcoal records from western North American forests have been developed from sites characterised by long-interval, stand-replacing fire regimes and from lake sediments. This is largely because lake and water-saturated bog environments most conducive to accumulating charcoal-bearing sediments are commonly found in cold, mesic, high-elevation settings in western North America where fires are less frequent, whereas the relatively few perennially wet sedimentary basins at drier, lower-elevation sites tend to have been altered by people to better impound water for livestock or human use. However, charcoal records can be developed from those suitable bogs and meadows that are found within drier lower-elevation forest types (Anderson and Smith 1997; Whitlock and Anderson 2003), although the processes of charcoal creation and deposition in these settings are less certain than for lakes, introducing additional interpretation challenges.

One major question surrounding the use of sedimentary charcoal to reconstruct fire histories concerns the reproducibility of these records. Because the development of high-resolution sedimentary charcoal chronologies is expensive and labour-intensive, such chronologies rarely are replicated to determine the consistency of charcoal patterns between different sediment samples collected within a single site. The limited literature is reviewed here. Comparing four charcoal sediment cores from a small Scottish lake, Edwards and Whittington (2000) observe that 'charcoal measures (concentrations, influx and charcoal to pollen ratios) all follow similar patterns, though with very different numerical values', suggesting the need for caution in the interpretation of charcoal records from any single core. From adjoining peat sediment cores taken 30 cm apart at a site in north-east England, Innes *et al*. (2004) found that the 'major trends and frequency peaks and troughs of the twin microcharcoal curves were found to correspond well', but that 'too precise an interpretation of microcharcoal data at this temporal scale may not be justified'. Similarly, a massively replicated study of sedimentary charcoal from 247 cores across 11 forested peat basins in south-east Norway (Ohlson *et al*. 2006) found many examples of 'horizontally aligned charcoal layers in neighbouring (peat sediment core) sequences that almost certainly originated from the same fire event', but also significant spatial heterogeneity of within-site charcoal records attributed to patchy surface fires.

In the present paper, we contribute information relevant to sedimentary charcoal analysis of non-lake sites. Our goals here are to investigate long-term records of moderately high-frequency fire activity from paired and replicated charcoal and tree-ring proxies of fire at two medium-elevation bog sites in the Jemez Mountains, northern New Mexico. We use these records to:

(1) demonstrate the replication of essential features of sedimentary charcoal records from duplicate cores within a deposit;
(2) reconstruct variable fire regimes and fire–climate relationships over millennial time scales at two sites with relatively high fire frequencies;
(3) compare fire history methods and interpretations between tree-ring and charcoal proxies of fire occurrence at the individual sites; and
(4) consider the particular challenges of developing and interpreting fire histories from bog and wetland settings in the Southwest.

Fire history of the south-western US and the Jemez Mountains

It is clear that fire has been a vital ecological process for at least several centuries in forested landscapes of the south-western United States (Swetnam and Baisan 1996, 2003), including the Jemez Mountains of northern New Mexico (Touchan *et al*. 1996; Allen 2002). An extensive network of dendrochronological fire history research sites has been developed in the Southwest (Swetnam *et al*. 1999), with multiple study sites in many mountain ranges across the region (Fulé *et al*. 2003; Swetnam and Baisan 2003; Brown and Wu 2005). Tree-ring fire-scar records document high-frequency surface fire regimes before ~1900 in most south-western ponderosa pine forests, and in many mixed-conifer forests (Swetnam and Baisan 1996). Livestock overgrazing and active fire suppression caused sharp declines in regional fire activity from the late 1800s through the late 1900s (Swetnam and Baisan 2003). These patterns are mirrored at fire-scar sites in the Jemez Mountains (Touchan *et al*. 1996; Allen 2002).

In contrast, comparable high-resolution sedimentary charcoal fire history sites are rare in the mountains of the Southwest. Several low-resolution (i.e. centennial-scale) records occur for the Kaibab Plateau of Arizona (Weng and Jackson 1999) and for the southern Rockies (Petersen 1981, 1985; Fall 1997). Recently, however, several high-resolution records of fire have been produced (i.e. Bair 2004; Toney and Anderson 2006; Anderson *et al*. 2008*a*, 2008*b*) that have the potential for reconstruction of fire patterns at decadal scales. These Holocene-length records show periods of synchrony in burning across broad spatial scales, suggesting the importance of climate in determining long-term changes in fire frequency in the mountains of the Southwest.

Study area

Chihuahueños and Alamo bogs are located in the Jemez Mountains of northern New Mexico (Fig. 1). The heart of this volcanic range is physiographically dominated by the Valles Caldera, formed by collapse after huge pyroclastic eruptions ~1.1 million years BP, and the central resurgent dome, Redondo Peak (Wolff and Gardner 1995). These relatively low mountains reach maximum elevations of ~3500 m. Chihuahueños Bog is located just outside the caldera rim on the north side of the Jemez Mountains at an elevation of 2925 m, within the Santa Fe National Forest (Fig. 1; Brunner-Jass 1999). The 2.3-ha bog is at the mouth of a small watershed near the lip of Chihuahueños Canyon (Fig. 2), situated on a low-relief upland (~45 m total relief in this watershed). Unpublished geological mapping indicates that Chihuahueños Bog occurs at the geological contact between

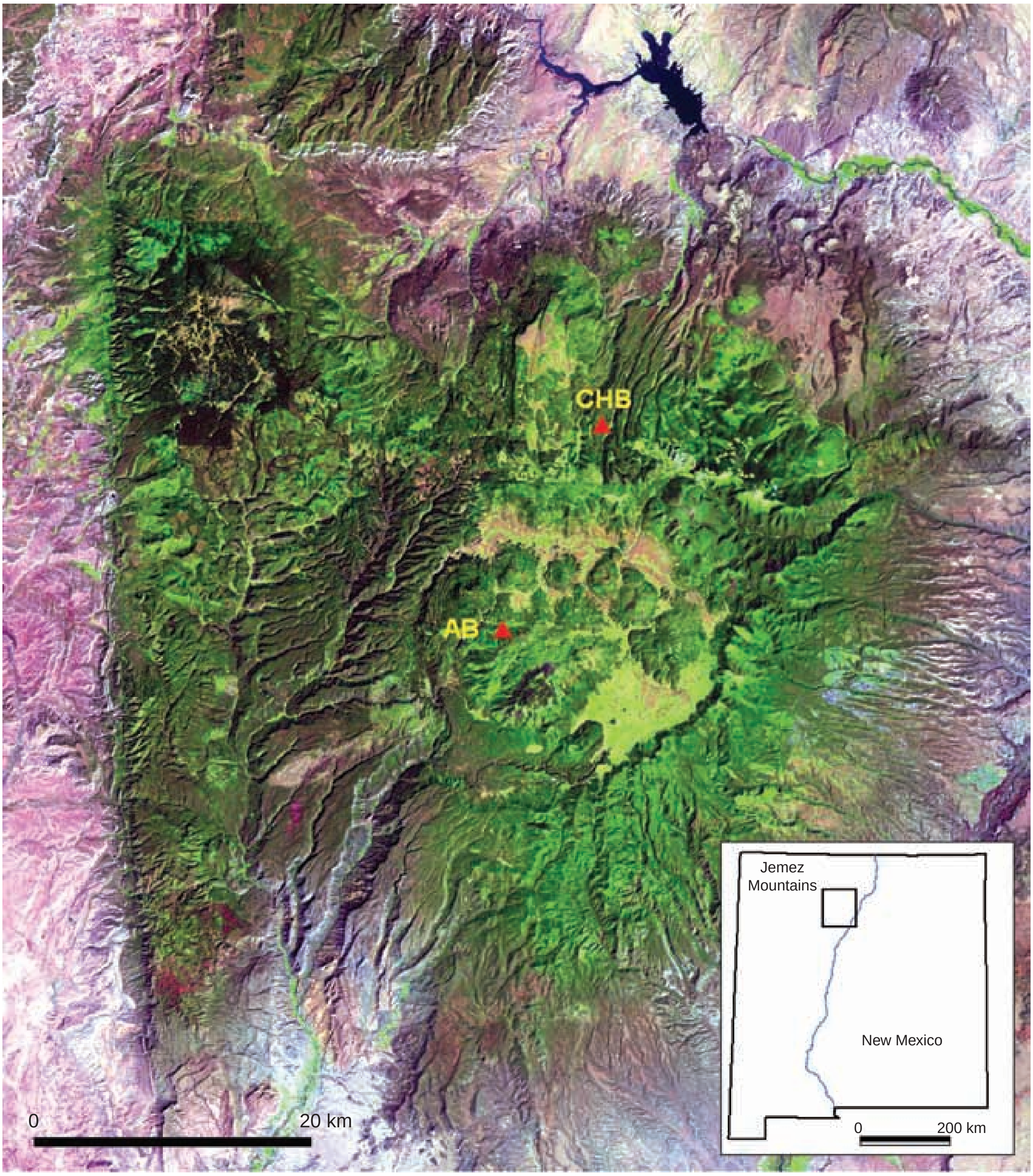

Fig. 1. True colour satellite image of the forested uplands (dark green) of the Jemez Mountains, with locations of Chihuahueños Bog (CHB) and Alamo Bog (AB). Inset map shows location of the image within New Mexico.

Bandelier Tuff to the south and an irregular Tschicoma dacite hill to the north, and perhaps the bog occupies a paleotopographic feature (Steve Reneau, pers. comm.). Although the bog is apparently kept wet throughout most years by subsurface water flows, after dry winters during extended drought episodes, the surface of large portions of the bog can dry out (C. D. Allen, pers. obs. in 2000 and 2006).

