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Development of the mixed conifer forest in northern New Mexico and its relationship to Holocene environmental change

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Abstract

Chihuahueños Bog (2925 m) in the Jemez Mountains of northern New Mexico contains one of the few records of late-glacial and postglacial development of the mixed conifer forest in southwestern North America. The Chihuahueños Bog record extends to over 15,000 cal yr BP. An *Artemisia* steppe, then an open *Picea* woodland grew around a small pond until ca. 11,700 cal yr BP when *Pinus ponderosa* became established. C/N ratios, $\delta^{13}C$ and $\delta^{15}N$ values indicate both terrestrial and aquatic organic matter was incorporated into the sediment. Higher percentages of aquatic algae and elevated C/N ratios indicate higher lake levels at the opening of the Holocene, but a wetland developed subsequently as climate warmed. From ca. 8500 to 6400 cal yr BP the pond desiccated in what must have been the driest period of the Holocene there. C/N ratios declined to their lowest Holocene levels, indicating intense decomposition in the sediment. Wetter conditions returned after 6400 cal yr BP, with conversion of the site to a sedge bog as groundwater levels rose. Higher charcoal influx rates after 6400 cal yr BP probably result from greater biomass production rates. Only minor shifts in the overstory species occurred during the Holocene, suggesting that mixed conifer forest dominated throughout the record.
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Keywords: Pollen analysis; Charcoal analysis; Isotope analysis; Paleoecology; New Mexico

Introduction

Mixed conifer forests are one of the most common forest types in southwestern North America, covering more than 600,000 ha in southern Colorado, northern Arizona and northern New Mexico (Pase and Brown, 1982). These forests—a mixture of *Pseudotsuga menziesii* (Douglas-fir), *Abies concolor* (white fir), and *Populus tremuloides* (trembling aspen), with *Pinus flexilis* (limber pine), *Pinus strobiformis* (southern white pine) and *Pinus ponderosa*—generally form a discontinuous forest belt between the higher subalpine zone of *Picea engelmannii* (Engelmann spruce) and *Abies lasiocarpa* var. *arizonica* (corkbark fir) and the lower elevation *P. ponderosa* forests.

Although Southwestern mixed conifer forests are important as habitat for threatened species, watersheds for domestic and agricultural water supplies, and for recreational uses, little is known about the long-term history of these forests, including the influence of climate change and forest disturbance on forest characteristics. This is especially true for the mixed conifer forests of the Jemez Mountains of northern New Mexico, which are surrounded by regions with rich histories of paleoenvironmental investigation. To the south and west, numerous packrat midden studies in the Chihuahuan (Van Devender, 1990; Elias, 1992; Elias and Van Devender, 1992; Betancourt et al., 2001; Holmgren et al., 2003,

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2006, 2007) and Great Basin (Betancourt and Van Devender, 1981; Betancourt, 1990) deserts have documented low-elevation vegetation change. To the north and west, several studies have concentrated on vegetation history of the higher elevation subalpine zone on the Colorado Plateau (Feiler et al., 1997; Anderson et al., 1999) or southern Rockies (Petersen and Mehringer, 1976; Fall, 1997; Vierling, 1998; and Toney and Anderson, 2006 among others). Several others document the development of the important *P. ponderosa* forest (Wright et al., 1973; Anderson, 1993; Weng and Jackson, 1999). A few studies include information on long-term fire histories in the *Picea-Abies* forests from sedimentary charcoal (Fall, 1997; Weng and Jackson, 1999; Bair, 2004; Toney and Anderson, 2006), but these studies are lacking for the mixed conifer forests.

Here we examine several sediment proxies-pollen, plant macrofossils, charcoal, carbon to nitrogen (C/N) ratios and isotopic (^{13}C, ^{15}N) signatures—from a small basin within the mixed conifer zone of north-central New Mexico to reconstruct former vegetation, climate and fire regimes over the last ca. 15,000 cal yr BP. The Chihuahueños Bog site is important as one of only a handful of potential sites for paleoecological reconstruction of this forest type. Our present knowledge from the Jemez Mountains is limited to unpublished reports (Brunner Jass, 1999; Ensey, 1997) and well borings of middle Pleistocene age (Sears and Clisby, 1952; Fawcett et al., 2007). This record is important in the emerging synthetic picture of vegetation change over a range of elevations in the Southwest (Anderson et al., 2004, in press), a region of sparse but growing population, and vast recreational and economic interests.

The Study Area

Chihuahueños Bog (2925 m; 9600 ft) is located on the northern flank of the Jemez Mountains (Fig. 1), a range that extends to ~3500 m elevation in north-central New Mexico. The range is the product of collapse after huge pyroclastic eruptions ~1.1 Ma, forming the present Valles Caldera (Wolff and Gardner, 1995). Mire sediments of the bog (~2.3 ha) formed within a small (<2 km^2) basin with no inflowing streams. Geologic mapping indicates that the bog occurs at contact between Bandelier Tuff on the south and a dacite hill on the north (S. Reneau, unpublished). A spillway near the eastern periphery of the bog is cut into bedrock ca. 2 m above the modern level of the bog and extends into Chihuahueños Creek canyon below. The spillway is a relict feature and was probably cut during the Pleistocene. The bog contains standing water during most years and is probably spring fed. However, after particularly dry winters (e.g., 2000 and 2006), large portions of the bog can dry out (Allen et al., in press).

The annual average maximum and minimum temperature and precipitation for the Pajarito Mountain station (3158 m [10,360 ft]; ca. 20 km SE of Chihuahueños Bog) are 10.0 °C, 0.6 °C and 53.6 cm, respectively (http://weather.lanl.gov). For Los Alamos (2256 m [7400 ft]), ca. 24 km SE of Chihuahueños Bog, similar parameters are 15.5 °C, 2.5 °C, and 45.9 cm (http://www.wrcc.dri.edu/summary/climsmnm.html). Maximum precipitation at both sites is recorded during the July–August summer monsoon, when 48% of the annual total at the Pajarito Mountain site occurs. Winter (Dec, Jan, Feb) is usually the

