Holocene Fire History and Climate Change in Rocky Mountain National Park: Pollen and Charcoal Evidence from Bear Lake

James P. Doerner, Ph.D.
Geography Program
School of Social Sciences
Heritage Resources Management and Education Institute (HRMEI)
University of Northern Colorado
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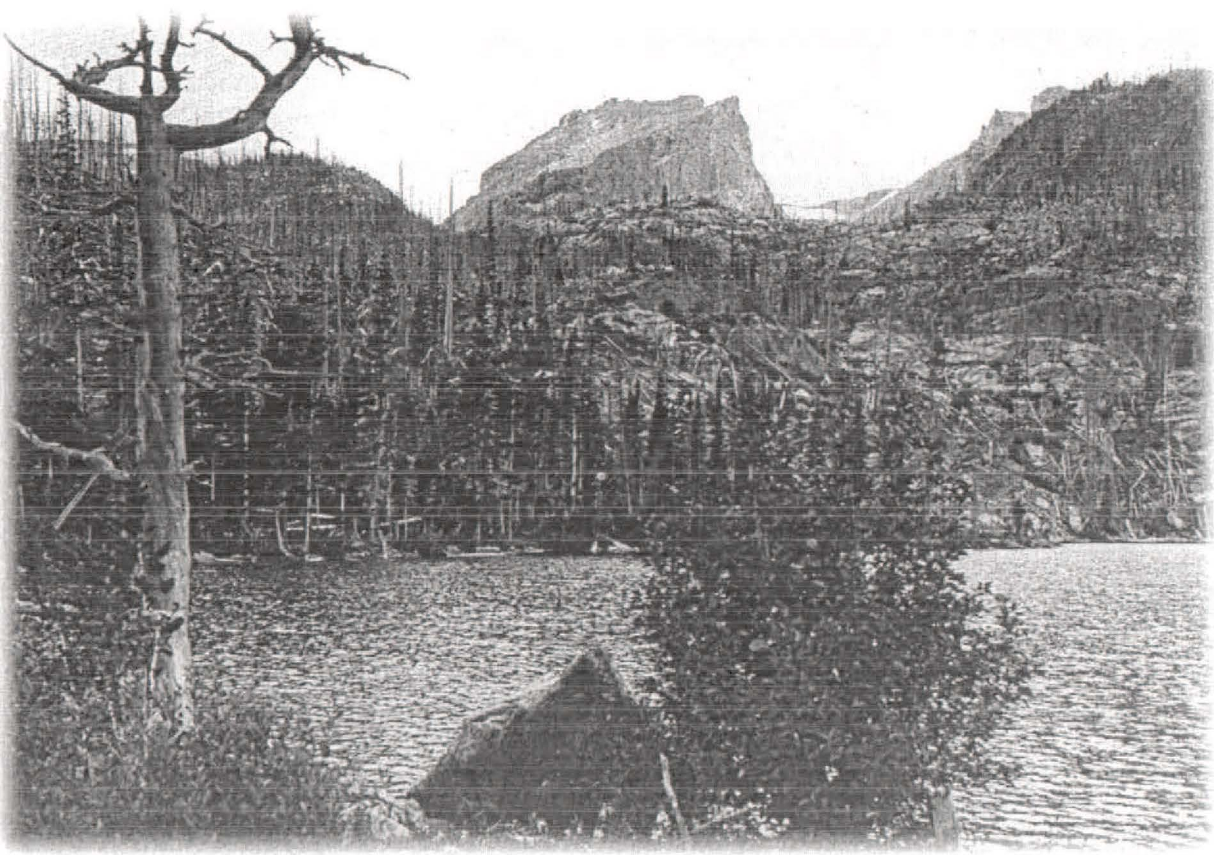

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INTRODUCTION

This report is prepared in support of the fire history and climate study conducted in Rocky Mountain National Park (RMNP) and funded by the National Park Service. This research is part of a joint effort between the University of Northern Colorado and the National Park Service (NPS Task Agreement Number *J1527050047* under Cooperative Agreement Number *CA 1248-00-007*) and reports on the history of Holocene climate change and fire in the Bear Lake region of RMNP. The data and findings in this report should be considered preliminary as this manuscript has not been subjected to external peer review.

The purpose of this study was to document the relation between Holocene climate and fire history in the subalpine forests of RMNP. Sediment cores were collected and subjected to charcoal, pollen, and sediment analysis. A long-term climate and fire history for the Bear Lake area was reconstructed from fossil pollen, sediment, and macroscopic charcoal data. Together these records explain the relation between climate and fire history during the last ca. 7000 years. Results suggest that fire frequency and intensity has varied with climate. The findings of this study can provide new insights into the natural processes that have shaped the present-day landscape and can be used to infer ecosystem response to climate variability.

Over the past twenty years, the forests of the western United States have experienced a series of large stand-replacing fires. Nearly three million hectares were burned in 1988; 2.7 million hectares in 1996; and 1.9 million hectares in 1994 (Whitlock 2001). In 2000, another 2.9 million hectares burned in eight western states (National Interagency Fire Center 2000). In 2002 the arson induced Hayman fire was propelled by record drought and extreme weather conditions (high winds and record-low relative humidity). This fire burned nearly 55,750 hectares and destroyed 600 structures in the Pike National Forest making it the worst forest fire in Colorado history. The scale of recent wildfires is due, in part, to land management practices that have effectively eliminated fire from many forested landscapes (*Nature* 2000).

Reconstructing past paleoecological change is crucial for understanding the Holocene environmental history of RMNP. During the Holocene the Park has experienced periods of climatic variability. Paleoecological studies indicate that the modern ecosystems of the RMNP are the result of a massive reshuffling of species that was brought about by environmental instability beginning during the last ice age and which continues to the present day (Elias 2001). These studies provide information about the climate that existed before humans began collecting observations of weather (e.g., temperature, precipitation, atmospheric pressure, wind speed and direction, etc.). Instead of instrumental measurements of weather and climate, paleoecologists use natural environmental or "proxy" records to infer past climate conditions. Proxy data, such as tree-rings, coral reefs, pollen, charcoal, organic-rich sediment cores, ice cores, and others are important sources of surrogate climate information.