The surface cover of Chihuahueños Bog is currently dominated by large sedges and some grasses (Anderson *et al*. 2008*b*; Fig. 2), including tufted hairgrass (*Deschampsia cespitosa*). The

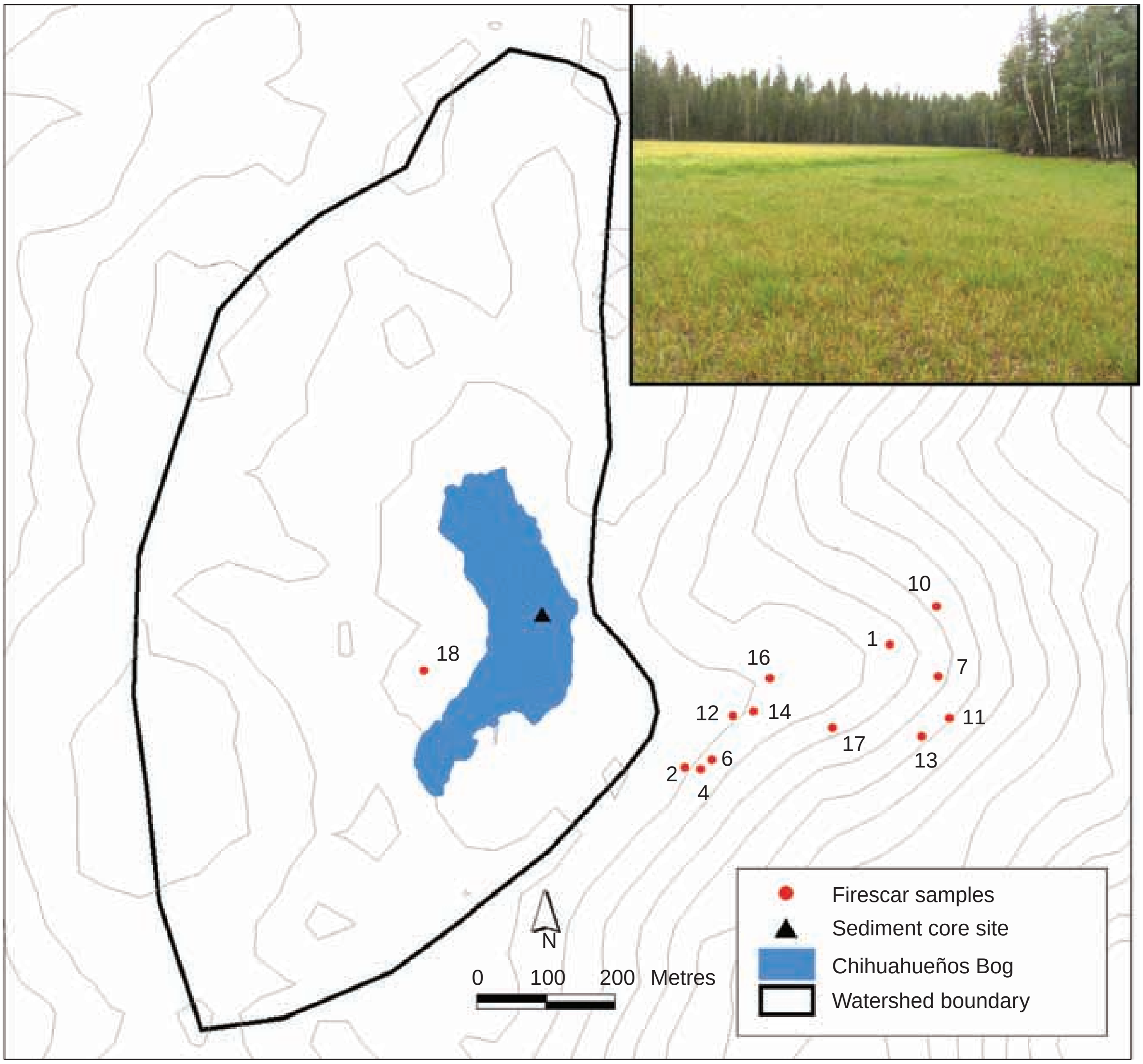

Fig. 2. Topographic map view of Chihuahueños Bog in its small, low-gradient watershed, and locations of the sediment core site and sampled fire-scarred trees, with tree sample numbers. Contour interval = 12.2 m (40 ft). Inset photograph shows Chihuahueños Bog surrounded by mixed-conifer forest.

bog occurs amid mixed-conifer forest, typical of that found elsewhere in the Jemez Mountains and the southern Rocky Mountains (Allen 1989), with nearly every conifer species extant in the Jemez Mountains growing in this small watershed. The upland forests are dominated by Douglas-fir (*Pseudotsuga menziesii*), with codominant species including white fir (*Abies concolor*), Engelmann spruce (*Picea engelmannii*), quaking aspen (*Populus tremuloides*), Colorado blue spruce (*Picea pungens*), corkbark fir (*Abies lasiocarpa* var. *arizonica*), and south-western white pine (*Pinus strobiformis*). Ponderosa pine (*P. ponderosa*) dominates the exposed south-east aspect canyon slopes below the bog level, with a few individuals found on the uplands too. Other woody species growing around the bog include common juniper (*Juniperus communis*), Gambel oak (*Quercus gambelli*), shrubby cinquefoil (*Potentilla fruticosa*), and kinnickinnick (*Arctostaphylos uva-ursi*). A variety of herbs and grasses grow in a relatively sparse understorey in the upland forest, including bluegrass (*Poa* sp.), bluebells (*Campanula parryi*), wild strawberry (*Fragaria* sp.), paintbrush (*Castilleja* sp.), pussytoes (*Antennaria* sp.), sage (*Artemisia* sp.), and yarrow (*Achillea lanulosa*). The upland forests throughout the small bog watershed have been heavily logged in recent decades, reducing the material available for dendrochronological sampling of fire scars; however, the adjoining upper slopes of Chihuahueños Canyon remain uncut, with many fire-scarred ponderosa and south-western white pines present.

Alamo Bog is located within the Valles Caldera National Preserve on the north-west flank of the resurgent dome of Redondo

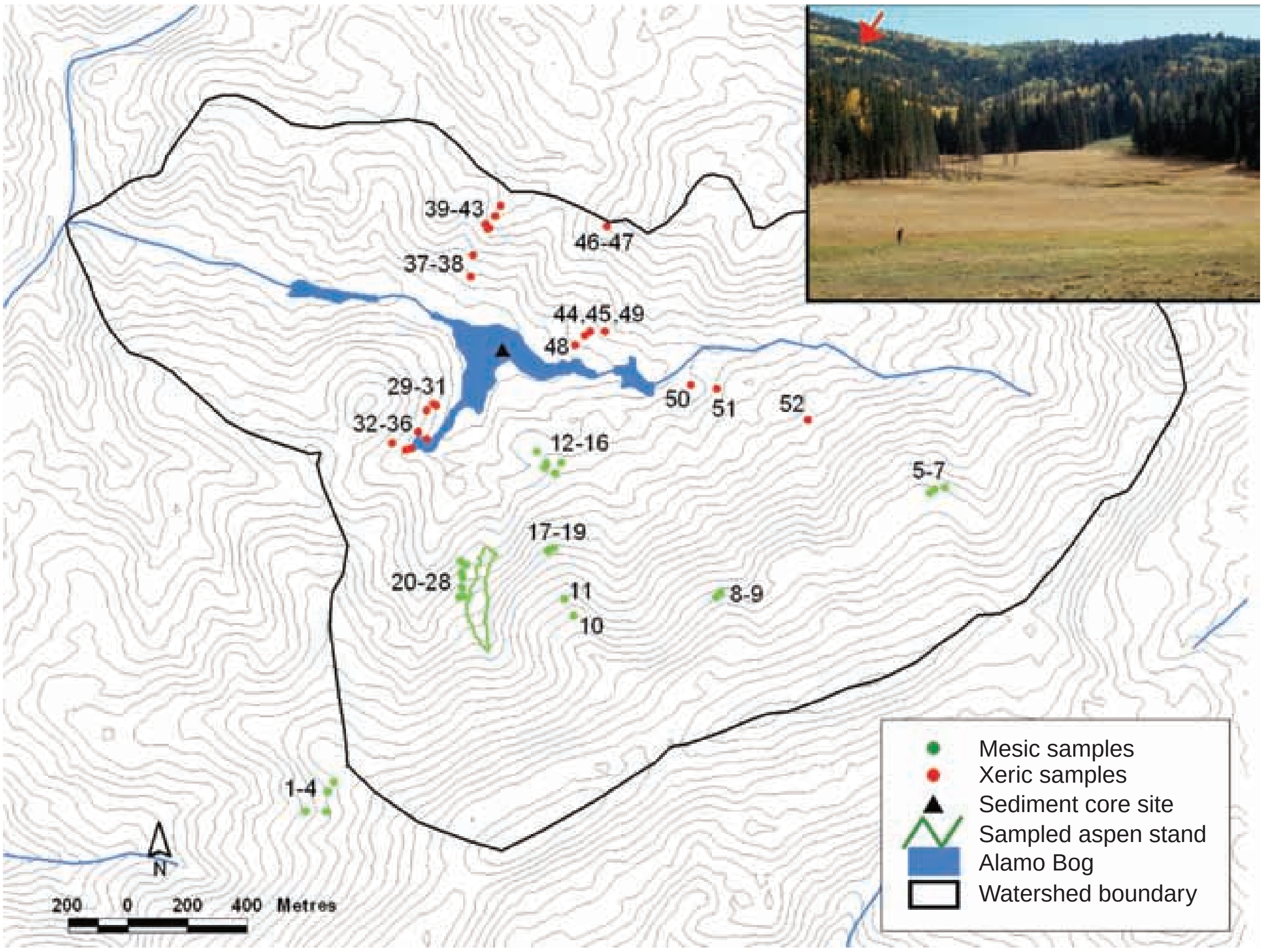

Fig. 3. Topographic map view of Alamo Bog in the Alamo Canyon watershed, with locations of the sediment core site, fire-scarred tree samples at red (xeric sites) and green (mesic sites) dots with tree sample numbers, and outline of the dated aspen stand that regenerated in 1879. Contour interval = 12.2 m (40 ft). Inset photograph shows Alamo Bog and mixed-conifer forest on north aspect slope; arrow indicates the sampled aspen stand.

Peak, at 2630 m elevation (Fig. 1; Brunner-Jass 1999). Alamo Bog extends as a linear wet meadow for >1 km along the drainage axis of Alamo Canyon (Fig. 3; Brunner-Jass 1999). This unusual fenlike feature is maintained by groundwater flows along the valley bottom, with pockets of upwelling water and hydrothermal gas venting, and portions have the 'bouncy' feel of a quaking bog. The Alamo Bog watershed exhibits substantial topographic relief, with steep forested slopes extending 400 m above the bog. North-facing slopes are currently blanketed in dense mixed-conifer forest, dominated by Douglas-fir and aspen, but characteristically including ponderosa pine on the lower slopes, white fir and south-western white pine in mid-slope stands, and grading into dominance by Engelmann spruce and corkbark fir at the highest slope positions. Understorey species in these mesic forests are similar to those at Chihuahueños Bog. In contrast, the south-facing slopes exhibit open stands of ponderosa pine and Gambel oak (and a few small groups of mixed-conifer species) interspersed among grasslands and dry meadows. Selective logging has removed large trees from most of the south-aspect hillslopes and all lower slopes near the bog, while the highest north-aspect slopes were clearcut in the early 1970s. Like Chihuahueños Bog, the current surface cover of Alamo Bog is dominated by large sedges and grasses, prominently including the big wetland bunchgrass, tufted hairgrass.

Two climate stations occur close to Chihuahueños Bog and Alamo Bog. Annual average maximum and minimum temperature and precipitation for the Pajarito Mountain station (3158 m (10 360 ft), ~20 km SE of Chihuahueños Bog and 17 km east of Alamo Bog) are 10.0°C, 0.6°C and 53.6 cm (Anderson *et al*. 2008*b*; http://www.weather.lanl.gov, accessed 10 January 2008). For the Los Alamos station (2256 m (7400 ft)), ~27 km SE of Chihuahueños Bog, and 24 km east of Alamo Bog, similar parameters are 15.5°C, 2.5°C, and 45.9 cm (Anderson *et al*. 2008*b*; http://www.wrcc.dri.edu/summary/climsmnm.html, accessed 10 January 2008). Maximum precipitation occurs during the July–August summer monsoon, recording nearly half the annual precipitation total. Winter (December–February) is usually the driest season, but spring (April–June) is also quite dry. The snowfree season is usually May through October, but snow can fall at any month at the Pajarito Mountain site (Anderson *et al*. 2008*b*).