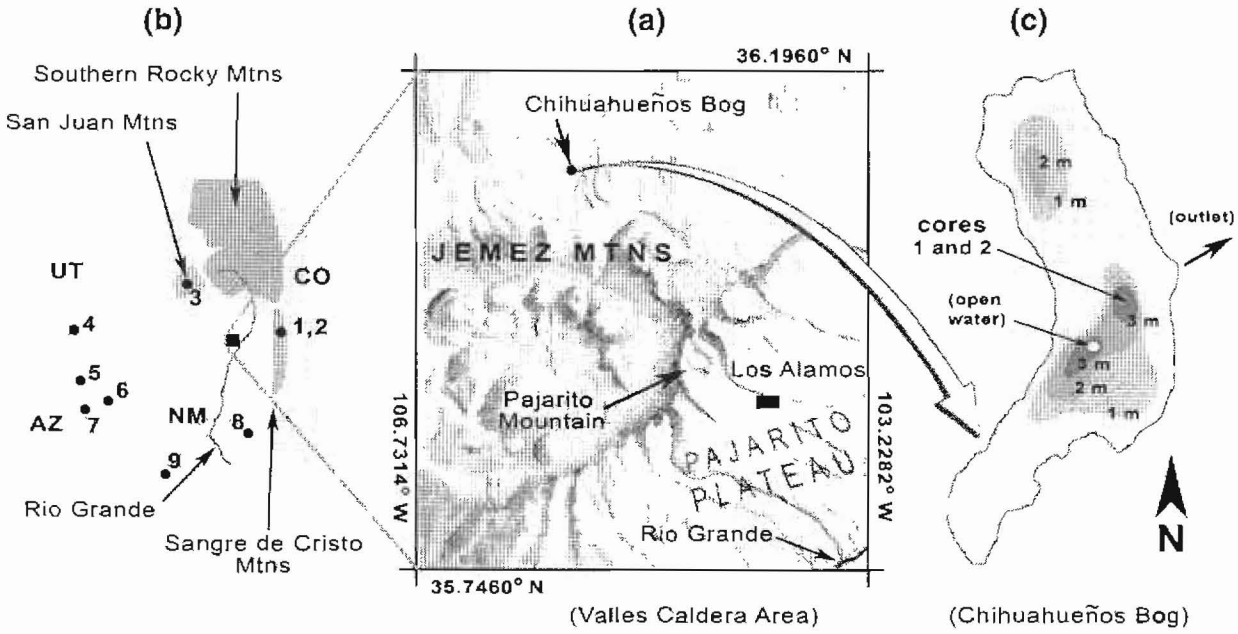

Figure 1. (a) Location of Chihuahueños Bog and vicinity, Jemez Mountains, northern New Mexico. (b) General location, with specific sites mentioned in the text: [1] Jiearita Bog (Bair, 2004); [2] Stewart Bog (Armour et al., 2002); [3] Little Molas Lake (Toney and Anderson, 2006); [4] Kaibab Plateau lakes (Weng and Jackson, 1999); [5] Stoneman Lake (Hasbargen, 1994); [6] Potato Lake (Anderson, 1993); [7] Montezuma Well (Davis and Shafer, 1992); [8] Rough Canyon middens (Betancourt et al., 2001); [9] Playas Valley middens (Holmgren et al., 2003). (c) Outline of Chihuahueños Bog, with peat isopleths, and coring locations.

driest season, but spring (Apr, May, Jun) is also quite dry. At Pararito Mountain, snow can fall in any month, but on most years the snow-free season is from May through October.

Vegetation communities in the Jemez Mountains are strongly affected by elevation and aspect. At the highest elevations (ca. 2900 to 3500 m), north-facing slopes contain forests of *Picea engelmannii* and *A. lasiocarpa* var. *arizonica*, while local areas of high elevation grasslands are found on south-facing slopes (Reneau and McDonald, 1996). Mixed conifer forests occur from ca. 2300 to 2900 m, with *Pinus ponderosa*, *Pseudotsuga menziesii*, *A. concolor*, *Populus tremuloides* and *Pinus flexilis*. *P. ponderosa* with *Quercus gambelii* (Gambel's oak) are more common on south-facing slopes, and dominate elevations 2100 to ca. 2600 m, while *Pinus edulis* (piñon)–*Juniperus monosperma* or *J. scopulorum* (juniper) woodlands occur between ca. 1900 and 2100 m elevation. Juniper grasslands, dominated by *J. monosperma*, *Artemisia tridentata* (big sagebrush), and *Bouteloua* sp. occur from ca. 1600 to 1900 m, while shrub steppe with *Sarcobatus* (greasewood), *A. tridentata*, and *Ephedra* (joint-fir) occur at elevations below this.

Chihualueños Bog is located within the mixed conifer forest and has affinities to the flora of the southern Rocky Mountains (Foxx and Tierney, 1985; Allen, 2004). Although the area immediately surrounding the bog has been heavily logged in recent years, nearly every conifer species growing in montane forests of the Jemez mountains is represented either along the shore of the bog or in the surrounding uplands. *P. strobiformis* and *P. ponderosa* are the dominant pines, while other co-dominant conifers include *Pseudotsuga menziesii*, *A. concolor* and *A. lasiocarpa* var. *arizonica*, *Picea engelmannii* and *P. pungens* (blue spruce). *Populus tremuloides*, *Q. gambelii*, *Arctostaphylos uva-ursi* (kinnickinnick) and *Juniperus communis* (common juniper) grow around the bog perimeter. Other shrubs and herbs include *Potentilla fruticosa* (shrubby cinquefoil), *Artemisia* sp., *Campanula parryi* (bluebells), *Iris missouriensis* (iris), *Fragaria* sp. (wild strawberry), *Castilleja* sp. (paintbrush), *Antennaria* sp. (pussytoes) and *Achillea lanulosa* (yarrow), among others. The modern surface cover of the bog is dominated by sedges and grasses, including *Deschampsia caespitosa* (tufted hairgrass).

Methods

The perimeter of Chihuahueños Bog was traversed and GPS coordinates were taken every 2 m to produce a map of the bog (Fig. 1). Steel rods were used to probe the depth of the bog. Two cores were taken with a Livingstone corer ca. 2 m apart in the middle of the bog where the sediments were the thickest. Core #1 (used in this study) measured 465 cm, while Core #2 measured 400 cm. Cores were sampled for pollen, charcoal, plant macrofossils, C/N ratios, ^{13}C and ^{15}N isotopic compositions and materials for radiocarbon dating at the Laboratory of Paleoecology (LOP), Northern Arizona University.

Magnetic susceptibility (MS; Sandgren and Snowball, 2001), a measure of the tendency of sediment to carry a magnetic remanence, was measured with a Sapphire Instruments SI2B meter, with an external coil operating at a frequency of F=800 Hz. MS was calculated from the coil readings. The results are expressed as dimensionless cgs units (cgsu).

Fossil pollen samples (1 cm^3) were taken at 15- to 25-cm (usually 20-cm) intervals along the length of the core. Processing followed a modified Faegri and Iversen (1989) process, including suspension in KOH, dilute HCl, HF and acetolysis solution. A known amount of *Lycopodium* spores were added for calculation of pollen concentration. Some samples containing high silt and clay were sieved (7-μm mesh). Pollen identifications were made using reference material at the LOP and published keys (Moore et al., 1991; Kapp et al., 2000). Where possible, *Pinus* grains were subdivided into subgeneric categories (Jacobs, 1985). *P. edulis*-type included *Pinus* subgenus *strobus* grains with verrucae on the leptoma and < 70 μm in total length. Larger (> 70 μm) grains in this group (also *Pinus* subgenus *strobus*), predominantly from high elevation white pines, were distinguished from *Pinus* subgenus *pinus* grains based on the latter's lack of verrucae on the leptoma. Pollen slides were scanned at 400×, to a minimum pollen sum of 300 grains. The pollen sum consisted of all terrestrial pollen types, and excluded wetland and aquatic pollen and spores. Pollen zones were defined by visual inspection of the graphed data. The complete pollen data are deposited in the North American Pollen Database (www.ngdc.noaa.gov/paleo/pollen.html).