The spatial coverage of paleoecological research in RMNP is expanded by reporting proxy results of environmental change preserved in sediment cores recovered from a subalpine lake (Bear Lake). Sediment cores contain a wealth of ecological and geomorphic information, which can illuminate climatic and climate-related environmental change. Special attention is paid to the link between climatic change and fire and their reflection in the sedimentation record. Charcoal and pollen data obtained from Bear Lake sediment cores provides a record of environmental change.

Previous Research in Rocky Mountain National Park

Paleoecological research from RMNP provides evidence of Holocene environmental change (Brunswig and Doerner 2001; Doerner et al. 2001; 2002; and Doerner 2004). In the early Holocene, (ca. 9000 to 8000 ^{14}C yrs BP[1]) conditions were warmer and wetter than modern times. There is evidence that suggests this was the warmest period of the Holocene and represents perhaps the "climatic optimum" for the last 10,000 years. The middle Holocene (ca. 8000 to 5200 ^{14}C yrs BP) was characterized by warm and possibly drier conditions as compared to the present day. At higher elevations (Lawn Lake fen) warmer summers and longer growing seasons resulted in rapid peat growth. At lower elevations (Beaver Meadows), higher temperatures and lower effective precipitation led to increased erosion and alluvial deposition and the disappearance of wetlands from valley bottoms. After about ca. 5200 ^{14}C yrs BP a regional climate change brought cooler conditions to the area. Cooler conditions

[1] ^{14}C yrs BP - radiocarbon years before present.

prevailed until ca. 2500 ^{14}C yrs BP. Climatic warming at this time resulted in peat formation in the Mt. Ida region and the development of a wetland near the Trail Ridge Game Drive site. Modern vegetation associations and climate conditions were likely established by around ca. 1800 ^{14}C yrs BP. Tree-ring studies from the RMNP show that tree invasion and establishment at upper treeline (~3414 - 3511 m) is likely related to the development of favorable climatic conditions (warmer and wetter) since the end of the "Little Ice Age" (ca. A.D. 1850) (Hessl et al. 1996; Hessl and Baker 1997a, 1997b).

The modern fire regime in RMNP is characterized by large, stand-replacing fires every 150-300+ years (Veblen et al. 1994; Kipfmueller and Baker 2000; and Buechling and Baker 2004). Recent tree-ring studies suggest that widespread fire in the subalpine forests of Rocky Mountain National Park is dependent on severe droughts (Sibold and Veblen 2006). These droughts are linked to coincidental changes in sea surface temperatures in the tropical and northern Pacific and northern Atlantic oceans. However, this information is temporally limited, as it is based on reconstructions established from tree-ring studies which are restricted to the past 400 to 500 years (the age of the oldest trees). These short-term records make it difficult to document variations that operate on multi-centennial or millennial time scales. Thus there is the need for additional long-term fire history studies in the RMNP.

Reconstructing Climate and Fire Histories

Pollen, sediment, and charcoal materials accumulate through time in lake, fen, and stream deposits of varying composition and thicknesses, depending on environmental and climatic conditions prevailing when sediments are deposited. To reconstruct the climate and fire history for Bear Lake three types of data were extracted from sediment cores: chronostratigraphic (time), lithostratigraphic (sediment), and biostratigraphic (pollen and charcoal).

Chronostratigraphic (time) data are based on a series of radiocarbon (^{14}C) age determinations obtained from organic-rich sediment layers recovered from the cores. Radiocarbon age determinations provide chronological control that allows rates of change to be calculated. The age of a fire event is established by interpolation from a series of radiometric ages. Lithostratigraphic data are based on biogeochemical properties of sediments related to their conditions of deposition. It includes the description of the sediments and magnetic susceptibility analysis. Biostratigraphic data are derived from pollen and charcoal analysis.

The basis of pollen analysis is that pollen grains and spores produced as a part of plant reproduction may be incorporated and preserved in lake mud, peat, or other organic-rich sediments which can be analyzed to reconstruct the vegetation of an area (Roberts 1989). Vegetation is often responsive to changes in environmental conditions. By reconstructing the past vegetation, it is possible to deduce information concerning former environmental conditions (Birks and Birks 1980). Pollen assemblages preserved in lake sediments reflect the surrounding vegetation, and changes in the pollen record over time provide a history of regional vegetation and climatic change. The extraction and analysis of fossil pollen in this study follows standard pollen techniques (Faegri and Iverson 1989).

Charcoal is produced when a fire incompletely combusts plant matter. Charcoal analysis quantifies the accumulation of charred particles in sediments during and following a fire event. Stratigraphic layers with abundant charcoal fragments (charcoal peaks) are inferred to be evidence of past fire events. These peaks must be distinguished from background charcoal in the stratigraphic record, which may be introduced through secondary processes such as erosion and sedimentation. The size of the charcoal particles can provide clues to the location of fires. Large particles (>125 microns) represent local fire events since larger particles travel only short distances. Small particles (< 125 microns) represent background accumulation since these fragments tend to travel further from the area burned. High-resolution analysis of macroscopic charcoal recovered from lake sediment has emerged as the standard technique to reconstruct long-term fire histories (Long et al. 1998). This technique was used to successfully reconstruct the Holocene fire history in Yellowstone National Park (Millspaugh et al. 2000; Whitlock et. al. 1997; and Whitlock and Millspaugh 1996) and is applied in this study.