Methods

Both Chihuahueños and Alamo bogs were cored in August 1996, after steel probing rods were used to find the deepest sediment deposits. A Livingstone corer was used to collect multiple cores at both sites. Cores were brought to the Laboratory of Paleoecology at Northern Arizona University for storage and analysis (Brunner-Jass 1999). Chihuahueños Bog sediment cores CHB-1 and CHB-2 were taken ~2 m apart in the middle of the bog where the sediments were the thickest with a Livingstone corer. CHB-1, the longer of the two cores, measured 465 cm. At Alamo Bog, sediment cores AB-3 and AB-4 were collected from ~2 m apart, with the deeper core AB-4 extending 496 cm. The longest core at each site was initially selected for laboratory analyses, including detailed stratigraphy, magnetic susceptibility, pollen, plant macrofossils, radiometric age dating, and charcoal – see Brunner-Jass (1999) and Anderson *et al*. (2008*a*) for details on the standard methodologies used. Measured ^{14}C ages, both radiometric and calibrated along with age uncertainties, and ^{210}Pb dates, are presented in table 2 in Anderson *et al*. (2008*a*). Subsequently we sampled the upper portions of each replicate core for charcoal content. Multiple radiometric methods were utilised to date these cores. Radiocarbon dates were obtained from dating charcoal fragments or bulk sediments. Radiocarbon ages were calibrated to calendar ages using CALIB version 5.0 (Stuiver *et al*. 1998). Gamma spectrometry (Appleby 2001) was used to develop ^{210}Pb and ^{137}Cs ages of whole sediment samples from the upper portions of each core.

High-resolution charcoal records were developed from all four cores by sampling every cm downcore for charcoal (Brunner-Jass 1999; Anderson *et al*. 2008*a*). Charcoal extraction and analyses followed the methods developed by Whitlock and Millspaugh (1996), with samples sieved through 125-μm and 250-μm screens. The two primary (long) cores were sampled at cm-resolution for the entire length of AB-3 and the upper 399 cm of CHB-1. Charcoal concentrations were also sampled for the upper portions only from the two replicate cores (CHB-2 and AB-4), to allow comparison of reconstructed charcoal patterns between cores within a site. The top 99 cm of CHB-2 were sampled at cm-scale resolution, and the upper 68 cm of AB-4 were sampled at 0.5 cm-scale resolution. We used CHAPS (Charcoal Analysis Programs; for details of this program see Whitlock *et al*. 2008) to reconstruct long-term fire episode frequencies (FEF) for the charcoal records at these two bog sites. Fire 'episodes' were determined for peak charcoal influx values that exceeded a threshold of 1.01 times the background charcoal influx rate, averaged across a 200-year moving window.

Fire-scarred conifer trees were located and sampled in the forests adjoining both Chihuahueños Bog and Alamo Bog (Figs 2 and 3). Where possible, samples were selected to emphasise (i) fire-scarred trees close to and upslope of each bog; (ii) representative coverage of the area and the forest types near and surrounding each bog; and (iii) clusters of fire-scarred trees. At Alamo Bog, we collected fire-scar samples from locations adjoining the bog as well as from situations farther upslope, from both xeric and mesic sides of this valley watershed, and in a network that almost completely surrounds the sediment core sites (Fig. 3). At Chihuahueños Bog, logging in recent decades has removed most of the older trees from the gentle terrain surrounding the bog, leaving almost no upland fire-scarred wood available to sample, only low rotten stumps of Douglas-fir and white fir that lacked useable fire-scar evidence. Thus the nearest fire-scarred samples were found 200–500 m from the bog on the more exposed upper slopes of Chihuahueños Canyon east of the bog (Fig. 2), with the exception of one Douglas-fir sample located 70 m west of the bog. At both sites, the high connectivity of the terrain and fuels between the bog and adjoining forests suggests that surface fires would have spread easily between these settings. Chainsaws were used to collect whole or partial cross-sections from both live and dead trees using standard methods (Arno and Sneck 1977). Full cross-sections were taken from dead trees and partial sections from live trees. Sampled species were primarily ponderosa pine, south-western white pine, and Douglas-fir. All conifer samples were transported to the Laboratory of Tree-Ring Research at the University of Arizona, where they were prepared and crossdated according to standard dendrochronological procedures (Stokes and Smiley 1968). Seasonal position of fire scars was assigned based on the relative position of individual scars within the annual growth rings. Dormant season fires, indicated by fire scars, were assigned to the subsequent year, based on the dominant occurrence of spring and early summer fires in the region (Barrows 1978; Dieterich and Swetnam 1984; Grissino-Mayer *et al*. 2004). Chihuahueños Bog fire scars were successfully crossdated from three live and 10 dead trees, and at Alamo Bog from nine live and 43 dead trees (C. D. Allen, unpubl. data). In addition, the origin date of one aspen stand in the Alamo Bog watershed (Fig. 3) was estimated by crossdating near-basal increment cores collected from 13 overstorey aspen trees within the stand (C. D. Allen, unpubl. data, cf. Margolis *et al.* 2007).

Fire-scar data were graphed and analysed with the FHX2 software (Grissino-Mayer 2001). We considered 'spreading' fires to occur in years with at least 10% of previously scarred sample trees recording a fire scar, and at least two trees scarred, along with a distance threshold if only two or three trees recorded a particular fire date – at Chihuahueños Bog the scarred samples had to be at least 100 m apart from each other, and at the much larger Alamo Bog site the samples had to be at least 400 m apart. There was only one instance at each site when a fire was counted as 'spreading' based on just two samples, and the Chihuahueños Bog samples were 175 m apart, and at Alamo Bog, the two trees were over 600 m apart and on opposite sides of the Alamo Bog sample point. Mean fire intervals were calculated between years with 'spreading' fire activity for time periods thought to have an adequate sample depth of scarred trees. A superposed epoch analysis (Swetnam and Baisan 2003) module in FHX2 was used to determine lagged inter-year relationships between the Palmer Drought Severity Index (PDSI), a measure of climatic moisture conditions, and fire activity as reconstructed from fire scars. For each bog site, we compared annual PDSI values from the Cook *et al*. (2004) dendroclimatic reconstruction for the nearest grid point (118, 107.5°W, 37.5°N) with years with at least 10% of previously scarred sample trees recording a fire scar, and at least two trees scarred.

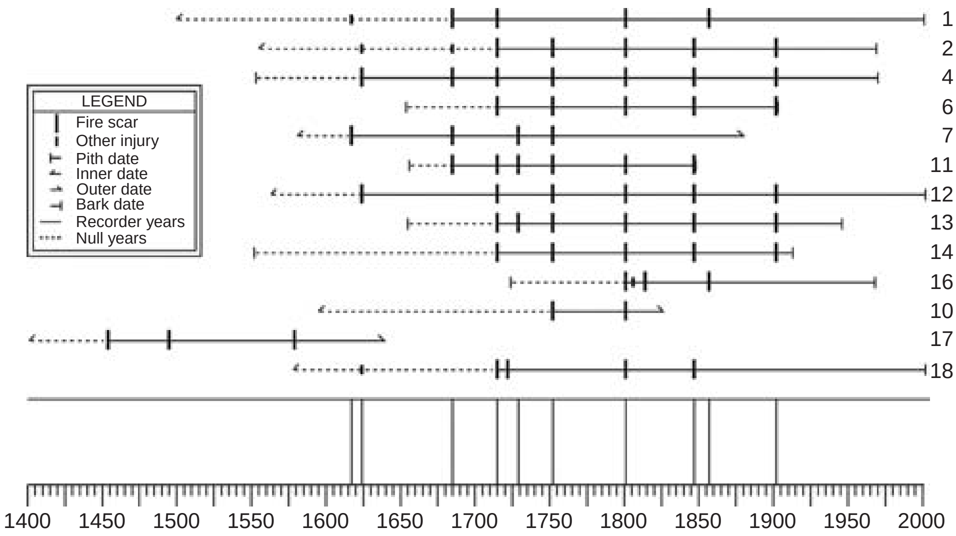

Fig. 4. Composite fire-scar chronology from forests adjoining Chihuahueños Bog. Horizontal lines show the calendar-year life-spans of individual trees (labelled with sample numbers), and the short vertical lines are fire-scar dates. The longer vertical lines at the bottom of the chronology indicate years with spreading fires, in which fire scarred at least 10% of previously scarred trees and a minimum of two samples. Note the synchrony of fire years across samples, and the cessation of spreading fires after 1902.

Results and discussion

Chihuahueños Bog

Cross-dated fire scars from 13 sampled trees in the forests adjoining Chihuahueños Bog recorded fires back to 1454 (Fig. 4). Nine spreading fires were recorded between 1624 and 1902. Fires typically scarred most of the sampled trees, indicating a spreading surface fire regime. For this period, the mean interval between spreading fires was 34.8 years (range 10 to 61 years), compared with a mean fire interval range of 11.1 to 15.3 years for the period 1801 to 1893 from four different mixed-conifer forest sites in the eastern Jemez Mountains (Touchan *et al*. 1996). The single tree (no. 18) sampled on the west side of Chihuahueños Bog (Figs 2 and 4) was closest to the bog and recorded five fire dates between 1624 and 1847, for a point mean fire interval of 55.8 years. The most recent fires at Chihuahueños Bog dated to 1857 and 1902, with no subsequent fire activity recorded, which is consistent with regional and local landscape patterns of historic fire suppression (Swetnam and Baisan 1996; Allen 2002). Fire seasonality could be determined for 29 of 64 scars, distributed as three dormant, 15 early earlywood, five mid-earlywood, and six latewood. After 1800, the fire-scar seasonality strongly shifted towards early season fires (one dormant, 10 early earlywood, and one latewood scar), as observed elsewhere in the Southwest (Swetnam and Baisan 2003).

Note that the scarred samples from the upper-slope forests near Chihuahueños Bog to the east were largely downhill of the bog in such a way that the recorded surface fires would readily spread upslope through relatively open forest stands with adequate surface fuels, with no topographic or fuels barriers to fire spread, providing ample opportunities for fire to reach the bog. Further, four of the five scar dates from the single dated upland tree on the west side of the bog (sample 18 in Figs 2 and 4) matched well replicated fire dates from the group of trees off the east side, supporting the idea that fires commonly burned between the upland mixed-conifer forests and the adjoining upper valley slope. Thus the only available fire-scar records from this site (which we sampled) are likely reasonable proxy indicators of the frequency with which spreading fires burned to the margins of Chihuahueños Bog.