For high-resolution charcoal analysis we analyzed the sedimentary charcoal content of contiguous sediment samples. Sediment sub-samples (5 cm^3) from each linear 0.5 cm of the core length were disaggregated in water. Sediment samples were sieved with 125- and 250-mm mesh, and examined using a dissecting microscope. The charcoal accumulation rate (CHAR) time series was created by dividing the charcoal concentration value of each sample by its corresponding deposition time.

Macrofossil samples were sieved from the core using 125- and 850-μm mesh, then sorted and identified by comparison to the reference collection at the LOP. Conifer genera were identified to species (except *Picea*) according to external and internal morphology. *Pseudotsuga* needle fragments were distinguished by their flat, petiolate leaves. Identification of *Pinus ponderosa* needles was confirmed by the occurrence of two fibrovascular bundles in the needle and a triangular exterior shape of the needle in cross-section (Harlow, 1947). Cyperaceae (sedges) were separated by shape and size into morphotypes (trigonous vs. lenticular, small vs. elongate).

C/N ratios, ^{13}C and ^{15}N compositions were measured on approximately 1–6 mg (depending on organic matter content) of dry and homogenized sediment. No pretreatment to remove the carbonate fraction of the sediment samples was performed as prior X-ray diffraction analysis indicated the samples were carbonate-free. Core depths for analyses spanned from ~5 to 322 cm and samples were taken at varying intervals (~2–20 cm). C/N ratios and ^{13}C and ^{15}N contents were measured in the Geochemistry and Geomaterials Research Laboratory (GGRL) at Los Alamos National Laboratory (LANL) using an elemental analyzer (EuroVector) coupled to an isotope ratio mass spectrometer run in continuous flow mode (Isoprime®). ^{13}C and ^{15}N compositions are expressed as deviation in per mil (‰) of the ratios $^{13}C/^{12}C$ and $^{15}N/^{14}N$ in the sample with

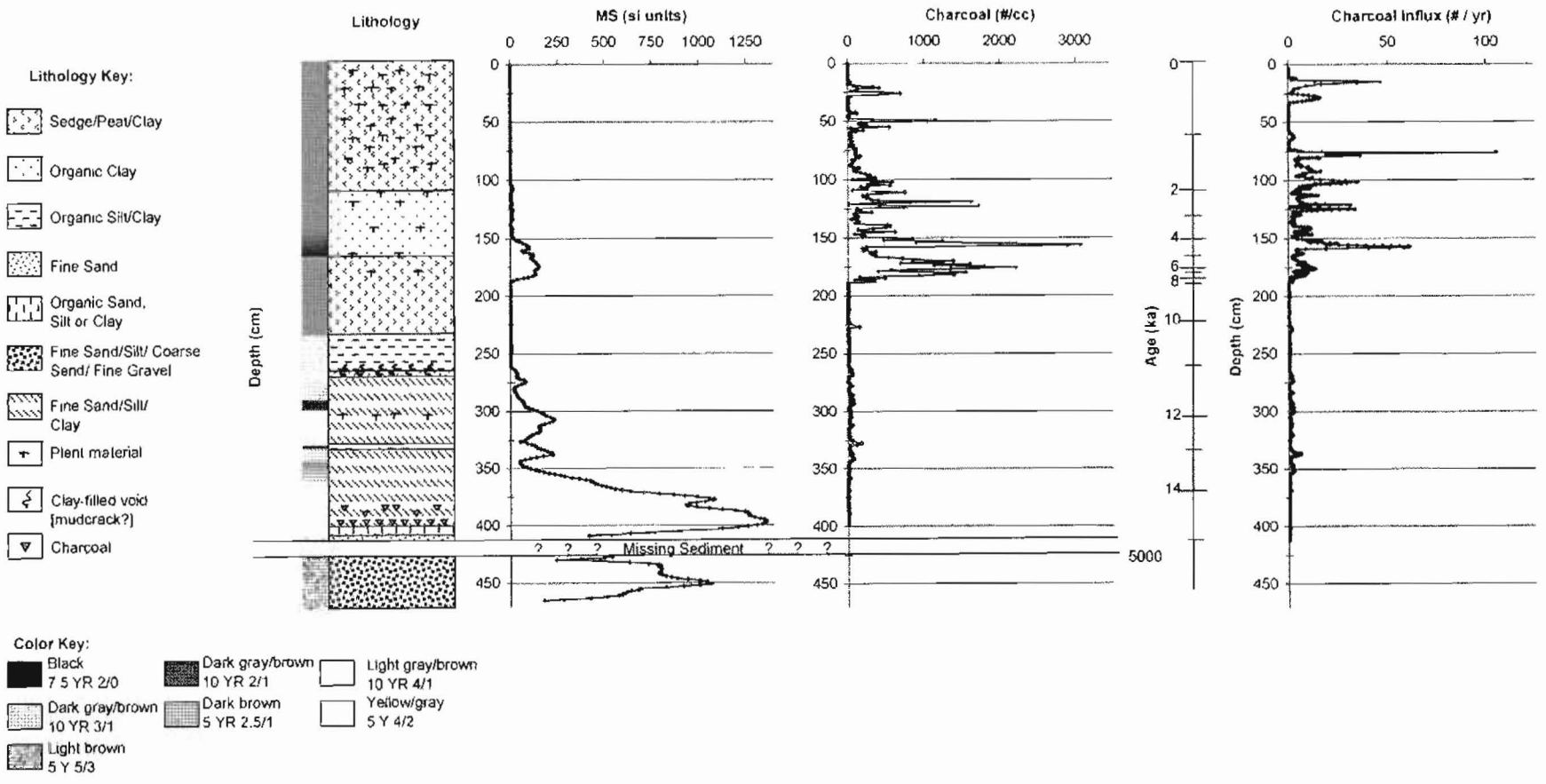

Figure 2. Core lithology, magnetic susceptibility, charcoal concentration and charcoal influx values for Chihuahueños Bog core 1.

Table 1
Radiometric Ages for the Chihuahueños Bog sediment core

Site name	Core	Laboratory number	Depth (cm)	Age (^{14}C yr BP, ^{210}Pb, ^{137}Cs, Historic)	SD (±)	^{13}C/^{12}C	Cal yr BP (2 s.d.)	Median probability (used for graphing)	Calibration	Date type	Material
Chihuahueños Bog	1	USC Geology	6	AD 1963	N/A	N/A	−13	−13	N/A	^{137}Cs	Sediment
	1	USC Geology	17	AD 1890	N/A	N/A	60	60	N/A	^{210}Pb	Sediment
	1	USC Geology	21	AD 1865	N/A	N/A	85	85	N/A	^{210}Pb	Sediment
	1	Beta-176475	48–51	1320	40	−24.7	1176–1302	1254	CALIB 5.0	AMS	Charcoal
	1	Beta-202658	54–58	990	40	−26.1	795–964	902	CALIB 5.0	AMS	Peat, Chitin
	1	Beta-160243	101–105	1840	70	−25	1601–1927	1773	CALIB 5.0	Bulk	Peat
	1	Beta-160244	162.5–166.1	4290	70	−25	4783–5047	4864	CALIB 5.0	Bulk	Peat
	1	Beta-176476	188–189	8130	40	−22.3	8996–9139	9070	CALIB 5.0	AMS	Charcoal
	1	AA-39836	217.7–222.9	9100	61	unknown	10177–10425	10262	CALIB 5.0	AMS	Sediment
	1	Beta-114177	340–350	11850	80	−25	13471–13876	13711	CALIB 5.0	Bulk	Peat

respect to the ratio in the Pee Dee Belemnite (PDB) standard for carbon and atmospheric air standard for nitrogen,

$$\delta = [(R_{\text{sample}}/R_{\text{standard}}) - 1]^{*}1000$$

where R_{sample} and R_{standard} are the ratios $^{13}C/^{12}C$ or $^{15}N/^{14}N$ of the sample and standard respectively. Precision of the measurements was <1 for C/N ratios and 0.1‰ and 0.3‰ for $\delta^{13}C$ and $\delta^{15}N$ values, respectively.