STUDY AREA

Bear Lake is located on the eastern side of the continental divide at an altitude of 2888 meters (UTM Zone 13T 444,943 mE; 4,462,755 mN; Fig. 1). It occupies a glacial depression that was dammed by a Pleistocene moraine. The lake has a surface area of about 3.93 hectares. At its deepest point, Bear Lake is approximately ten meters deep, although the depth of the lake fluctuates seasonally. The sediments are mainly composed of soft gyttja, an organic-rich lake mud.

The lake is situated in the subalpine Engelmann spruce and subalpine fir forest. The subalpine spruce-fir forests are the highest, most continuous and pristine forests in Colorado (Mutel and Emerick 1992). Spruce is the dominant species on the dry sites as well as very wet sites (Peet 1981). Where conditions are the driest, fir is generally absent from the subalpine forests (Peet 1988). Spruce is more successful at establishing itself on mineral soils following fires (Alexander 1974; Peet 1981), whereas fir is more successful at establishing itself in the shade and on organic substrates (Knapp and Smith 1982). In areas where stands are mixed, the forest canopy is usually dominated by spruce but most of the seedlings and saplings in the understory are fir (Peet 1988). Disturbance areas are indicated by stands of quaking aspen and lodgepole pine.

The forest surrounding Bear Lake was burned by a large fire that dates to A.D. 1900 (Lee 1917). This fire burned an area approximately 1382 ha in size (Fig. 1; Sibold et al. 2006). Another fire much smaller in scale (172 ha) also burned near the lake in A.D. 1902 (Fig. 1; Sibold et al. 2006). Bear Lake was chosen for study due to its ease of access and because the fires that burned in historic times (Fig. 2.) are documented. This site had the potential to allow a specific fire episode from a known time period to be correlated to a specific charcoal peak likely to be found in the sediment core.

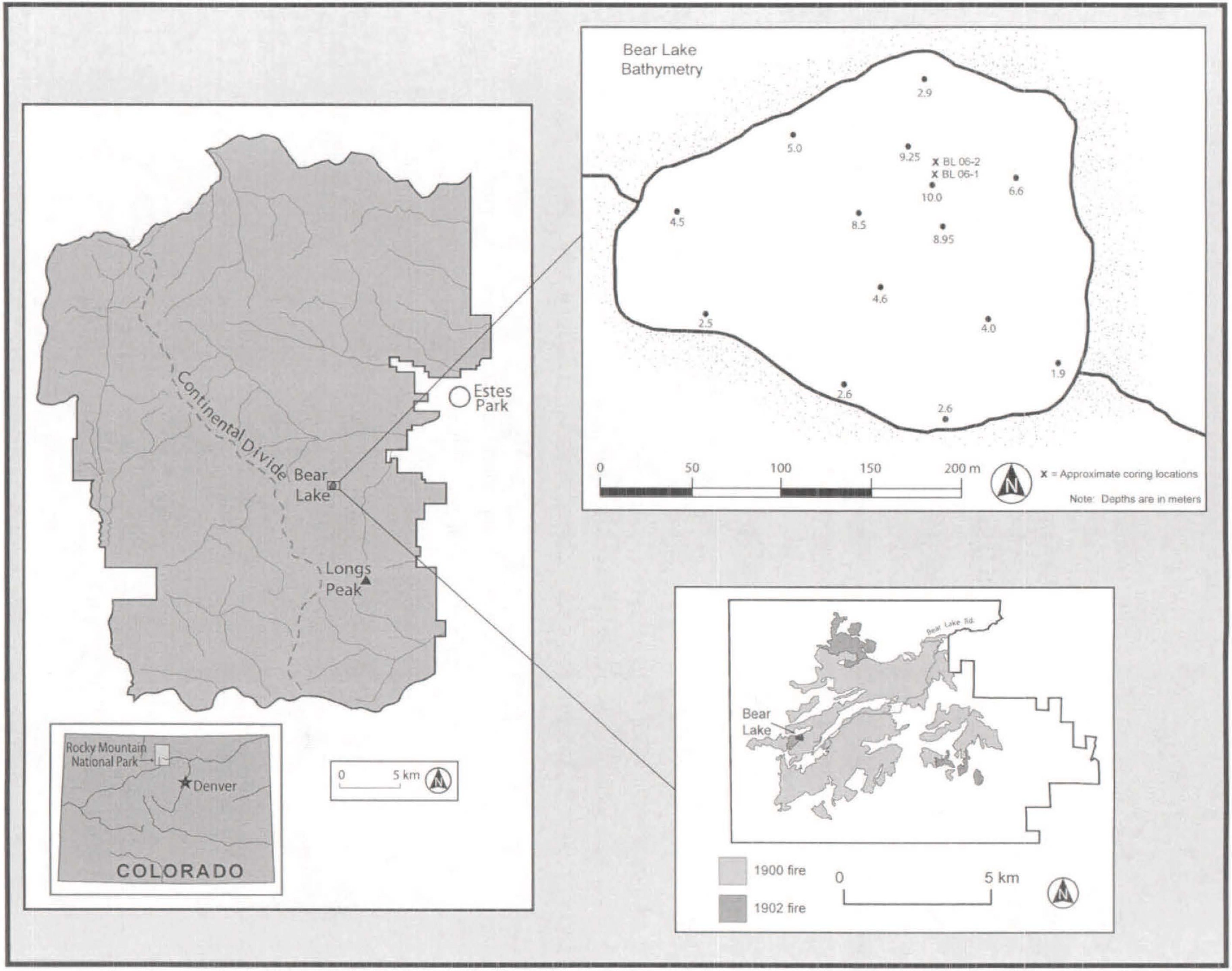

Figure 1. Map showing Rocky Mountain National Park, the Bear Lake study area, the coring site locations, and the extent of the 1900 and 1902 Bear Lake fires (fire data derived from Sibold et al. 2006).

Figure 2. Photograph showing tree mortality and survivorship in the Bear Lake area. The photograph was taken on August 3, 1916 by W.T. Lee of the United States Geological Survey.