Superposed epoch analysis for widespread fires at Chihuahueños Bog between 1618 and 1906 (Fig. 5) showed a PDSI departure exceeding -2 during fire years (year $= 0$), indicating very dry conditions with a statistical significance level $>99.9\%$. This pattern of extreme dryness in fire years is typical of mesic, high-productivity, upper-elevation forest types in the Southwest with abundant fuels, where fire occurrence is largely controlled by the episodic occurrence of dry climate conditions (Swetnam and Baisan 1996; Allen 2002), rather than interannual fuel availability as seen in more xeric lower-elevation ponderosa pine forests where wet conditions in years preceding a fire also often are important.

Considering the ~15 000 calendar year (cal year) Chihuahueños Bog sediment record, charcoal concentrations varied markedly through time (Fig. 6*a*), reflecting changes in climate, vegetation, and fire regimes. Initial charcoal concentrations were low (mostly ones or tens of particles/cm^3) from the basal 50 cm of sand and gravel deposits in this core, reflecting tundra or steppe vegetation surrounding a small pond (Anderson *et al*. 2008*b*). Development of spruce–*Artemisa* woodland ~14 000 cal years BP at Chihuahueños Bog was followed by transitions to mixed-conifer forest by ~11 700 cal years BP, which, with modifications, continues to today (Brunner-Jass 1999; Anderson *et al*. 2008*b*). The Chihuahueños Bog charcoal record exhibited modest increases in charcoal deposition typical of spruce woodland or spruce forest (Anderson *et al*. 2008*b*) by ~14 000 cal years BP, but with little indication of increased

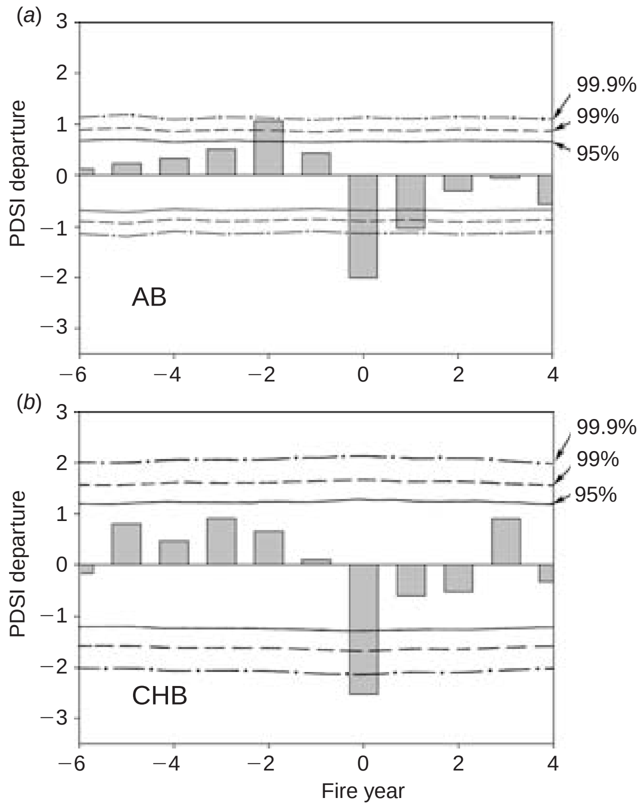

Fig. 5. Superposed epoch analysis for widespread fires at Chihuahueños Bog (CHB) and Alamo Bog (AB) between 1600 and 1879. The solid, dashed, and dashed-dotted lines represent 95%, 99%, and 99.5% confidence intervals, respectively.

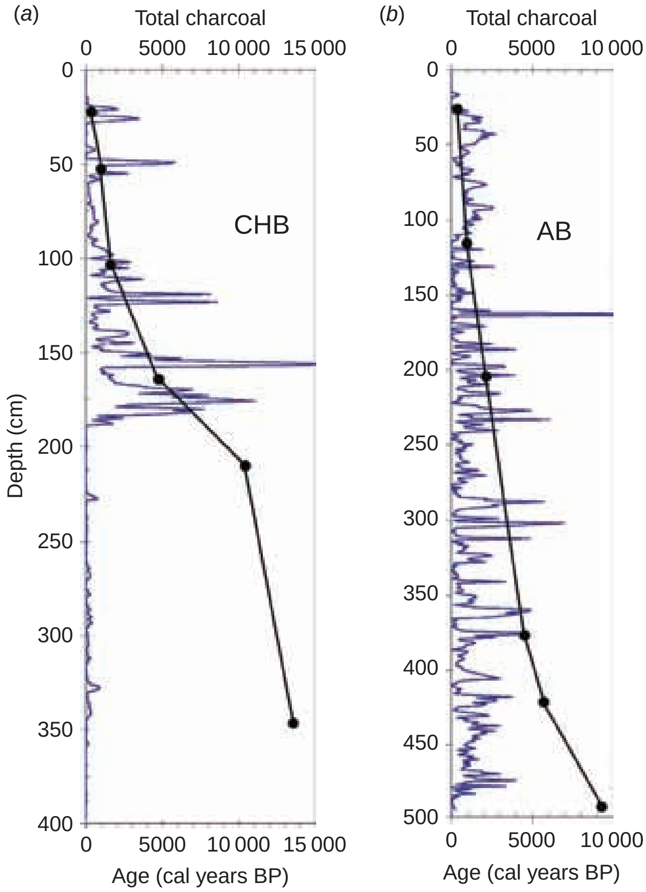

Fig. 6. Total charcoal particles/cm^3 with depth (top *x*-axis scale), along with ^{14}C age–depth curves (solid black circles plot median ^{14}C calendar ages using bottom *x*-axis scale). (*a*) Chihuahueños Bog core CHB-1. Note major increase in charcoal concentrations with climate transition in early Holocene (at 185 cm). (*b*) Alamo Bog core AB-3. For both (*a*) and (*b*), note near complete absence of charcoal since ~1900 (top ~20 cm).

fire activity through the change to mixed-conifer forests in the earliest Holocene.

Major increases in Chihuahueños Bog charcoal influx and concentrations occurred shortly before 8000 cal years BP (Figs 6*a* and 7*a* and *b*), associated with intensified warming and strengthening of the summer monsoon (Friedman *et al*. 1988), probably with elevated lightning ignition rates (Anderson *et al*. 2008*a*). However, fire history interpretations of this big increase in background charcoal from ~8000 to 6000 cal years BP are confounded by the apparent concurrent drying of the Chihuahueños Bog basin, inferred from the accompanying macrofossils, lack of pollen preservation, and low sedimentation rate (over 2000 years represented by only ~25 cm of sediment) (Brunner-Jass 1999; Anderson *et al*. 2008*b*). Because plotting charcoal as a flux of particles cm^{-2} year^{-1} (Fig. 7*a* and *b*) confirms the generally high background rates of charcoal deposition since 8000 cal years BP but removes the 8000–6000 cal years BP 'bulge' seen in raw background concentrations (Fig. 6*a*), the concentration bulge is an artefact of the low sedimentation rate or perhaps burning or oxidation of organic sediments during this time period. Also, the lower temporal resolution of each sample cm from this short dry-environment portion of the core essentially smooths any higher-resolution fluctuations in charcoal influx or concentration, explaining the relative lack of variability (peaks and dips) in charcoal trends during this period. The high overall charcoal influx rates and concentrations observed in the Chihuahueños Bog sediments since ~8000 cal years BP are much greater than the peak deposition rates found in sediments from higher elevation lakes in this region (Anderson *et al*. 2008*a*).

A different pattern emerges after ~1900 (Figs 6*a* and 8*a*; Anderson *et al*. 2008*a*), when charcoal concentrations declined to essentially zero in the top 16 cm of CHB-1 (mean = 1.5 particles cm^{-3}, range = 0–6). Although relatively little charcoal was also recovered from 29 to 40 cm depth in this core (Fig. 8*a*), substantial non-zero charcoal concentrations actually occurred in this zone (mean = 25.4 particles cm^{-3}, range = 6–58).

The patterns of charcoal deposition observed in the top portions of core CHB-1 (Fig. 8*a*) were replicated quite well in the top metre of core CHB-2 (Fig. 8*b*), including the near-absence of any charcoal in the uppermost layers. This almost complete lack of charcoal in the uppermost horizons of both cores, which by ^{210}Pb dating of CHB-1 corresponded to fire cessation in the late 1800s, is consistent with the fire-scar evidence that the last spreading local fires occurred in 1857 and 1902 (Fig. 4). The striking deficit of charcoal deposition since ~1900, clearly replicated by two

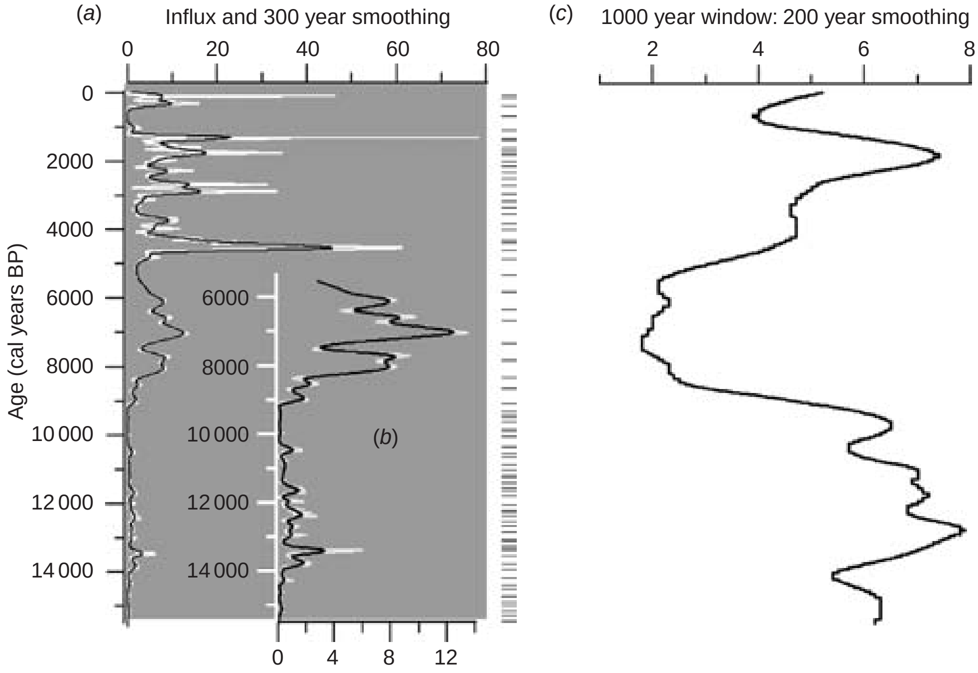

Fig. 7. (*a*) Chihuahueños Bog core CHB-1 influx of charcoal particles cm^{-2} $year^{-1}$ (white line), smoothed influx rate (black line), and fire 'episodes' indicated by '—', with higher resolution inset (*b*) for the period >6000 cal years BP. (*c*) Smoothed fire episode frequencies (FEF, episodes/1000 years) for core CHB-1, showing highest fire frequency estimated during late Pleistocene when influx is low and declines during early Holocene despite consistent high influx.