Material for radiocarbon ages consisted either of small charcoal fragments or bulk sediments. Radiocarbon ages were calibrated to calendar ages using CALIB 5.0 (Stuiver et al., 1998). Sediment samples for ^{210}Pb and ^{137}Cs dating consisted of whole sediment from the upper portion of the core. These sediments were dried to constant weight in an oven at ca. 75 °C. Three to 5 g of the pulverized sediments were used in the gamma counting. Excess ^{210}Pb and fallout ^{137}Cs activities were measured non-destructively by gamma spectrometry using a high-resolution, low background well-type Ge detector (Appleby, 2001).

Results

Core lithology and chronology

The Chihuahueños Bog sediments are primarily organic in the upper portion of the core, grading to more inorganic sediment below. From the core surface to ca. 171 cm depth, sediments are mostly dark brown to black, alternating between sedge peat and peaty clay, but with increasing clay content downcore (Fig. 2). Between ca. 171 and 236 cm, sediments are mostly similar to those overlying this section, but with some dark mottling. Sediments from ca. 235 to 300 cm have higher clay and lower organic content. From ca. 300 to 406 cm, the core consists of clayey silts with fine sand grains interspersed throughout. A very coarse, well-sorted sand layer occurs at 406–410 cm. Sediments between 410 and 422 cm depth were not retrieved during coring, but those below 422 cm are olive-colored, with increasing sands and gravel to the core bottom at 465 cm.

The age model is based on a combination of ^{137}Cs and ^{210}Pb decomposition series ages in the upper portion of the profile and calibrated ages from seven ^{14}C dates downcore. Maximum ^{137}Cs deposition (i.e., AD 1963–64) occurred at 6 cm depth. Downcore to ca. 21 cm we used the ^{210}Pb age relationship (0.146 cm/yr). All seven ^{14}C ages (except for Beta-176475) occurred in stratigraphic order (Table 1; Fig. 3). Our chronology for most of the core consists of linear interpolation between adjacent radiocarbon ages, using the median value of the calibrated age of the date.

Fossil pollen and macrofossils

Pollen Zone I (ca. 15,000 to 11,700 cal yr BP)

Pollen Zone I is divided into two subzones—Ia (ca. 15,000 to 14,000 cal yr BP) and Ib (ca. 14,000 to 11,700 cal yr BP). *Artemisia* and Poaceae (grass) pollen dominate the percentage diagram during zone I, but additional pollen types are important in zone Ia, including Brassicaceae (mustard family), *Sarcobatus*, and *Betula* (birch) (Fig. 4). Also important here are wetland plants, including *Salix* (willow), *Thalictrum* (meadow rue) and *Sphagnum*. In subzone Ib, *Picea* pollen percentages increase,

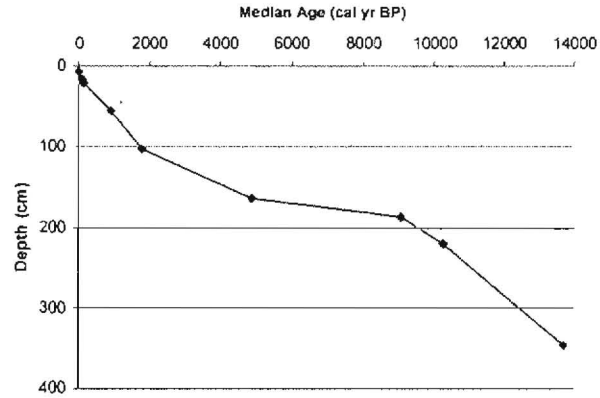

Figure 3. Age-depth curve for Chihuahueños Bog core #1. Ages (diamonds) are graphed as the median probability of calibrated radiocarbon years. Square is Beta-176475, which was considered too old and not used in construction of curve.

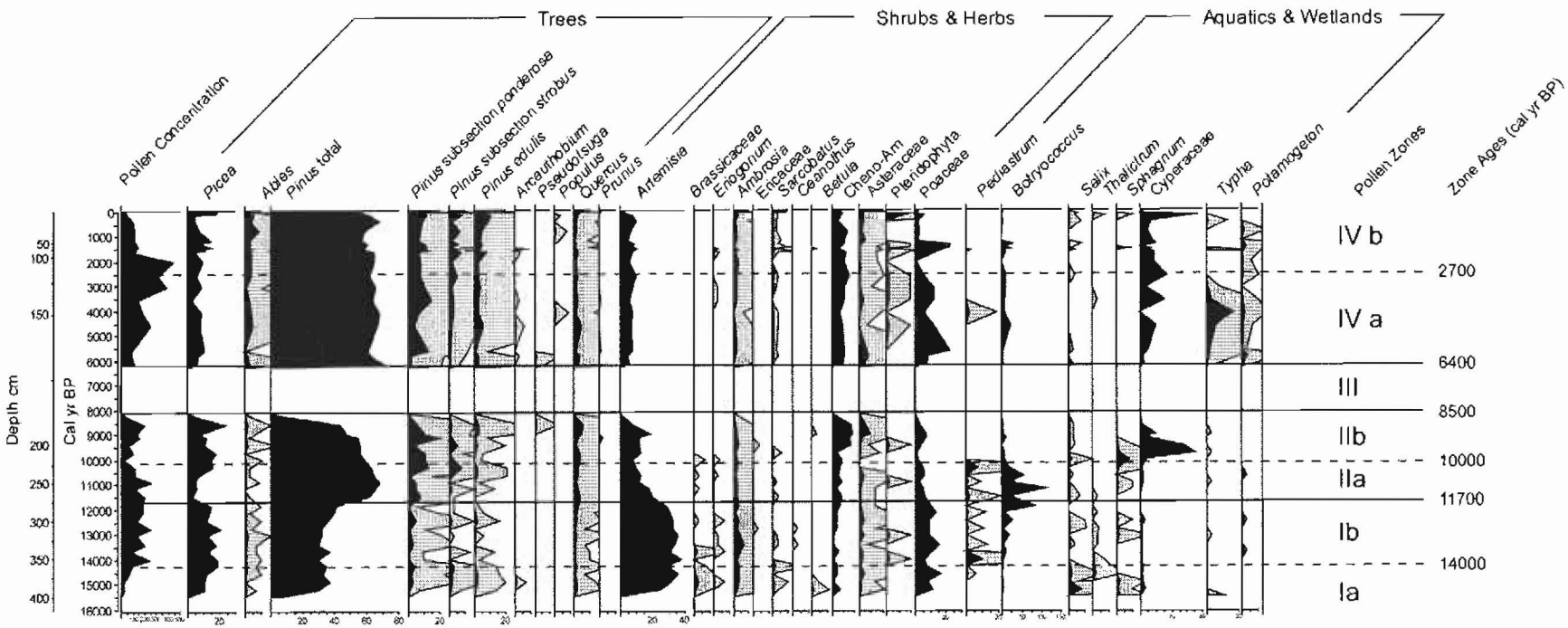

Figure 4. Summary pollen percentage data from Chihuahueños Bog core #1. Note silhouette is percentage times 10. Pollen zones Ia to IVb are shown on the right.

and *Picea* needle fragments are first found at the transition of Zone Ia to Ib (Fig. 5). Aquatic microfossils (*Pediastrum* and *Botryococcus*) are essentially absent during Ia but increase during Ib, while the wetland pollen types listed above decline.