METHODS AND PROCEDURES

Lake Coring

In the late winter/early spring of 2006, two sediment cores were extracted from Bear Lake. Prior to coring, a bathymetric map was used to determine the deepest part of the lake. At the time of the coring, the lake surface was frozen (ice thickness ranged from 45 to 60 cm) and the ice surface served as the coring platform. The water depth was approximately 10 m and cores were extracted from the deepest part of the lake (Fig. 1).

On March 30, 2006 a core 2.30 m (BL 06-1) in length was recovered from Bear Lake using a 5-cm diameter square rod piston corer. This device recovers 1 m long segments of undisturbed lake sediments (Fig 3a). This 2.30 m core is identified as BL 06-1. The sediments were extruded from the coring device in the field and were briefly described. Each core segment was wrapped in plastic wrap and aluminum foil and transported to the Paleoecology Laboratory at the University of Northern Colorado for analysis. Weather conditions at the time of the coring prevented the recovery of the sediment-water interface and the upper lake sediments.

On April 22, 2006 the lake was cored a second time to recover the sediment-water interface (Fig 3b). Using a piston-equipped plastic pipe as a coring device, the sediment-water interface and the uppermost lake sediments were recovered at this time. This short core was 38 cm in length is identified as BL 06-2. The plastic pipe containing these sediments was sealed in the field and transported to the UNC Paleoecology Laboratory for analysis.

Magnetic Susceptibility

In the laboratory, both cores (BL 06-1 and BL 06-2) were split lengthwise and the sediments described. Sub-samples of sediments were collected for radiocarbon dating, magnetic susceptibility, charcoal, and pollen analysis. Bulk samples of sediment were submitted for accelerator mass spectrometry (AMS) radiocarbon dating. Magnetic susceptibility measurements were conducted using standard techniques (Thompson and Oldfield 1986). Magnetic susceptibility was measured at 1-cm intervals in the core using a Bartington meter and was recorded in standard units (κ).

Figure 3a. Image showing a section of the Bear Lake core (BL 06-1) as it is extracted from the coring device (March 30, 2006; Image by Bill Butler).

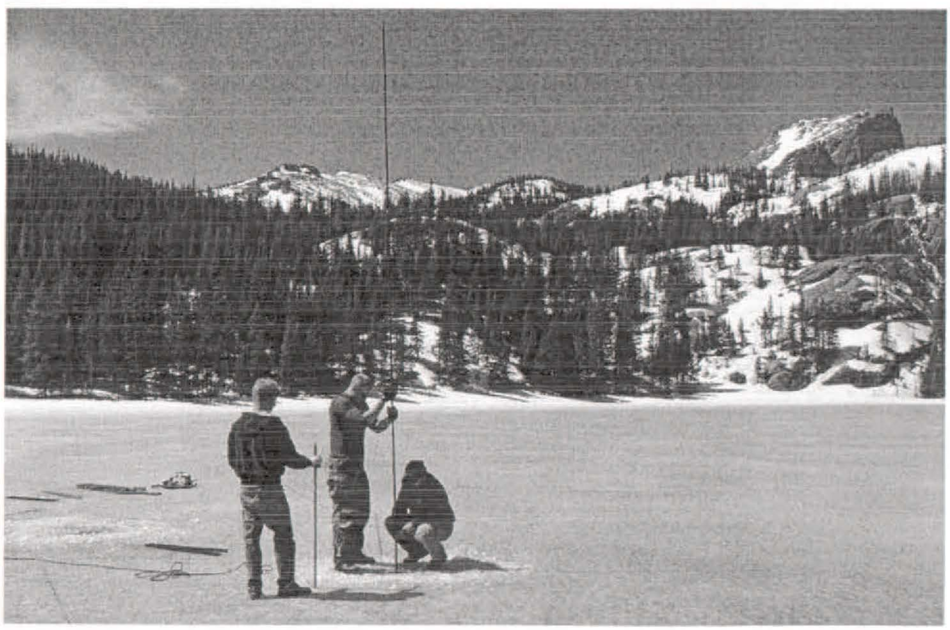

Figure 3b. Image showing the coring of Bear Lake (April 22, 2006).

Pollen Analysis

Samples for pollen analysis (1 cm^3) were taken at 5-cm intervals throughout the core. Pollen samples were prepared using standard pollen extraction techniques (Faegri et al., 1989). Known quantities of Lycopodium spores were added to each sample to calculate pollen percentages and concentrations (grains/cm^3). Pollen accumulation rates, PAR, (grains/cm^2/yr) were calculated by dividing pollen concentrations by deposition time (yr/cm). Pollen residues for each sample were stained and stored in glass vials containing silicone oil.

Pollen spectra from mountain environments can be difficult to interpret due to the long-distance transport of pollen grains (Maher, 1972). Markgraf (1980) found that strong gradient winds transport substantial amounts of pollen upslope from lower elevations so that the pollen rain at higher elevations contains a mixture of both high and lower elevation taxa. Conversely, she also found that the pollen rain at lower elevations contained few high elevation taxa. Pollen diagrams from the Rocky Mountains present additional problems of interpretation because many species do not produce significant amounts of pollen to signal changes in their relative abundance (Beiswenger, 1991). As a result, pollen reconstructions rely heavily on the limited taxa that produce large amounts of wind transported pollen (i.e., *Pinus*, *Picea*, *Artemisia*, Chenopodiaceae, and Poaceae) or on the presence of indicator taxa that often present in only small amounts (Doerner and Carrara 1999).

The pollen taxa from the Bear Lake cores were divided into three classes: 1) trees (arboreal), 2) shrubs and herbs (non-arboreal), and 3) aquatic-types. In the construction of the percentage diagram, the pollen sum is based on terrestrial taxa only (arboreal and non-arboreal). Pollen grains classified as "indeterminate" or "unknown" were excluded from the pollen sum. The percentage values for the aquatic-type were based on the total pollen sum (arboreal, non-arboreal, and aquatic-types classes). Pollen was identified to the lowest possible taxonomic level at magnifications of 400x and 1000x by comparison with the pollen reference collections and published keys (Kapp, 1969; McAndrews et. al., 1973). A minimum of 300 terrestrial pollen grains were counted for each level sampled in the core.