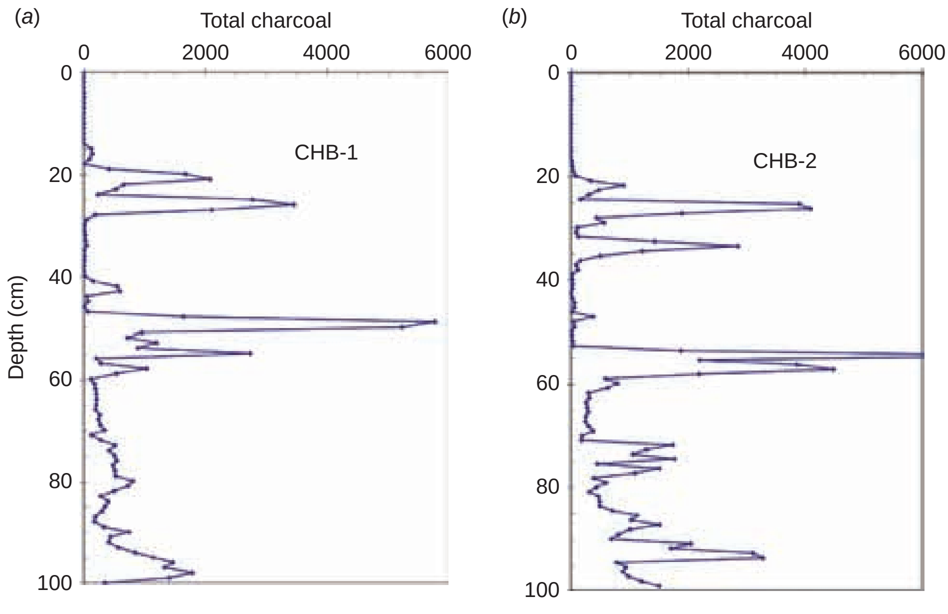

Fig. 8. Replicated concentrations of charcoal (particles cm^{-3}) in the top meter of Chihuahueños Bog cores CHB-1 (*a*), and CHB-2 (*b*), displaying consistent charcoal patterns. Note complete lack of charcoal in the top horizons, corresponding with fire-scar data of last widespread surface fire in 1902.

cores, appears to be an anomaly over the last ~9000 years at Chihuahueños Bog (Fig. 7*a*).

At Chihuahueños Bog, the CHAPS runs yielded an estimated FEF ranging around ~5 fire events/1000 years over the course of the past 15 000 years (Fig. 7*c*), or a mean interval of 200 years between fires. Highest FEF values of 7–8 events/1000 years were estimated for the late Pleistocene and early Holocene (before 9500 cal years BP) when charcoal influx was relatively

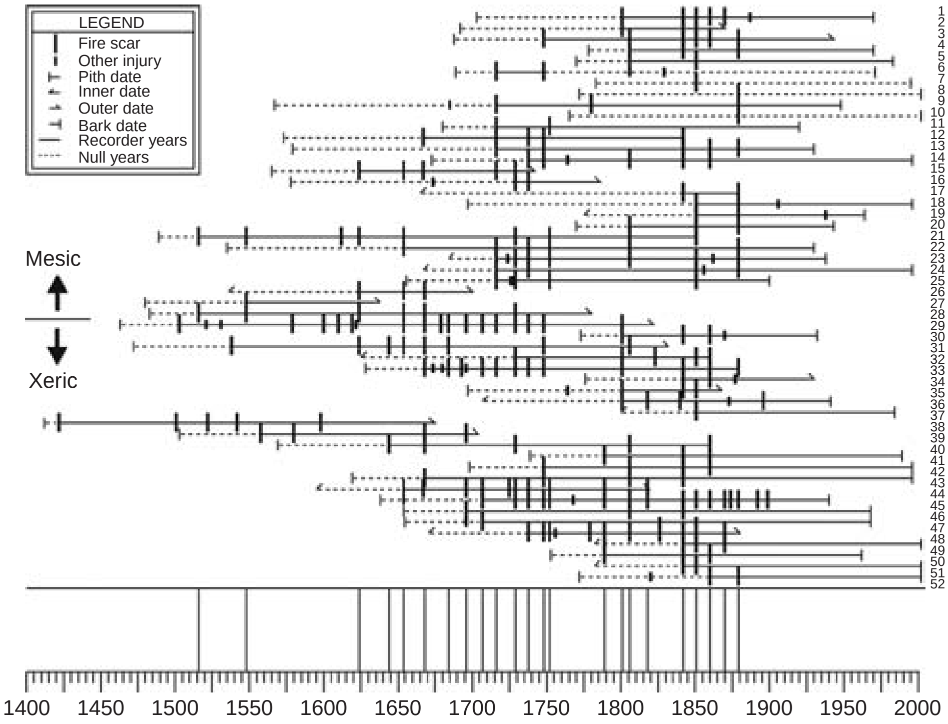

Fig. 9. Composite fire-scar chronology from the Alamo Bog watershed. Horizontal lines show the calendar-year life-spans of individual trees (labelled with sample numbers), and the short vertical lines are fire-scar dates. The longer vertical lines at the bottom of the chronology indicate years with spreading fires, in which fire scarred at least 10% of previously scarred trees and a minimum of two samples. Xeric and mesic site trees are plotted in separate groups, with sampled trees arrayed within each site group from lowest elevation (bottom) to highest. Note the high frequency of fire activity before 1880, the synchrony of fire years across samples, and the cessation of spreading fires after 1879.

low, but variability was relatively high compared with the averaged (smoothed) influx, resulting in the discrimination of more fire 'events'. In contrast, FEF estimates dropped to ~2 fire events/1000 years during the mid-Holocene (~5500–8500 cal years BP), when background charcoal influx was high but few peaks were evident in the record, in part because the low sedimentation rate during this time period smoothed out influx variability, as multiple fire events are probably averaged into each cm^3 of sedimentary charcoal record. For the post-1600 period of overlap between the charcoal and well-replicated fire-scar records, only two charcoal fire 'events' were recognised, *v.* nine spreading fire-scar events. The overall FEF of 4–5 events/1000 years for this time window yielded a mean interval of ~222 years between fires, six times lower than the fire-scar-estimated mean interval of ~35 years for the period 1624–1902.

Alamo Bog

Cross-dated fire scars from 52 sampled trees in the forests adjoining and upslope of Alamo Bog recorded fires back to 1422 (Fig. 9). The last widely spreading fire occurred in 1879, with a few scars showing up on individual trees until 1899. Fire seasonality could be determined for 187 of 229 fire scars, distributed as 62 dormant, 61 early earlywood, 35 mid-earlywood, 22 late earlywood, and 7 latewood. Fire-scar seasonality consistently was dominated by early season fires throughout the pre-1900 time period.

Before 1900, fire frequencies in this watershed varied by forest type and landscape position. A history of high-frequency synchronously spreading fires is recorded in the more xeric portions of this watershed where ponderosa pine is dominant ($n = 24$ samples), with return intervals between spreading fires ranging from 4 to 27 years, and a mean fire return interval of 12.8 years from 1624 to 1879. High-frequency surface fire regimes of this sort were typical of pre-1900 ponderosa pine forests in the Jemez Mountains (Touchan *et al*. 1996). In contrast, the mesic mixed-conifer stands on the north aspects above Alamo Bog ($n = 28$ samples) show a longer mean fire return interval of 21.3 years for this same time window, with intervals ranging from 4 to 48 years. Despite the lower fire frequencies on the mesic slope side of this valley, fire date synchrony among widely dispersed mesic subsite samples, and between xeric and mesic subsite samples in many years (Figs 3 and 9), indicates that pre-1880 surface fires spread widely across this watershed and around the Alamo Bog sediment sample sites. Considering all sampled trees in this watershed yields a mean fire interval of 13.4 years for the period 1624–1879, as the higher-frequency xeric subsite samples drive the joint fire interval statistics.

In addition, tree-ring establishment dates were estimated to be 1880 (±2 years) for 10 of 13 sampled aspen trees from an aspen stand ~300 m upslope of Alamo Bog (Fig. 3). This corresponds

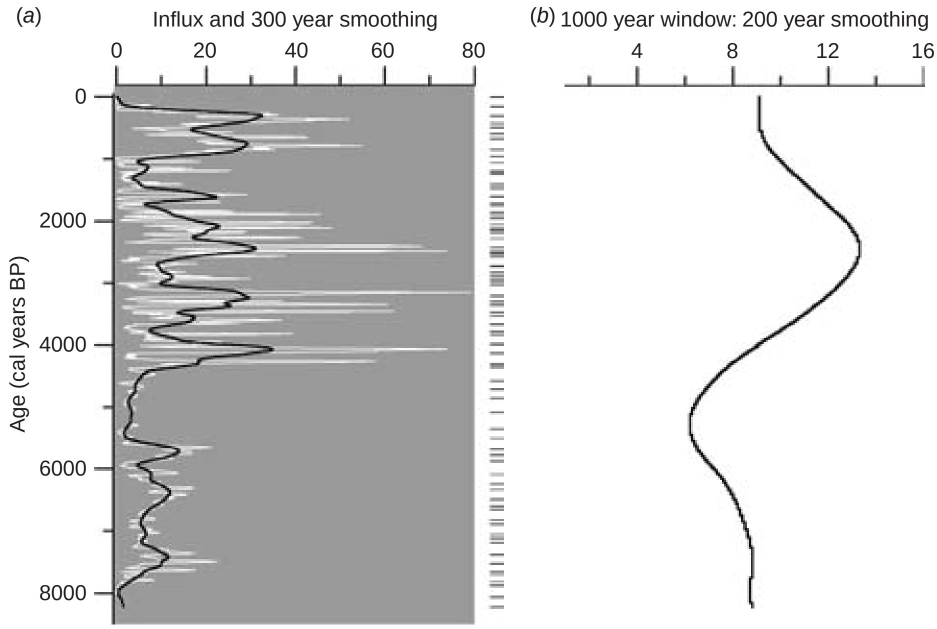

Fig. 10. (*a*) Alamo Bog core AB-3 influx of charcoal particles cm^{-2} year^{-1} (white line), smoothed influx rate (black line), and fire episodes indicated by '—'; (*b*) smoothed fire episode frequencies (FEF, episodes/1000 years) for core AB-3, showing higher-frequency bulge during mid–late Holocene.

well with the 1879 date of the last widespread surface fire in that area (Fig. 9), suggesting that this particular aspen stand regenerated from a high-severity burn patch within the mixed-conifer forest matrix on that north-facing slope. The observed combination of old-growth conifer forest with basal fire scars present and interspersed even-aged aspen stands indicates that a mixed-severity fire regime (with both widespread surface fires and interspersed crown fire patches) historically characterised this mesic portion of the Alamo Bog watershed.