Pollen Zone II (ca. 11,700 to ca. 8500 cal yr BP)

Pollen Zone II is also divided into two subzones – IIa (ca. 11,700 to 10,000 cal yr BP) and IIb (ca. 10,000 to 8500 cal yr BP). Throughout the zone, *Artemisia* pollen percentages decline. Though *Picea* percentages also decline briefly (Fig. 4) plant macrofossils attest to its continued presence around the site (Fig. 5). However, *Pinus* pollen increases substantially. We are unsure of the species of *Pinus* represented, but the increase in *P. ponderosa*-type is suggestive of either ponderosa or lodgepole pine. *Pinus* subsection *strobus* pollen (e.g., *P. flexilis* or *P. strobiformis*) also increases after ca. 10,500 cal yr BP. During this zone also, *Quercus* pollen (Fig. 4) and *Pseudotsuga* needle fragments (Fig. 5) first become abundant, while Poaceae pollen is at a minimum (Fig. 4). By ca. 10,000 cal yr BP, indicators of open water (i.e., the microalgae, *Pediastrum* and *Botryococcus*; rooted aquatic macrophytes *Isoetes* and *Chara*) decline and are replaced by shallow-water rooted aquatics (seeds of *Nuphar* and *Nymphaea*), as well as wetland plants (Cyperaceae).

Pollen Zone III (ca. 8500 to ca. 6400 cal yr BP)

Pollen and terrestrial plant macrofossils are absent from sediments deposited during Zone III time (Figs. 4 and 5). A few plant macrofossils of Cyperaceae and *Potamogeton* were recovered, but the numbers are reduced substantially from Zone II time below and Zone IV time above (Fig. 5). In addition, indicators of a persistent water body (*Pediastrum* and *Botryococcus*) are absent. The sediment in this core section is highly compacted, dense, and contains higher clay content than sections above or below. The lack of pollen, plant macrofossils and aquatic algae suggests a period of intense decomposition occurred during Zone III time.

Pollen Zone IV (ca. 6400 to present)

Pollen Zone IV is also divided into two subzones – IVa (ca. 6400 to 2700 cal yr BP) and IVb (ca. 2700 cal yr BP to present). Pollen of mixed conifers dominates, especially *Pinus* pollen, with *P. ponderosa* type, *P.* subsection *strobus*, and *P. edulis* types increasing throughout the zone. *Abies* pollen also increases during this zone and *Picea* remains important, with larger numbers of *Picea* and *Pseudotsuga* needle fragments found during subzone IVb than before (Fig. 5). *Quercus*, *Ambrosia*, and Cheno-am pollen are important types; pollen of Poaceae and spores of pteridophytes are most abundant during Zone IV time (Fig. 4). For wetland plants, Cyperaceae pollen dominates with *Typha* during subzone IVa. Pollen and plant macrofossils of *Potamogeton* are common, but remains of open water algae (*Pediastrum* and *Botryococcus*) are nearly absent.

Charcoal stratigraphy

Charcoal is extremely abundant in much of the bog sediments, often exceeding 10,000 particles/cm^3. Charcoal was present in all of the >1500 levels analyzed. Charcoal accumulation rates (CHAR: particles/cm^2/yr) were calculated for the past ca. 14,000 yr by multiplying the charcoal concentration by the sediment deposition rate (Fig. 2). We also calculated fire episode frequencies (FEF's) using the Charcoal Analysis

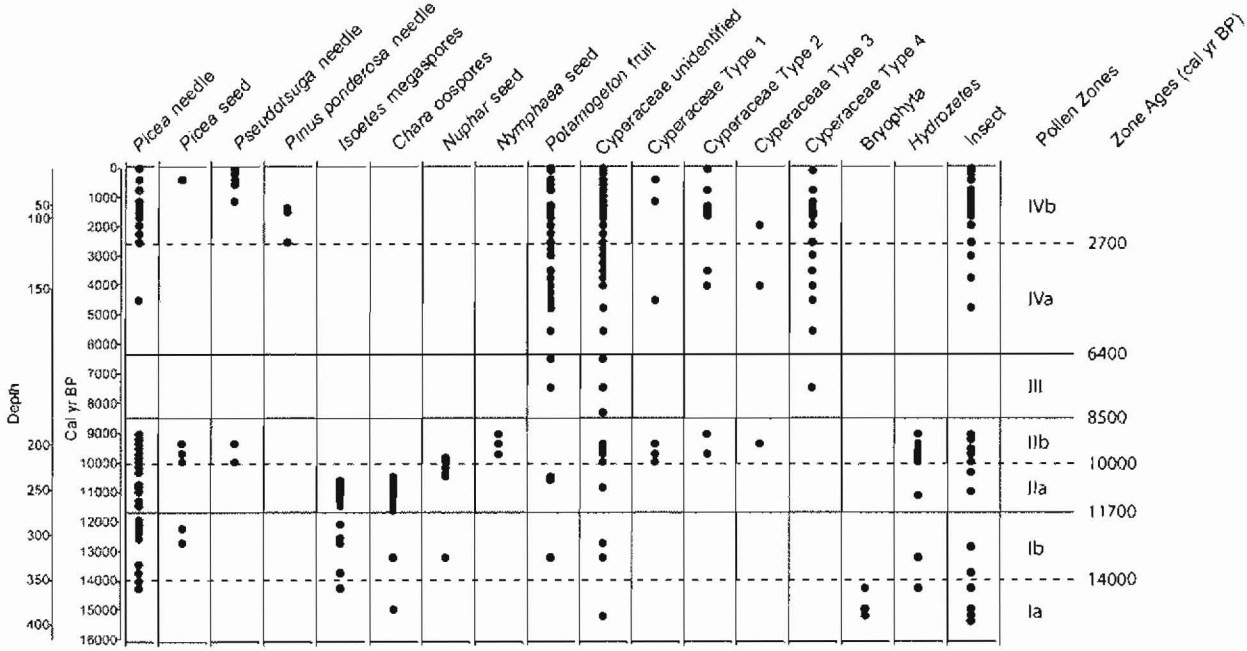

Figure 5. Summary plant macrofossil data from Chihuahueños Bog core #1. Macrofossils are shown as presence or absence only. Pollen zones Ia to IVb are shown on the right.