Charcoal Analysis

Sedimentary charcoal was analyzed to identify background trends, past fire episodes, and long-term fire frequencies. Charcoal analysis was completed using methods described by Whitlock and Larsen (2001). Samples of 1-2.5 cm^3 were taken at 1-cm intervals and soaked in sodium hexametaphosphate and bleach for at least 24 hours. Samples were washed through a 125-μm screen, and residues were counted in gridded petri dishes. Macroscopic charcoal fragments were identified and counted under a stereomicroscope using 10-40x magnification. Charcoal concentration (number of particles per cm^3) was calculated by dividing charcoal counts by the volume of sediment sieved.

The sedimentary charcoal record was analyzing using the statistical program *CharAnalysis*[2] (Higuera et al. 2007). This program converts charcoal concentrations to high resolution charcoal accumulation rates (CHARs) based on sediment chronologies. The CHAR records are composed of two elements: 1) a slowly varying trend that is referred to as the background component; and 2) short-term fluctuations around the background component referred to as the peaks component (Long et al., 1998). The background component represents long-term variations in fuel loads, regional fire activity, and/or changes in the levels of charcoal introduced to the sedimentary record during non-fire years (Long et al., 1998; Whitlock and Millspaugh, 1996). Large positive deviations of CHAR above the background component are considered to represent a pulse of charcoal accumulation related to a single fire or episode of fires in the catchment during the time span represented by the sample (Briles 2005).

The *CharAnalysis* program separates the charcoal record into the background and peaks components, and it establishes thresholds to identify peaks related to "local" fires. Identified charcoal peaks are treated as a local fire occurrence or a fire episode. Once the fire-frequency regimes are estimated the program develops models to calculate the mean fire return intervals (FRIs) within the identified time periods using maximum likelihood techniques (Clark 1989, Johnson & Gutsell 1994, Higuera et al. 2007). The mean fire interval is the arithmetic average of time intervals between fire events.

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[2] The CharAnalysis program is available for free and can be downloaded at http://charanalysis.googlepages.com.

RESULTS

Stratigraphy, Radiocarbon Ages and Chronologies

The sediments in the Bear Lake cores (BL 06-1 and BL 06-2) are composed of soft gyttja, a fine-grained organic-rich lake mud (Fig. 4). A total of eight accelerator mass spectrometry (AMS) radiocarbon ages were obtained on bulk samples organic materials from the cores (Table 1). In the long core (BL 06-1) the sample depths are estimated based on their stratigraphic position because the upper sediments were not recovered during core extraction (Fig. 4). An age of 550 ± 40 ^{14}C yr BP was obtained at a depth of 32 cm. An age of 1030± 40 ^{14}C yr BP was obtained at 62 cm depth. The sample from 102 cm yielded an age 1980 ± 40 ^{14}C yr BP while the sample from 172 cm had an age of 4040 ± 40 ^{14}C yr BP. The sample from 232 cm was dated at 5680 ± 40 ^{14}C yr BP. Finally, an age of 6120 ± 40 ^{14}C yr BP was obtained from a bulk sample of organic sediment at a depth of 257 cm. In the short core (BL 06-2) the sample from 5 cm depth was determined to be modern (101.2 +/- 0.4 pMC) while the sample from 32 cm had an age of 550 ± 40 ^{14}C yr BP.

TABLE 1. Radiocarbon ages, dating method, calibrated calendar age for the Bear Lake sediment cores

Depth (cm)	^{14}C yr BP	Material Dated	Laboratory Number	Dating Method[a]	Calibrated Calendar Age (yrs BP) with 2 sigma range[b]
			BL 06-2 (short core)		
5	Modern	Gyttja	Beta 232557	AMS	--
32	550 ± 40	Gyttja	Beta 234442	AMS	540 (510 to 570)
			Bear Lake 06-1 (long core)		
32	550 ± 40	Gyttja	Beta 232551	AMS	540 (510 - 570)
62	1030± 40	Gyttja	Beta 232552	AMS	940 (910 – 990)
102	1980 ± 40	Gyttja	Beta 232553	AMS	1930 (1860 – 2000)
172	4040 ± 40	Gyttja	Beta 232554	AMS	4520 (4420 – 4620)
232	5680 ± 40	Gyttja	Beta 232555	AMS	6450 (6400 – 6550)
255	6120 ± 40	Gyttja	Beta 232556	AMS	7000 (6890 – 7160)

[a] Accelerator mass spectrometry method.
[b] Calendar age used in the age-depth model. Ages are derived from CALIB 5.1.2 calibration curves (Stuiver et al., 1998) with the 2 sigma age range given in parentheses.