Superposed epoch analysis for widespread fires at Alamo Bog between 1510 and 1883 (Fig. 5) shows a PDSI departure exceeding -2 during fire years, indicating very dry conditions with a statistical significance level $>99.9\%$. In addition, superposed epoch analysis shows a significant ($>99\%$) tendency towards wet conditions 2 years before fire years, which is typical of high-frequency fire regimes in fuel-limited south-western ponderosa pine ecosystems (Swetnam and Baisan 1996), including sites in the Jemez Mountains (Touchan *et al*. 1996). This 2-year lag is thought to reflect the buildup of fine fuels (grasses, pine needles) from the wet years, enhancing the fuel connectivity above thresholds that enabled widespread surface fire activity in subsequent dry years (Allen 2007).

The $\sim$9000 cal year Alamo Bog record displays extremely high concentrations of charcoal throughout most of the AB-3 core length (Fig. 6*b*), with particularly high influx values between $\sim$300 and 4700 cal years BP (Fig. 10*a*). As at Chihuahueños Bog, the observed charcoal concentrations at Alamo Bog are often thousands of particles cm^{-3}, up to 40$\times$ greater than the peak concentrations found in higher elevation lakes in this region (Anderson *et al*. 2008*a*). As at Chihuahueños Bog, charcoal is essentially absent only from the topmost portions of the long Alamo Bog sediment core. Charcoal concentrations in the top 70 cm of replicate core AB-4 show the same basic patterning as upper core AB-3 (Fig. 11), although concentration peaks and valleys do not match precisely. Overall, there is a near-complete absence of charcoal in the uppermost horizons of both cores, which by ^{210}Pb dating of AB-3 corresponds to fire cessation largely occurring by the late 1800s, consistent with the fire-scar evidence that the last widespread local fire occurred in 1879. As dated, the upper portions of the AB-4 record indicate that charcoal deposition continued well into the 1900s, but comparison with the tree-ring fire-scar record, the patterns and dating in uppermost AB-3, and the improbably close stratigraphic proximity between the ^{210}Pb date of 1922 at 27 cm depth and the radiocarbon date of 600 at 40 cm suggest that the ^{210}Pb dating may be somewhat inaccurate in this core.

At Alamo Bog, the CHAPS analysis reconstructed an estimated FEF of $\sim$9 fire events/1000 years over the course of the past 8000+ years (Fig. 10*b*), or a mean fire interval of 111 years between fires. Highest FEF values of 12–13 events/1000 years were estimated for $\sim$1500–3500 cal years BP, a late Holocene maximum in FEF seen at several other sites in the southern Rocky Mountains (Anderson *et al*. 2008*a*). The lowest FEF estimates of 6–7 fire events/1000 years occur in the mid-Holocene ($\sim$4500–6500 cal years BP), when both background and peak charcoal fluxes declined in the Alamo Bog record. The lower FEF values calculated in the earlier portions of this core may result in part from the relatively low sedimentation rates during this time period that smooth out influx variability, making it more likely that multiple fire events were averaged into each cm^3 of sedimentary charcoal record. Over the past 500 years (the highest temporal resolution portion of the Alamo Bog record), the FEF of $\sim$9 events/1000 years yields a mean fire interval (MFI) of 111 years between fires, almost nine times lower

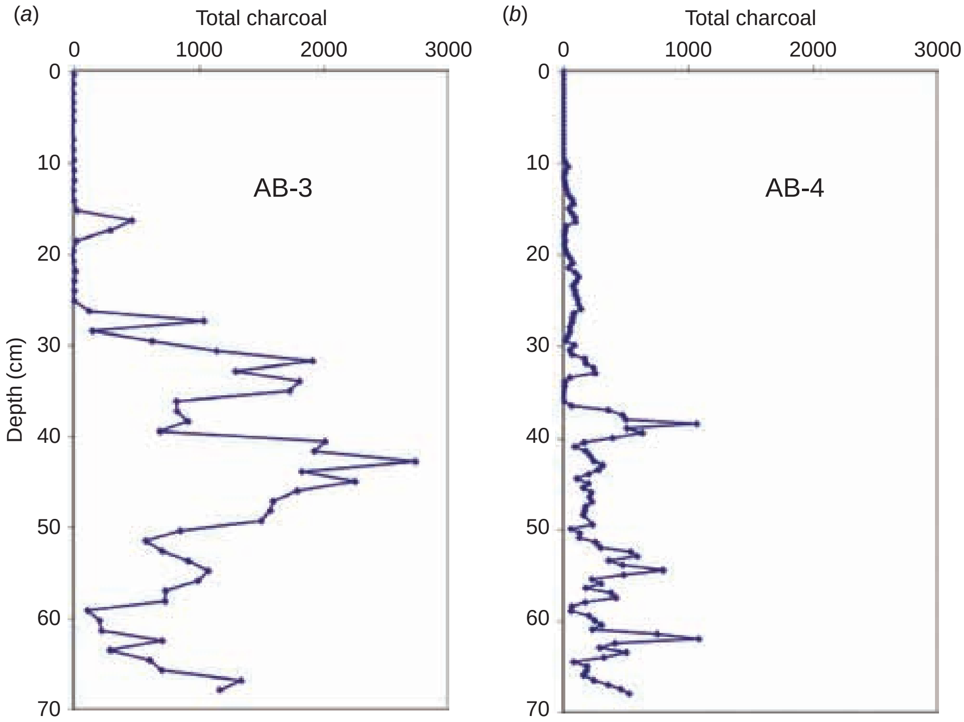

Fig. 11. Concentrations of charcoal (particles cm^{-3}) in the top 70 cm of Alamo Bog cores (*a*) AB-3 and (*b*) AB-4, showing complete lack of charcoal in the top horizons of these replicate cores, consistent with fire-scar data of last widespread fire in 1879.

than the fire-scar estimated MFI of ~13 years for the period 1644–1879.

Particularities of fire history interpretations from bog sedimentary charcoal records

Uncertainty relating to transport processes

Interpretation of sedimentary charcoal records from bogs and wetlands is challenged by uncertainties in paleocharcoal production and deposition processes (Whitlock and Anderson 2003). Charcoal recovered from lake sediments must originate in flammable terrestrial ecosystems in the surrounding landscape, and be transported into the lake via aeolian processes (e.g. lofted by convection from high-intensity crown fires and transported downwind) or by surface runoff. Where steep burnable slopes adjoin a sedimentary basin, accelerated post-fire runoff and erosion (Veenhuis 2002) can transport charcoal directly to a lake margin, where the charcoal can mix and diffuse throughout the lake, eventually to settle and incorporate into deep-water sediments where modern samples are often extracted. As a result, background and peak charcoal concentrations from lake sediments are likely attenuated, and indeed low concentrations are generally observed from lake sediments in the southern Rocky Mountains (Anderson *et al*. 2008*a*). In contrast, whereas surface runoff transport of substantial paleofire charcoal to at least the margins of Alamo Bog is plausible owing to the steepness of the long adjoining slopes, the small Chihuahueños Bog watershed consists of gentle, low-relief terrain much less conducive to accelerated runoff and erosion processes. In addition, charcoal carried by overland flow to the edge of a bog is likely to be filtered out and deposited near the bog margins owing to the low slope gradient and dense and hummocky vegetation cover on the bog surface, and, unlike for lakes, redeposition due to sediment focussing processes is less likely to occur. Thus much or all of such charcoal may not reach the deep sediments of the bog interior where core sampling typically occurs.

Uncertainty relating to taphonomic processes

Notwithstanding the complications listed above, the Chihuahueños Bog and Alamo Bog sediment cores both display extremely high charcoal concentrations throughout most of the Holocene, suggesting dominance of *in situ* charcoal production and deposition processes. In particular, the density of tall perennial bunchgrasses and sedges that dominate the surfaces of both bogs is continuous enough to sustain spreading fire through the dead and dry aerial components of this fine-textured fuel type, even if the bog surface itself is wet. Further, during severe drought episodes (when tree-rings record high probabilities of fire spreading widely through surrounding forest vegetation), the surface portions of these bogs can dry out (C. D. Allen, pers. obs.), also leaving the exposed organic surface sediments at risk of combustion if exposed to fire, or of oxidation and loss of organic matter. Some combination of frequent *in situ* burning of abundant fine aerial fuels and perhaps even surficial peat sediments could readily generate the high peak charcoal concentrations found in cores from interior portions of both of these bogs. These high peak and background levels of charcoal must be accounted for in the use of bog charcoal records to reconstruct the fire history of adjoining upland forests.

Additionally, the stratigraphic integrity of bog sediments can be physically disrupted by the footprints and wallows of animals (e.g. cattle, elk, and deer). Historically, such bioturbation may be greatest during dry years when cattle (or native ungulates in the past) can walk farther into bogs without getting stuck (C. D. Allen, pers. obs.). This factor can be more important when a limited number of radiometric dates are obtained for a core, providing potential for substantial unrecognised temporal transpositions of charcoal-bearing sediments within the bog sediments of any given core sample, introducing unknown artefacts into fire history analyses.

Challenges to fire history interpretation of sedimentary charcoal records from high-frequency fire regime settings

Fire scars indicate relatively high-frequency fire regimes at Chihuahueños Bog and Alamo Bog, with pre-1900 mean return intervals ranging between 13 and 35 years. Accurate interpretation of such high frequencies from sedimentary charcoal records would require decadal- or even subdecadal-scale sampling resolution. Yet typical sedimentation rates are sufficiently low that even high-resolution sediment sampling resolution is too coarse to identify individual fire events at such high-frequency fire sites, as each cm downcore can represent decades to centuries of sediment deposition. In such situations, most individual centimetres likely include the charcoal from multiple fire events, resulting in high 'background' charcoal concentrations and an inability to distinguish the individual fires. Our comparison of the high-resolution tree-ring data with the coarser sedimentary charcoal records suggests that the commonly used CHAPS analyses may be less appropriate for high-frequency fire regime sites such as these because the CHAPS methodology, which is based on treatment of charcoal peaks as synonymous with fire events, effectively constrains the number of identifiable event peaks, resulting in an unrealistically low estimate of FEF (cf. Brunelle and Whitlock 2003). Thus at high-frequency fire sites, it may be unclear how variability in peak charcoal concentrations or influx rates quantitatively reflect fire frequency or severity. In such cases of high-frequency fire records, changes in the magnitude of background concentrations or influx rates of charcoal may provide a more interpretable index of fire activity through time than changes in FEF, although Marlon *et al*. (2006) found that variations in 'fire frequency had little influence on background charcoal trends' for 15 low-frequency fire sedimentary charcoal records from the north-western USA.

The identification of these issues and constraints with interpretation of sedimentary charcoal fire records does not diminish their essential utility in assessing millennial-scale patterns of fire activity. Although not the focus of the present paper, there are also general challenges associated with the interpretation of dendrochronological fire-scar records (Swetnam and Baisan 1996; Swetnam *et al*. 1999; Baker and Ehle 2001; Van Horne and Fulé 2006). In the case of the fire-scar records reported here, we believe that the estimates of widespread surface fire intervals are reasonable given the broad spatial dispersion of fire-scarred trees (especially at the Alamo Bog site), close proximity to and lack of fire barriers between the trees and bogs, high synchronism of the fire-scar dates used to estimate widespread fires, and the strong match of these fire years with climate data (cf. Falk 2004; Van Horne and Fulé 2006).