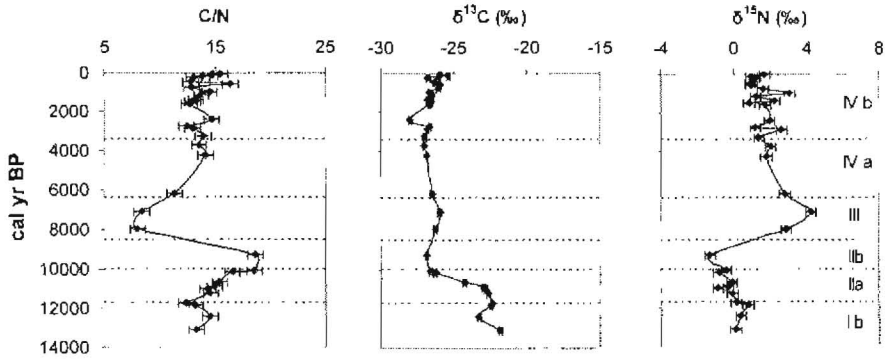

Figure 6. C/N ratios, $\delta^{13}C$ and $\delta^{15}N$ signatures of bulk sedimentary organic matter from Chihuahueños Bog. Pollen zones Ib through IVb are indicated by dashed lines.

Programs (CHAPS; Long et al., 1998; Whitlock and Anderson, 2003) commonly used for records of vegetation with long fire rotations. However, our calculations reported elsewhere (Allen et al., in press; Anderson et al., in press) suggested very unrealistic FEF for the Chihuahueños Bog record, and so we do not report those results here. For example, fire-scar data for the period AD 1624 and 1902 averaged one fire every 34.8 yr (range=10 to 61 yr) (Allen et al., in press), while CHAPS calculated latest Holocene FEF equivalent to one fire every 200 to 250 yr. We conclude that CHAR values are probably more appropriate for reconstructing fire history at sites where the sampling interval is as long as, or longer than the time between fires, such as occurs in sites within mixed conifer forest.

Charcoal particles are present in low quantities during the early part of the record, when steppe and woodland vegetation dominated the landscape around the pond. Charcoal influx during the period of mixed conifer establishment (Zone II) actually contains the lowest values of the entire record, with some periods containing only a few charcoal particles (i.e., ca. 9150 and 10, 200 cal yr BP). Charcoal influx increases again after ca. 8000 cal yr BP, and remains abundant for the rest of the record. During Zone III, when the wetland dried, charcoal increased to moderate influx values (>13 particles/cm^2/yr). Influx values increase considerably to maximum values after ca. 4600 cal yr BP. Charcoal influx remains consistent, with periodic spikes, for the remainder of the core, with the exception of minimal charcoal values between ca. 900 and 400 cal yr BP (Fig. 2).

Carbon and nitrogen elemental and isotopic analyses

C/N ratios

The C/N and $\delta^{13}C$ and $\delta^{15}N$ records span the last ca. 13,100 years C/N ratios help determine the relative input of lacustrine and terrestrial plants, each with characteristic values of <10 and >20, respectively (Meyers, 2003). Chihuahueños Bog C/N values ranged from 8 to 19 (Fig. 6). In the earliest section of the C/N record (ca. 13,000 to 11,700 cal yr BP, pollen zone Ib), ratios indicate a mixture of inputs to sedimentary material from lacustrine algae and terrestrial plants, During pollen zones II and III (ca. 11,700 to 6400 cal yr BP), C/N ratios fluctuate between values for these two end members with lowest values found in zone III (ca. 8500 to 6400 cal yr BP). By the time of pollen zone IV (ca. 6400 cal yr BP to present), C/N ratios increase from a value of ~11 to 14 indicating the increased input of terrestrial organic matter relative to zone III.

$\delta^{13}C$ values of bulk sedimentary material

$\delta^{13}C$ values are important in determining the relative inputs from different plant groupings (Meyers, 2003; Osmond et al., 1981; Boon and Bunn, 1994); these ranged from −21.8 to −28.0‰ (Fig. 6) with heavier (less negative) values in the earliest section of the core in pollen zones Ib and IIa (ca. 13,000 to 10,600 cal yr BP). A shift towards the characteristic values of lacustrine algae and C_3 plants (Table 2) is observed by the end of zone IIa and during zone IIb (ca. 10,000 to 8500 cal yr BP) followed by a slight increase in the signatures during zone III (ca. 8500 to 6400 cal yr BP). From ca. 6000 cal yr BP to the present, the $\delta^{13}C$ averages ~−27.0‰, well within the range characteristic of C_3 land plants and lacustrine algae.

$\delta^{15}N$ values of bulk sedimentary material

$\delta^{15}N$ values are also important in differentiating terrestrial and aquatic plant inputs, and these ranged from −1.3 to 4.2‰ (Fig. 6) with lighter values (more negative) observed in the earliest section of the core (ca. 13,000 to 9000 cal yr BP). During pollen zone Ib (ca. 13,000 to 11,700 cal yr BP), $\delta^{15}N$ values start around 0‰, within the typical range of terrestrial plants and characteristic as well of the photosynthetic cyanobacteria (Meyers, 2003). During pollen zone II (ca. 11,700 to 8500 cal yr BP) $\delta^{15}N$ values become slightly lighter, reaching a value of −1.29‰ (ca. 9200 cal yr BP). An abrupt shift is observed during pollen zone III (ca. 7000 cal yr BP) to the heaviest value of

Table 2
Potential range of $\delta^{13}C$ values of organic matter sources of sedimentary material

Organic matter source	$\delta^{13}C$ signature
C_3 plants	−25‰ to −30‰ [a]
C_4 plants	−11‰ to −15‰ [a]
Aquatic plants (includes emergent, submerged and floating)	−10‰ to −50‰ [b]
Lacustrine algae	−25‰ to −30‰ [a]

[a] Meyers (2003).
[b] Osmond et al. (1981); Boon and Bunn (1994).

4.2‰. From ca. 6000 cal yr BP to the present, $\delta^{15}N$ values approach values of ~1‰, close to the average value of terrestrial plants.

Discussion

Although the mixed conifer forest is an important ecosystem in northern New Mexico, and especially in the Jemez Mountains, virtually nothing is known about the postglacial history of forest development in the region. One reason is the lack of suitable sites—lakes are rare in this arid landscape, and most of those have accumulated sediment only over the last few millennia (Ensey, 1997). The record from Chihuahueños Bog is important in this regard, as it contains a nearly continuous record of vegetation change since the late glacial.

While the characteristics of vegetation in northern New Mexico during the maximum Pinedale glaciation are unknown at present, an extensive ice cap existed on the highest elevations of the Sangre de Cristo range to the east (Porter et al., 1983). Two dates constrain deglaciation there, including ca. 14,100 cal yr BP (12,160±40 ^{14}C yr BP; Jicarita Bog, Bair, 2004) and 14,000 cal yr BP (12,120±95 ^{14}C yr BP; Stewart Bog, Armour et al., 2002). Further to the north, treeline in the southern Rockies was ca. 500 m lower in elevation, with alpine plants found today above 3300 m occupying areas below 2800 m, and modern subalpine forests (ca. 3300 to 2700 m elevation) growing below 2300 m (Maher, 1961; Legg and Baker, 1980; Markgraf and Scott, 1981). Late-glacial winters were colder with increased winter precipitation, and summers were drier than today (Vierling, 1998; Markgraf and Scott, 1981; COHMAP, 1998; Kutzbach et al., 1998).