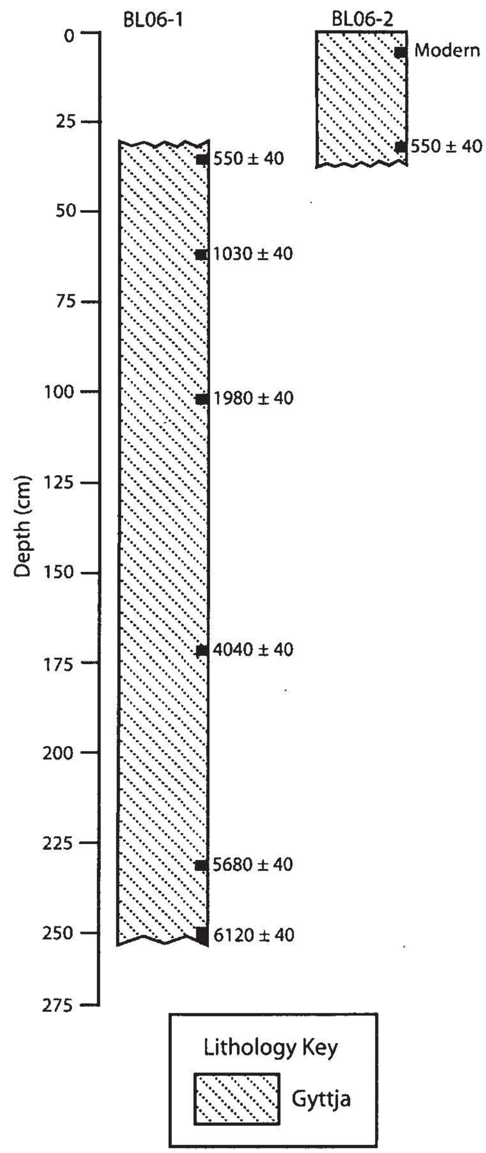

Figure 4. Lithology and radiocarbon ages for the Bear Lake cores.

The radiocarbon age determinations (Table 1) were used to build an age depth model for Bear Lake (Fig. 5a and 5b) and for calculating charcoal accumulations rates used by the *CharAnalysis* program. However, radiocarbon years are not directly equivalent to calendar years because of variations in atmospheric ^{14}C. Therefore, the conventional radiocarbon ages were converted to calendar years based on the INTCAL98 Radiocarbon Age Calibration (Stuiver et al. 1998).

Pollen Analysis

Pollen and spores representing twenty-eight taxa were identified in the cores. Only the most abundant and ecologically important taxa are presented on the pollen diagrams. The pollen diagrams includes a category called Cheno/Am that represents plants from the Chenopodiaceae (goosefoot) family and the genus *Amaranthus*. The pollen (and CHAR) diagrams for Bear Lake were divided into four zones based on constrained cluster analysis (Grimm, 1988) and the visual inspection of the pollen frequencies (Figs. 6 and 7), charcoal influx, background CHAR, and fire episode frequency (Figs. 9 and 10).

Zone 1a extends the top (0 cm) to the base (38 cm) of the BL 06-2 core (Fig. 6). This zone is characterized by high the percentages of tree pollen (74%). *Pinus* (pine) averages about 61% with *Picea* (spruce) averaging about 7%. *Artemisia* (sage) percentages are the high, averaging 14.5%. The total pollen accumulation rate (PAR) is the greatest in this zone, averaging about 10,930 grains/cm^2/yr and ranging between 6150 and 17,080 grains/cm^2/yr. Magnetic susceptibility (κ) averages 6.7 and ranges from 1.7 to 11.4 (10^{-6} SI units).

Zone 1b extends from the top of the BL 06-1 core (the estimated depth is 28 cm) to 100 cm (Fig. 7). Tree pollen remains high (69%) with *Pinus* averaging 56%, *Picea* 5%, and *Quercus* (oak) 4.5%. *Artemisia* percentages peak here, averaging 16%. Total PAR averages 7430 grains/cm^2/yr and ranges from 5400 to 10,060 grains/cm^2/yr. The pollen accumulation rates for both oak and sage types significantly increase in this zone (Fig. 8). Magnetic susceptibility also increases, averaging 11.4 and ranging from 4.3 to 34.1 κ.

Zone 2 reaches from 100 to 145 cm. The percentage of tree pollen averages 73% (*Pinus* 60%, *Picea* 7.5%, and Quercus 2.8%) in this zone. *Artemisia* percentages