Summary and conclusions

We have developed long-term records of moderately high-frequency fire activity from paired and replicated charcoal and tree-ring proxies of fire at two medium-elevation bog sites in the Jemez Mountains, northern New Mexico. In the present paper, we use these records to:

(1) Demonstrate the replicability of the essential features of sedimentary charcoal records from duplicate cores within a deposit;
(2) Reconstruct variable fire regimes and fire–climate relationships over millennial time scales at two historically frequent fire sites;
(3) Compare fire history methods and interpretations between tree-ring and charcoal proxies of fire occurrence at the individual sites; and
(4) Consider the particular challenges of developing and interpreting fire histories from bog and wetland settings in the Southwest.

Our research demonstrates the reproducibility of major trends in charcoal records from adjacent cores in these sedimentary deposits, as well as some spatial heterogeneity, consistent with the findings of Edwards and Whittington (2000), Innes *et al*. (2004), and Ohlson *et al*. (2006) from peat and lake sediments in northern Europe. The replicated charcoal patterns from the Jemez Mountains bogs increases confidence in our interpretation of long-term fire histories from southern Rocky Mountains sedimentary records (see Anderson *et al*. 2008*a*).

The paired charcoal and tree-ring methods provide complementary information that aids site-specific interpretations, as shown by many other studies (see Introduction). But unlike studies where fire is infrequent, and individual charcoal peaks correspond to distinct fire events, correspondence between documented fires in the tree-ring scar record and the sedimentary charcoal record is less precise at these frequent-fire sites from New Mexico. For instance, during the time period of overlap of the two methodologies, the sedimentary record considerably underestimates the fire episode frequency when compared with the tree-ring record. This suggests that, over the longer record, fire episode frequencies for high-frequency records such as Chihuahueños and Alamo Bogs may be underestimated by programs such as CHAPS. Thus, although we present analyses here using CHAPS, we place more emphasis on the trends in fire episode frequencies, rather than on the absolute value itself, and we also interpret the temporal changes primarily in terms of changes in background concentrations of charcoal.

Several additional challenges constrain joint interpretation of the long charcoal and shorter tree-ring records from these two particular bogs, and call for caution in directly linking the fire scar and sedimentary charcoal patterns. Diverse vegetation patterning in the Alamo Bog watershed – with higher fire frequency ponderosa pine forest on relatively xeric south-facing slopes, and somewhat lower fire frequency mixed-conifer forest on more mesic north-facing slopes – complicates the interpretation of the sedimentary charcoal record. Charcoal deposition processes in both bogs are less well known than similar processes in lakes (Whitlock and Anderson 2003), and the effects of changes in hydrologic status of the bog, such as wetting and drying, on charcoal formation and deposition processes are largely unknown. Extremely high charcoal concentrations, abundant fine fuels of the grassy wetland vegetation, and the fire-scar history of relatively frequent surface fires in adjoining forests suggests that pre-1900 surface fires likely spread through aerial herbaceous fuels across both bogs in many years. Thus past surface fires might have produced abundant *in situ* charcoal, as well as charcoal influx from surrounding forested slopes. *In situ* charcoal production seems particularly probable at Chihuahueños Bog, given that thick herbaceous bog vegetation would have strongly filtered post-fire water-borne sediments from the adjoining low-relief uplands of this small watershed, potentially precluding the in-wash deposition of such high charcoal concentrations as are found in the central bog sample locations. However, wind erosion could have transported post-fire surface charcoal from adjoining forests to accumulate in the centres of both of these low-lying bogs, especially before regrowth of burned grassy bog vegetation, and charcoal eroded by wind from standing burned snags could have been blown over winter snow into these bogs for years after fire even after herbaceous regrowth (Whitlock and Anderson 2003). Burning of the peaty surface bog sediments could have eliminated some of the organic sedimentary deposits during extreme droughts at both sites (cf. Huber and Markgraf 2003), leaving high charcoal concentrations. The substantial background concentrations of charcoal also likely reflect the high frequency of fire activity affecting these bogs relative to the variable temporal resolution represented by 0.5–1-cm sediment sampling intervals, further complicating the interpretation of observed charcoal peaks as discrete fire 'events' (in contrast to relatively direct calculations of event frequency for long-interval stand-replacing fires from subalpine forest lake basins). Bioturbation of the bog sediments by hoof action from ungulates (e.g. livestock, elk and deer), especially during droughts, could alter the charcoal concentration profiles found within individual sedimentary core samples.

The historic cessation of fire since ~1900 seen in the paired and replicated charcoal and tree-ring records at these historically high-frequency fire sites is consistent with many other tree-ring fire histories from the Jemez Mountains and the Southwest as a whole (Swetnam and Baisan 1996), as well as the known regional histories of inadvertent fire suppression since the late 1800s due to livestock overgrazing and active fire suppression by land management agencies since the early 20th century. The unique near-absence of modern charcoal deposition replicated both within and between these two bog sites, combined with high background and peak levels of charcoal throughout most of the rest of the Holocene sediments from these sites, increases the robustness of the interpretation that this post-1900 lull in fire activity is anomalous at millennial time scales for at least these two localities. Similar gaps in charcoal deposition from uppermost sediment horizons are being found at some other sediment core sites in the Southern Rocky Mountains (Anderson *et al.* 2008*a*), even though these sites historically had lower frequency fire regimes. Determining the geographic extent of this pattern will require the development of regional networks of additional charcoal sediment records from sites historically subject to high-frequency fire (generally drier, low to mid elevation, unglaciated landscapes), where it is difficult to find unmanipulated, persistently wet basins that are needed to foster long-term sediment records.

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References

Allen CD (1989) Changes in the landscape of the Jemez Mountains, New Mexico. PhD Dissertation, University of California, Berkeley, USA.

Allen CD (2002) Lots of lightning and plenty of people: an ecological history of fire in the upland southwest. In 'Fire, Native Peoples, and the Natural Landscape'. pp. 143–193. (Island Press: Washington, DC)

Allen CD (2007) Cross-scale interactions among forest dieback, fire, and erosion in northern New Mexico landscapes. *Ecosystems (New York, N.Y.)* **10**, 797–808. doi:10.1007/S10021-007-9057-4

Anderson RS, Smith SJ (1997) The sedimentary record of fire in montane meadows, Sierra Nevada, California, USA: a preliminary assessment. In 'Sediment Records of biomass burning and global change'. (Eds JS Clark, H Cachier, JG Goldammer, B Stocks) NATO ASI Series 1: Global Environmental Change, Vol. 51. pp. 318–328. (Springer: Berlin)

Anderson RS, Hallett DJ, Berg E, Jass RB, Toney JL, de Fontaine CS, DeVolder A (2006) Holocene development of boreal forests and fire regimes on the Kenai Lowlands of Alaska. *The Holocene* **16**(6), 791–803.

Anderson RS, Allen CD, Toney JL, Jass RB, Bair AN (2008*a*) Holocene vegetation and forest fire regimes in subalpine and mixed-conifer forest sites, southern Rocky Mountains, USA. *International Journal of Wildland Fire* **17**, 96–114. doi:10.1071/WF07028

Anderson RS, Jass RB, Toney JL, Allen CD, Cisneros-Dozal M, Hess M, Heikoop J, Fessenden J (2008*b*) Development of the mixed-conifer forest in northern New Mexico, and its relationship to Holocene climate change. *Quaternary Research*, in press.

Appleby PG (2001) Chronostratigraphic techniques in recent sediments. In 'Tracking environmental change using lake sediments. Vol. 1: Basin analysis, coring, and chronological techniques'. (Eds WM Last, JP Smol) pp. 171–203. (Kluwer Academic Publishers: Dordrecht)

Arno SF, Sneck KM (1977) A method for determining fire history in coniferous forests of the mountain West. USDA Forest Service, General Technical Report INT 42, pp. 1–28. (Ogden, UT)

Bair AN (2004) A 15000 year vegetation and fire history record from the southern Sangre de Cristo Mountains of northern New Mexico. MS Thesis, Northern Arizona University, USA.

Baker WL, Ehle DL (2001) Uncertainty in surface fire history: the case of ponderosa pine forests in the western United States. *Canadian Journal of Forest Research* **31**, 1205–1226. doi:10.1139/CJFR-31-7-1205

Barrows JS (1978) Lightning fires in Southwestern forests. Final Report prepared by Colorado State University for USDA Intermountain Forest and Range Experiment Station. (Ogden, UT)

Bogan MA, Allen CD, Muldavin EH, Platania SP, Stuart JN, Farley GH, Melhop P, Belnap J (1998) Southwest. In 'National status and trends report'. (Eds MJ Mac, PA Opler, PD Doran) pp. 543–592. (US Geological Survey: Washington, DC)

Briles CE, Whitlock C, Bartlein PJ (2005) Post-glacial vegetation, fire, and climate history of the Siskiyou Mountains, Oregon, USA. *Quaternary Research* **64**, 44–56. doi:10.1016/J.YQRES.2005.03.001

Brown PM, Wu R (2005) Climate and disturbance forcing of episodic tree recruitment in a south-western ponderosa pine landscape. *Ecology* **86**, 3030–3038. doi:10.1890/05-0034

Brunelle A, Whitlock C (2003) Post-glacial fire, vegetation, and climate history in the Clearwater range, Northern Idaho, USA. *Quaternary Research* **60**, 307–318. doi:10.1016/J.YQRES.2003.07.009

Brunelle A, Whitlock C, Bartlein P, Kipfmueller K (2005) Holocene fire and vegetation along environmental gradients in the Northern Rocky Mountains. *Quaternary Science Reviews* **24**, 2281–2300. doi:10.1016/J.QUASCIREV.2004.11.010

Brunner-Jass RM (1999) Fire occurrence and paleoecology at Alamo Bog and Chihuahueños Bog, Jemez Mountains, New Mexico, USA. MS Thesis, Northern Arizona University, USA.

Cook EC, Woodhouse C, Eakin CM, Meko DM, Stahle DW (2004) Long-term aridity changes in the western United States. *Science* **306**, 1015–1018. doi:10.1126/SCIENCE.1102586

Dieterich JH, Swetnam TW (1984) Dendrochronology of a fire-scarred ponderosa pine. *Forest Science* **30**, 238–247.

Edwards KJ, Whittington G (2000) Multiple charcoal profiles in a Scottish lake: taphonomy, fire ecology, human impact and inference. *Palaeogeography, Palaeoclimatology, Palaeoecology* **164**, 67–86. doi:10.1016/S0031-0182(00)00176-0

Falk DA (2004) Scaling rules for fire regimes. PhD Dissertation, University of Arizona, Tucson.