There is no evidence that the Jemez Mountains were glaciated. The lack of a sedimentary record prior to ca. 15,000 cal yr BP suggests dry conditions during the pleniglacial there. During the late-glacial period, low pollen concentrations and a predominance of *Artemisia* and Poaceae pollen suggest tundra or steppe vegetation initially existed around a shallow lake in the basin. Plant remains of tree species are absent early in the sequence, but the establishment of *Picea* around the lake suggests a transition to spruce parkland after 14,000 cal yr BP. Fire probably occurred periodically in these environments, but little charcoal was produced. Prior to 14,000 cal yr BP, the pond was generally unproductive, but establishment of aquatic macrophytes after this time suggests greater productivity then. This early *Picea* parkland period encompasses the Bølling-Allerød and Younger Dryas climatic oscillations. While hypothesized to have occurred at other locations in the southern Rockies (Menounos and Reasoner, 1997; Reasoner and Jodry, 2000) and Sangre de Cristo Mountains (Armour et al., 2002) these climatic fluctuations are not obvious in the Chihuahueños Bog record using our present sampling interval strategy.

The C and N records support the vegetation reconstruction, but provide better data on the local paleoenvironment. Based on C/N ratios and $\delta^{13}C$ and $\delta^{15}N$ records, pollen zone Ib and IIa include a mixture of terrestrial and aquatic inputs. Heavy $\delta^{13}C$ values could be derived from a combination of sources. Presence of C_4 plants on the landscape (e.g. certain species of Poaceae and Cyperaceae), or presence of terrestrial plants with high water-use efficiency and therefore heavy ^{13}C signatures (Farquhar et al., 1982; Farquhar and Richards, 1984) (for instance, modern specimens of *Artemisia* collected locally at lower elevation on the Pajarito Plateau have ^{13}C values of ~−23‰) could contribute to these values. A third explanation includes enhanced aquatic productivity (Hodell and Schelske, 1998; Brenner et al., 1999; Meyers, 2003). Major changes in these parameters occur during pollen zone IIa (ca. 11,700 to 10,000 cal yr BP). Similarly, $\delta^{15}N$ values around 0.0‰ during pollen zone Ib and IIa could indicate, in addition to terrestrial inputs, enhanced aquatic productivity in the shallow pond, as evidenced by the abundance of algae species (*Pediastrum* and *Botryococcus*) accompanied by discrimination against the heavy isotope by algae in a nitrogen-rich environment (Wada and Hattori, 1976; Boyle, 1993; Hodell and Schelske, 1998; Brenner et al., 1999; note that nitrogen supply would need to exceed demand to allow such discrimination to be expressed). Other possibilities come from inputs from submerged aquatic plants (e.g. some species of *Potamogeton* can have $\delta^{15}N$ signatures as low as 0.0‰; Boon and Bunn, 1994) and/or the presence of nitrogen-fixing cyanobacteria, although we lack evidence for this.

Warmer conditions during the earliest Holocene in the southern Rockies led to upward elevational shifts by subalpine conifers there (Elias et al., 1991). Some authors have suggested wetter conditions at this time as well (e.g., Andrews et al., 1975; Petersen and Mehringer, 1976; Petersen, 1981). By about 11,500 cal yr BP at Chihuahueños Bog, the decline in *Artemisia* and Poaceae suggests that *Picea* parkland was invaded by *Pinus* (either *P. ponderosa* or *P. contorta*). No plant macrofossils of either species were recovered, but establishment of *P. ponderosa* would be consistent with other sites in the Southwest (Anderson, 1989, 1993; Weng and Jackson, 1999; Anderson et al., 2000), and the occurrence of *Quercus* (probably *Q. gambelii*)—a common co-dominant today in *P. ponderosa* forests of the region (Dick-Peddie, 1993) is also supportive. With the expansion of other white pines (perhaps *P. flexilis* or *strobiformis*) by 10,500 cal yr BP, followed by *Pseudotsuga* by 10,000 cal yr BP, came the establishment a of mixed conifer forest around the pond. Fire may have been relatively unimportant during this transition, judging from low charcoal influx values. Alternatively, processes inhibiting deposition of charcoal at the coring site may have prevailed.

Several studies (Anderson, 1989; Betancourt, 1990; Toney and Anderson, 2006) have suggested that expansion of *P. ponderosa* resulted from expansion of the summer monsoon with increased summer moisture. More direct evidence comes from changes in wood cellulose deuterium, with more positive deuterium values in the early Holocene, indicating a southerly source for precipitation (Friedman et al., 1988). At Chihuahueños Bog, the increase in aquatic algae suggests wetter conditions. The presence of both *Pediastrum* and *Botryococcus* during this transition (ca. 11,700 to 10,000 cal yr BP) is accompanied by elevated C/N ratios given the high C content in those algae species (Banerjee et al., 2002; Metzger and Largeau, 2005). These changes also occur during transition from a small pond to a wetland by 10,000 cal yr BP, with

loss of open water indicators, and replacement first by rooted aquatics (*Isoetes* and *Chara*), then by the shallow-water floating-leaved aquatics (*Nuphar*, *Nymphaea*) and wetland sedges. C/N ratios may be indicative of increased terrestrial inputs to the sediments. This situation continued throughout the early Holocene, perhaps because the combination of a small drainage basin with generally warm, arid (i.e., high evaporation rates) conditions allowed natural hydroseral changes to proceed at a rapid rate during the early Holocene.

By 8500 cal yr BP, however, fossil and sedimentary evidence suggests that the wetland dried out nearly completely for over 2000 yr. C/N ratios reached the lowest value (8) and $\delta^{13}C$ and $\delta^{15}N$ signatures became enriched by 0.9 and 5.52‰, respectively. The decrease in C/N ratios is consistent with a period of decomposition (Chen et al., 2003), which would have enhanced C loss from accumulated organic matter. Decomposition could also potentially enrich the $\delta^{13}C$ and $\delta^{15}N$ signatures of the remaining organic matter due to microbial processing (Fogel and Tuross, 1999; Kramer et al., 2003). We suggest that this was due to lowered water tables in this relatively small drainage basin. If so, this event suggests that the period 8500 to 6400 cal yr BP was the driest time period of the Holocene.

Increased deposition of charcoal suggests that fires occurred regularly in the drainage. The topographic relief in the Chihuahueños Bog drainage basin is low—ca. 45 m (Allen et al., in press)—with few barriers to stop fire from burning dry herbaceous plant material on the wetland surface itself. Fire occurrence may have also contributed to decreased C/N ratios, at least temporarily by increasing the availability of inorganic nitrogen (Christensen, 1973; Neary et al., 1999). Increased $\delta^{15}N$ signatures in soil organic matter have also been observed as a result of fires (Grogan et al., 2000), potentially augmenting the trend in the $\delta^{15}N$ record.