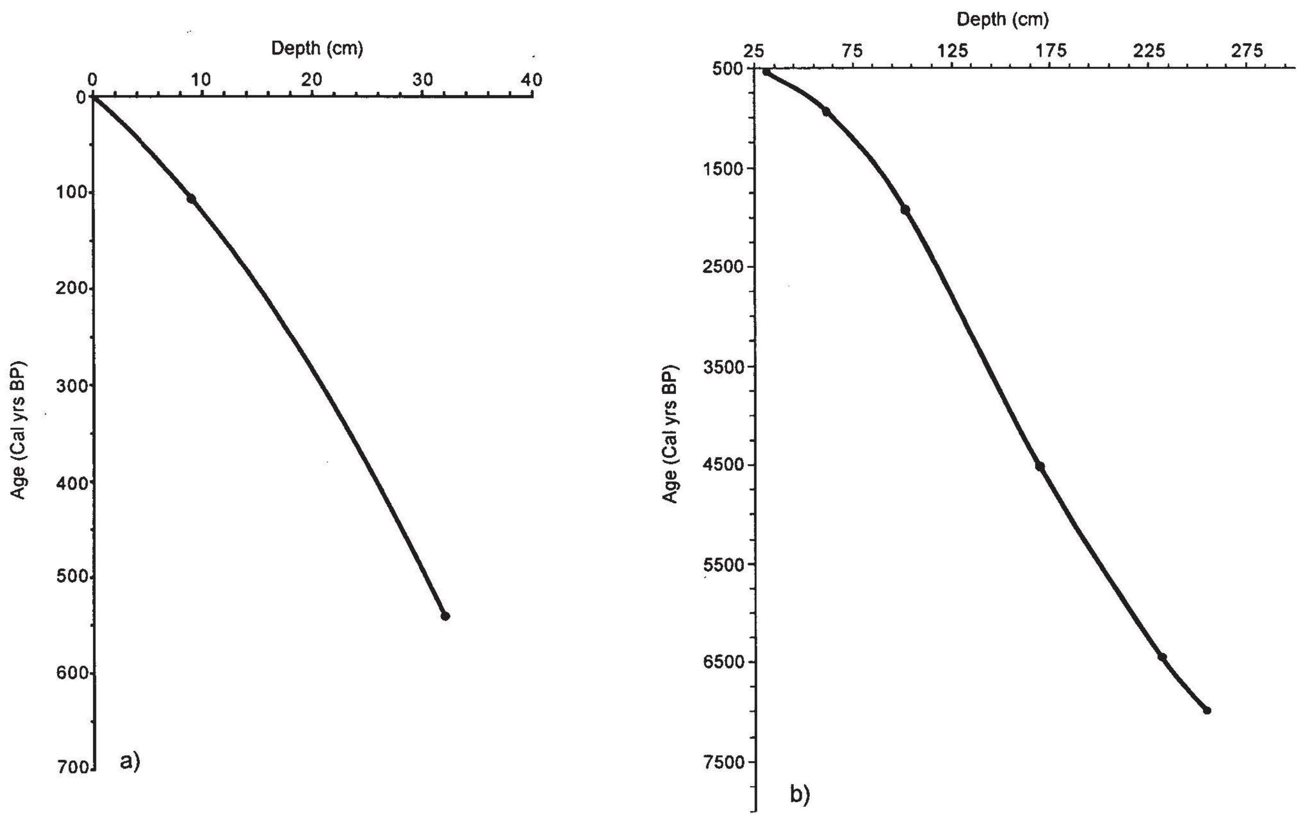

Figure 5. Bear lake age-verses-depth curve: a) Calibrated age (cal yrs BP)-versus-depth curve for the Bear Lake short core (BL 06-2). b) Calibrated age (cal yrs BP)-versus-depth curve for the Bear Lake long core (BL 06-1).

decline to 11.4% while Cheno-Am (6.1%) and Asteraceae (sun-flower family, 2.1%) values increase. The total PAR average declines 5510 grains/cm^2/yr, the lowest average for all zones. PARs for pine and spruce drop significantly in this zone (Fig. 8). Magnetic susceptibility values increase to an average of 12.5 and range between 6.4 to 17.5 κ.

Zone 3 extends from 145 to 230 cm. The percentage of tree pollen increases to an average of 79% with *Pinus* accounting for 62% and *Picea* about 11%. *Artemisia* percentages average 9% with Cheno-Am and Asteraceae averaging 5.4% and 1% respectively. The PAR averages 5880 grains/cm^2/yr, with a range between 3840 and 11,100 grains/cm^2/yr. Magnetic susceptibility values are highest in this zone, with an average of 15.4 and a range from 5.9 to 49.6 κ.

In zone 4 (230 to 257 cm) the pollen spectrum is also dominated by tree pollen, with an average of 81.5%. *Pinus* peaks at 64.5% with *Picea* averaging 9%. Non-arboreal pollen types average only 18.5% with *Artemisia* decreasing to a low of 6.6%. Other important non-arboreal types include Cheno-Am at 6.1% and *Sarcobatus (greasewood)* averaging 1.7%. The PAR declines slightly to 5870 grains/cm^2/yr and ranges between 3580 to 8600 grains/cm^2/yr. Magnetic susceptibility values remain high averaging 11.8 and ranging from 2.9 to 19.4 κ.

Charcoal Analysis

The *CharAnalysis* program requires that all radiocarbon dates be converted to calendar years to calculate a continuous fire history. Therefore all ages discussed in this section are provided in calendar years before present (cal yrs BP) rather than radiocarbon ages (^{14}C yrs BP). The charcoal zones used for this analysis correspond to the zones established by the pollen analysis.

To decompose the CHAR time series, a range of background window-widths were considered. A background window-width of 500 years adequately fit the variations in CHAR for long core (BL 06-1) whereas a 300 year window was applied to the short core (BL 06-2). Fire activity in the Bear Lake area has varied between two and five episodes/1000 yr over the last ca. 7000 cal yrs BP (Figs. 9c and 10c). For the short core (BL06-2) the *CharAnalysis* program identified three charcoal peaks (Fig. 9). The largest peak, at 9 cm depth, (41 pieces cm^{-2} peak^{-1}) corresponds to the historic fire in the Bear