Fall PL (1997) Timberline fluctuations and late Quaternary paleoclimates in the Southern Rocky Mountains, Colorado. *Geological Society of America Bulletin* **109**, 1306–1320. doi:10.1130/0016-7606(1997)109<1306:TFALQP>2.3.CO;2

Friedman I, Carrara P, Gleason J (1988) Isotopic evidence of Holocene climate change in the San Juan Mountains, Colorado. *Quaternary Research* **30**, 350–353. doi:10.1016/0033-5894(88)90010-5

Fulé PC, Heinlein TH, Covington WW, Moore MM (2003) Assessing fire regimes on Grand Canyon landscapes with fire-scar and fire-record data. *International Journal of Wildland Fire* **12**, 129–145. doi:10.1071/WF02060

Gavin DG, Brubaker LB, Lertzman KP (2003) An 1800-year record of the spatial and temporal distribution of fire from the west coast of Vancouver Island, Canada. *Canadian Journal of Forest Research* **33**, 573–586. doi:10.1139/X02-196

Gavin DG, Hu FS, Lertzman KP, Corbett P (2006) Weak climatic control of forest fire history during the late Holocene. *Ecology* **87**, 1722–1732. doi:10.1890/0012-9658(2006)87[1722:WCCOSF]2.0.CO;2

Grissino-Mayer HD (1996) A 2129-year reconstruction of precipitation for north-western New Mexico, USA. In 'Tree rings, environment, and humanity'. (Eds JS Dean, DM Meko, TW Swetnam) pp. 191–204. (Radiocarbon: Tucson, AZ)

Grissino-Mayer HD (2001) FHX – software for analyzing temporal and spatial patterns in fire regimes from tree rings. *Tree-Ring Research* **57**, 113–122.

Grissino-Mayer HD, Swetnam TW (2000) Century-scale climate forcing of fire regimes in the American Southwest. *The Holocene* **10**, 213–220. doi:10.1191/095968300668451235

Grissino-Mayer HD, Romme WH, Floyd-Hanna ML, Hanna D (2004) Climatic and human influences on fire regimes of the southern San Juan Mountains, Colorado, USA. *Ecology* **85**(6), 1708–1724. doi:10.1890/02-0425

Hallett DJ, Hills LV (2006) Holocene vegetation dynamics, fire history, lake level and climatic change in the Kootenay Valley, south-eastern British Columbia, Canada. *Journal of Paleolimnology* **35**, 351–371. doi:10.1007/S10933-005-1335-6

Hallett DJ, Walker RC (2000) Paleoecology and its application to fire and vegetation management in Kootenay National Park, British Columbia. *Journal of Paleolimnology* **24**, 401–414. doi:10.1023/A:1008110804909

Hallett DJ, Mathewes RW, Walker RC (2003) A 1000-year record of forest fire, drought and lake-level change in south-eastern British Columbia, Canada. *The Holocene* **13**(5), 751–761. doi:10.1191/0959683603HL660RP

Higuera PA, Sprugel DG, Brubaker LB (2005) Reconstructing fire regimes with charcoal from small-hollow sediments: a calibration with tree-ring records of fire. *The Holocene* **15**(2), 238–251. doi:10.1191/0959683605HL789RP

Huber UM, Markgraf V (2003) Holocene fire frequency and climate change at Rio Rubens Bog, southern Patagonia. In 'Fire and Climatic Change in Temperate Ecosystems of the Americas. Ecological studies 160'. (Eds TT Veblen, WL Baker, G Montenegro, TW Swetnam) pp. 357–380. (Springer-Verlag: New York)

Innes JB, Blackford JJ, Simmons IG (2004) Testing the integrity of fine spatial resolution palaeoecological records: microcharcoal data from near-duplicate peat profiles from the North York Moors, UK. *Palaeogeography, Palaeoclimatology, Palaeoecology* **214**, 295–307. doi:10.1016/J.PALAEO.2004.04.004

Kitzberger T, Brown PM, Heyerdahl EK, Swetnam TW, Veblen TT (2007) Contingent Pacific–Atlantic Ocean influence on multicentury wildfire synchrony over western North America. *Proceedings of the National Academy of Sciences of the United States of America* **104**, 543–548. doi:10.1073/PNAS.0606078104

Laird LD, Campbell ID (2000) High resolution paleofire signals from Christina Lake, Alberta: a comparison of the charcoal signals extracted from two different methods. *Palaeogeography, Palaeoclimatology, Palaeoecology* **164**, 111–123. doi:10.1016/S0031-0182(00)00179-6

MacDonald GM, Larsen CPS, Szeicz JM, Moser KA (1991) The reconstruction of boreal forest fire history from lake sediments: a comparison of charcoal, pollen, sedimentological, and geochemical indices. *Quaternary Science Reviews* **10**, 53–71. doi:10.1016/0277-3791(91)90030-X

Margolis EQ, Swetnam TW, Allen CD (2007) A stand-replacing fire history in upper montane forests of the Southern Rocky Mountains. *Canadian Journal of Forest Research* **37**, 2227–2241.

Marlon J, Bartlein PJ, Whitlock C (2006) Fire–fuel–climate linkages in the north-western USA during the Holocene. *The Holocene* **16**(8), 1059–1071. doi:10.1177/0959683606069396

Millspaugh SH, Whitlock C (1995) A 750-year fire history based on lake sediment records in central Yellowstone National Park, USA. *The Holocene* **5**(3), 283–292. doi:10.1177/095968369500500303

Mohr JA, Whitlock C, Skinner CN (2000) Post-glacial vegetation and fire history, eastern Klamath Mountains, California, USA. *The Holocene* **10**(5), 587–601. doi:10.1191/095968300675837671

Ohlson M, Korbol A, Okland RH (2006) The macroscopic charcoal record in forested boreal peatlands in south-east Norway. *The Holocene* **16**(5), 731–741. doi:10.1191/0959683606HL955RP

Patterson WA, Edwards KJ, Maguire DJ (1987) Microscopic charcoal as a fossil indicator of fire. *Quaternary Science Reviews* **6**, 3–23. doi:10.1016/0277-3791(87)90012-6

Petersen KL (1981) 10000 years of climate change reconstructed from fossil pollen, La Plata Mountains, southwestern Colorado. PhD Dissertation, Washington State University, Pullman.

Petersen KL (1985) Palynology in Montezuma County, Southwestern Colorado: the local history of Pinyon Pine (*Pinus edulis*). In 'Late Quaternary Palynology of the American Southwest'. (Eds B Jacobs, OK Davis, PL Fall) pp. 47–62. (American Association of Stratigraphic Palynologists Foundation: Dallas, TX)

Pitkänen A, Lehtonen H, Huttunen P (1999) Comparison of sedimentary microscopic charcoal particle records in a small lake with dendrochronological data: evidence for the local origin of microscopic charcoal produced by forest fires of low intensity in eastern Finland. *The Holocene* **9**, 559–567. doi:10.1191/095968399670319510

Stokes MA, Smiley TL (1968) 'An introduction to tree-ring dating.' (University of Chicago Press: Chicago, IL)

Stuiver M, Reimer PJ, Bard E, Beck JW, Burr GS, Hughen KA, Kromer B, McCormac FG, van der Plickt J, Spurk M (1998) INTCAL98 radiocarbon age calibration 24000–0 cal BP. *Radiocarbon* **40**, 1041–1083.

Swetnam TW, Baisan CH (1996) Historical fire regime patterns in the southwestern United States since AD 1700. In 'Fire Effects in Southwestern Forests: Proceedings of the 2nd La Mesa Fire Symposium'. (Ed. CD Allen) pp. 11–32. USDA Forest Service General Technical Report RM-GTR-286. (Fort Collins, CO)

Swetnam TW, Baisan CH (2003) Tree-ring reconstructions of fire and climate history in the Sierra Nevada and Southwestern United States. In 'Fire and Climatic Change in Temperate Ecosystems of the Americas. Ecological studies 160'. (Eds TT Veblen, WL Baker, G Montenegro, TW Swetnam) pp. 158–195. (Springer-Verlag: New York)

Swetnam TW, Betancourt JL (1998) Mesoscale disturbance and ecological response to decadal climatic variability in the American Southwest. *Journal of Climate* **11**, 3128–3147. doi:10.1175/1520-0442(1998)011 <3128:MDAERT>2.0.CO;2

Swetnam TW, Allen CD, Betancourt JL (1999) Applied historical ecology: using the past to manage for the future. *Ecological Applications* **9**, 1189–1206. doi:10.1890/1051-0761(1999)009[1189:AHEUTP]2.0.CO;2

Toney JL, Anderson RS (2006) A post-glacial palaeoecological record from the San Juan Mountains of Colorado, USA: fire, climate and vegetation history. *The Holocene* **16**, 505–517. doi:10.1191/0959683606HL946RP

Touchan R, Allen CD, Swetnam TW (1996) Fire history and climatic patterns in ponderosa pine and mixed-conifer forests of the Jemez Mountains, northern New Mexico. In 'Fire effects in southwestern forests: Proceedings of the 2nd La Mesa Fire Symposium'. (Ed. CD Allen) pp. 33–46. USDA Forest Service General Technical Report RM-GTR-286. (Fort Collins, CO)

Van Horne ML, Fulé PZ (2006) Comparing methods of reconstructing fire history from fire scars in a south-western United States ponderosa pine forest. *Canadian Journal of Forest Research* **36**, 855–877. doi:10.1139/X05-289

Veenhuis J (2002) Effects of wildfire on the hydrology of Capulin and Rito de los Frijoles Canyons, Bandelier National Monument, New Mexico. US Geological Survey, Water Resources Investigations Report 02–4152. (Albuquerque, NM)

Weng C, Jackson ST (1999) Late-glacial and Holocene vegetation history and paleoclimate of the Kaibab Plateau, Arizona. *Palaeogeography, Palaeoclimatology, Palaeoecology* **153**, 179–201. doi:10.1016/S0031-0182(99)00070-X

Westerling AL, Hidalgo HG, Cayan DR, Swetnam TW (2006) Warming and earlier spring increases western US fire activity. *Science* **313**, 940–943. doi:10.1126/SCIENCE.1128834

Whitlock C, Anderson RS (2003) Fire history reconstructions based on sediment records from lakes and wetlands. In 'Fire and Climatic Change in Temperate Ecosystems of the Americas. Ecological studies 160'. (Eds TT Veblen, WL Baker, G Montenegro, TW Swetnam) pp. 3–31. (Springer-Verlag: New York)

Whitlock C, Millspaugh S (1996) Testing assumptions of fire history studies: An examinationa of modern charcoal accumulation in Yellowstone National Park. *The Holocene* **6**, 7–15.

Whitlock C, Shafer SL, Marlon J (2004) The role of climate and vegetation change in shaping past and future fire regimes in the north-western US and the implications for ecosystem management. *Forest Ecology and Management* **178**, 5–21. doi:10.1016/S0378-1127(03)00051-3

Whitlock C, Bartlein P, Briles C, Brunelle A, Long CJ, Marlon J (2008) Long-term relations among fire, fuel, and climate in the north-western US based on lake sediment studies. *International Journal of Wildland Fire* **17**, 72–83. doi:10.1071/WF07025

Wolff JA, Gardner JN (1995) Is the Valles Caldera entering a new cycle of activity? *Geology* **23**, 411–414. doi:10.1130/0091-7613(1995)023 <0411:ITVCEA>2.3.CO;2

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