Substantiating evidence for this warm and/or dry interval comes from additional sites within the Southwest, although the timing varies between locales. The record from Stewart Bog sediments in the Sangre de Cristo Mountains to the east (Armour et al., 2002) is most similar to that from Chihuahueños Bog. There, low sedimentation rates and absence of periglacial activity suggest the warmest and driest Holocene conditions occurred between 9000 and 5750 cal yr BP. At Little Molas Lake in the San Juan Mountains to the northwest, Holocene fire activity was highest ca. 7000 to 5800 cal yr BP, with sedimentary evidence indicating lowest lake levels there 6230 to 5900 cal yr BP (Toney and Anderson, 2006). To the south, dated packrat middens are rare or absent from sites in southeast Arizona, southwest New Mexico, and far west Texas during the early to middle Holocene (Betancourt et al., 2001; Holmgren et al., 2003, 2006, 2007). Spaulding (1991) suggested that midden production tracks the abundance of woody perennials, which in turn respond to winter precipitation. If so, the decline in middens from the early to the middle Holocene represents the most arid portion of the Holocene in the southern deserts as well. However, in central and north-central Arizona, maximum aridity may have been confined to the early Holocene (Stoneman Lake; Hasbargen, 1994), or persisted into the middle and late Holocene (e.g., Montezuma Well [Davis and Shafer, 1992; Blinn et al., 1994] and Potato Lake [Anderson, 1993]). A shallower lake phase existed at Kaibab Plateau sites (northern Arizona; Weng and Jackson, 1999) somewhat later than at Chihuahueños Bog, from 6600 to 4230 cal yr BP.

Water tables rose by 6400 cal yr BP, allowing development of a wetland dominated by Cyperaceae with *Typha* (cattail) and *Potamogeton* (Fig. 4). With increased soil moisture came the development of the modern mixed conifer forest, which included most of the species found around the wetland today. This is also confirmed by the C/N ratios and the $\delta^{13}C$ and $\delta^{15}N$ values. C/N ratios increase with respect to the ratios during pollen zone III and remain around 14 (ca. 4000 cal yr BP to present), while $\delta^{13}C$ and $\delta^{15}N$ values remain in the range of values observed in terrestrial and aquatic plants (Osmond et al., 1981; Boon and Bunn, 1994; Meyers, 2003). Charcoal influx is greatest in the record during this time. Due to the spiked nature of the record, it is likely that fires starting in the forest burned into the wetland on occasion.

Though at least two Neoglacial periglacial events (ca. 5630 and 2900 cal yr BP) and two small cirque glacial advances (ca. 4040 cal yr BP and the Little Ice Age) were noted by Armour et al. (2002) for the southern Sangre de Cristo Mountains of New Mexico, changes in vegetation around Chihuahueños Bog appear to have been gradual throughout the late Holocene. This is typified by a consistent increase over the last 6000 yr in pollen of *Abies* (Fig. 4), perhaps indicating increased winter precipitation from a strengthened ENSO (Rodbell et al., 1999; Moy et al., 2002; Friddell et al., 2003; Rein et al., 2005), and greater soil moisture. Coincidentally, pollen of *Pinus edulis* also increases in the Chihuahueños Bog record (Fig. 4). There is no evidence that *Pinus edulis* grew near the lake, but this increase is noted at many sites within the southern Rockies (Anderson et al., in press), and its representation in the pollen record of Chihuahueños Bog probably reflects its expansion at elevations lower than Chihuahueños, perhaps due to increasing winter insolation and temperatures (Holmgren et al., 2007).

Summary and conclusions

Little is known about the postglacial history of the mixed conifer forests of the Southwest, and the Chihuahueños Bog record contributes to our understanding of that important vegetation type. This lack of knowledge is due largely to the distribution of sedimentary deposits in the Southwest. For instance, most sites with continuous stratigraphic records come from high elevation subalpine forests where lake basins are common. At lower elevations, where small lake basins are rare or absent, studies from packrat middens track vegetation changes. Appropriate sites from elevations in between these two extremes are rare, and long records such as from Chihuahueños Bog in the mixed conifer forest are rarely preserved.

Changes in vegetation from the Chihuahueños Bog record are consistent with climate models of the Holocene. Thompson et al. (1993) estimated annual surface temperature and other climatic factors using empirically derived boundary conditions built within a general circulation model. Dominant conclusions of this study were (1) atmospheric airflow patterns were strongly influenced by

the position and height of the Laurentide Ice Sheet, which diverted the westerlies as much as 18 degrees latitude south of their present average position, and (2) surface temperatures were 1 to 2 °C higher than present in the early Holocene due to increased summer insolation. For large areas encompassing the southern Rockies, the study showed a reduced annual temperature of ca. 2–6 °C at 18,000 cal yr BP, ca. 0.5–4.5 °C cooler at 12,000 cal yr BP, essentially modern temperatures at ca. 9000 cal yr BP, and a ca. 0.1–0.3 °C increase during the middle Holocene. Similar values were determined by Bartlein et al. (1998) for the same region.

Many features of the Chihuahueños Bog record are concordant with this model. Colder temperatures certainly influenced development of a steppe, then *Picea* woodland, around the pond during the late glacial. Occurrence of an initial small pond suggests cold and wet conditions then, while the occurrence of *Artemisia* steppe suggests cold and dry conditions. We suggest that colder temperatures would have allowed for greater effective precipitation, filling the small pond, even if actual precipitation values were low.

Increased summer insolation during the glacial–interglacial transition allowed for climate warming and expansion of species such as *Pinus ponderosa*, *Pseudotsuga menziesii* and *Quercus gambelii* to higher elevations during the early Holocene. Higher summer insolation also certainly contributed to declining groundwater tables after 10,000 cal yr BP at Chihuahueños Bog, which was not offset by any increase in summer precipitation from the development of the summer monsoon. Decreased effective precipitation culminated in maximum drying of the wetland after 8500 cal yr BP. It is unclear why the wetland would have remained essentially dry for over 2000 yr until ca. 6400 cal yr BP, but the reason must lie at least partially in the shallowness of the basin and the small extent of the drainage area for the wetland. Declining in summer insolation (Kutzbach and Guetter, 1986; Kutzbach et al., 1993) contributed substantially to late Holocene cooling, with declining summer temperatures and increasing effective precipitation at most sites, including Chihuahueños Bog, within the region.

The fire history as deduced from the charcoal influx record produced some surprises here. Little charcoal early in the record when steppe and woodland dominated was anticipated, as was greater charcoal deposition during the late Holocene when mixed conifer forest dominated. However, the lack of charcoal during the early Holocene when reconstructed vegetation was dominated by *Pinus* and other conifers was unexpected. This suggests that fire histories from sites such as Chihuahueños Bog may be complicated by changes in sedimentation and sediment type. In some instances, the fire record may consist not only of upland fires but those that burned across the deposit itself (Whitlock and Anderson, 2003; Allen et al., in press).

C/N ratios as well as $\delta^{13}C$ and $\delta^{15}N$ values of lacustrine sediments, which are influenced by species composition and the relative inputs of autochthonous and allochthonous materials, were in agreement with pollen-based reconstructions. The combination of proxies—pollen, plant macrofossil, charcoal and carbon and nitrogen stable isotopic composition—has provided a powerful combination of tools for paleoenvironmental analysis. Even so, additional studies are needed from other sites within the modern mixed conifer forests of the Southwest to widen our knowledge of the history of this important vegetation type.

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