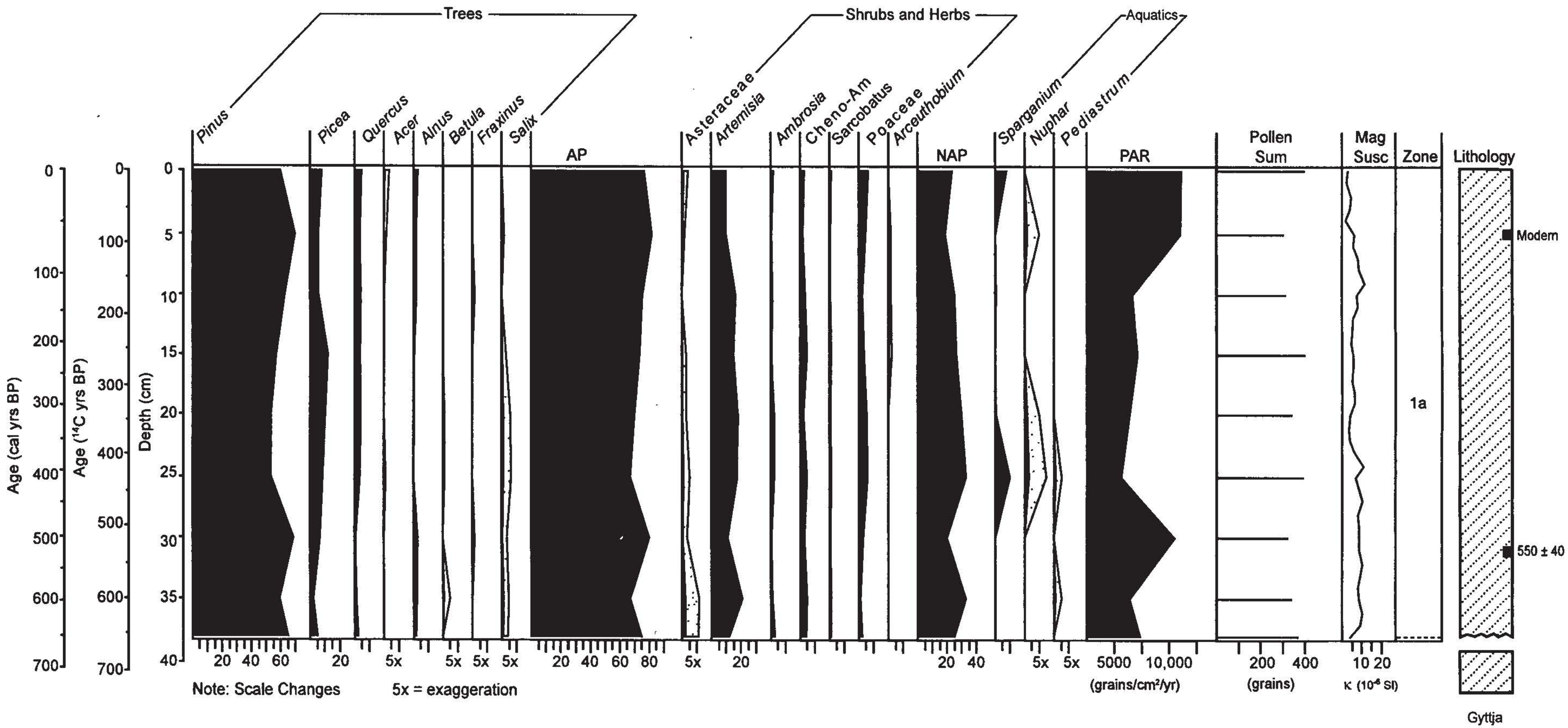

Figure 6. Pollen percentage diagram with pollen accumulation rate (PAR), magnetic susceptibility, lithology, and radiocarbon dates for the Bear Lake core (BL 06-2).

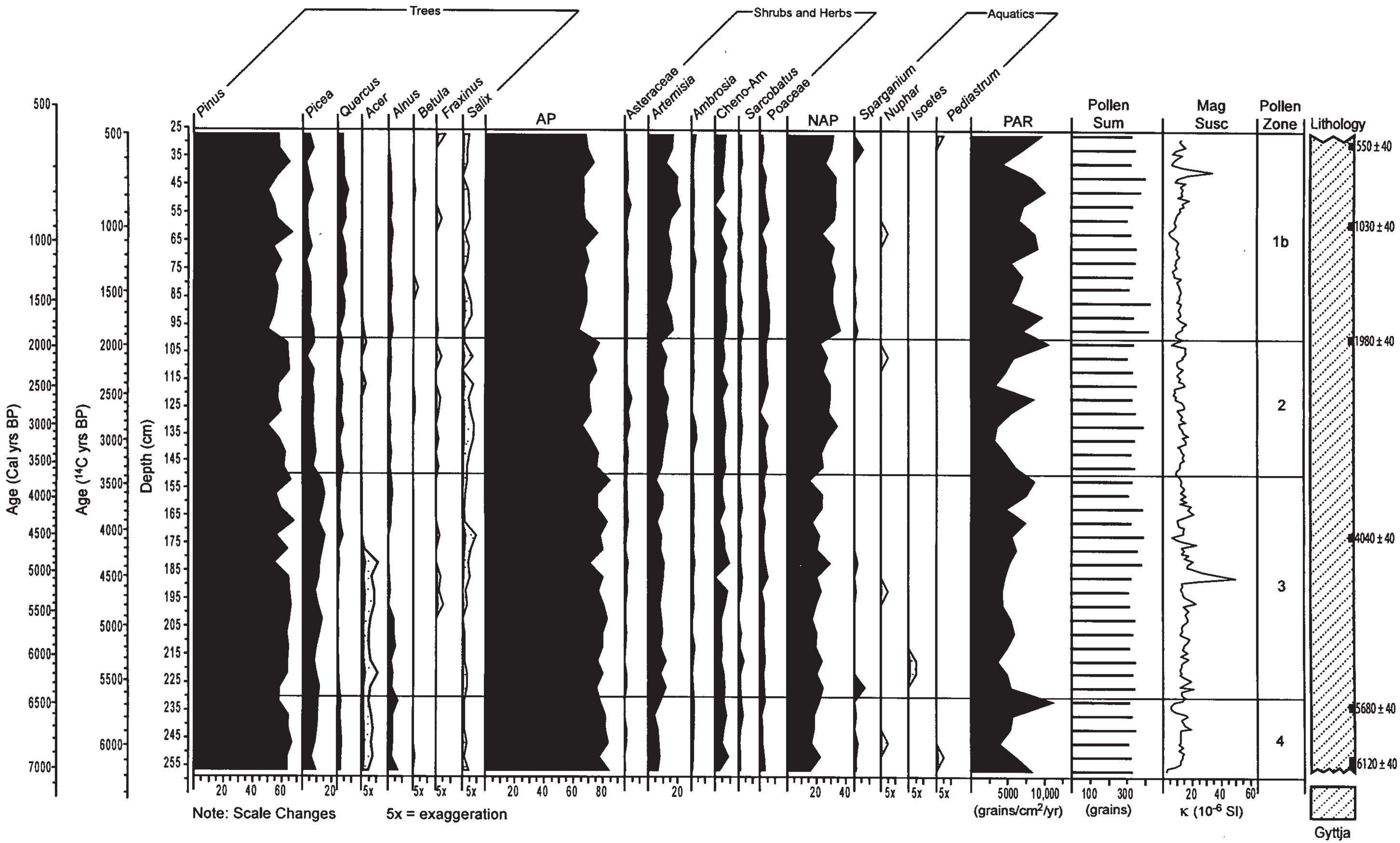

Figure 7. Pollen percentage diagram with pollen accumulation rate (PAR), magnetic susceptibility, lithology, and radiocarbon dates for the Bear Lake core (BL 06-1).

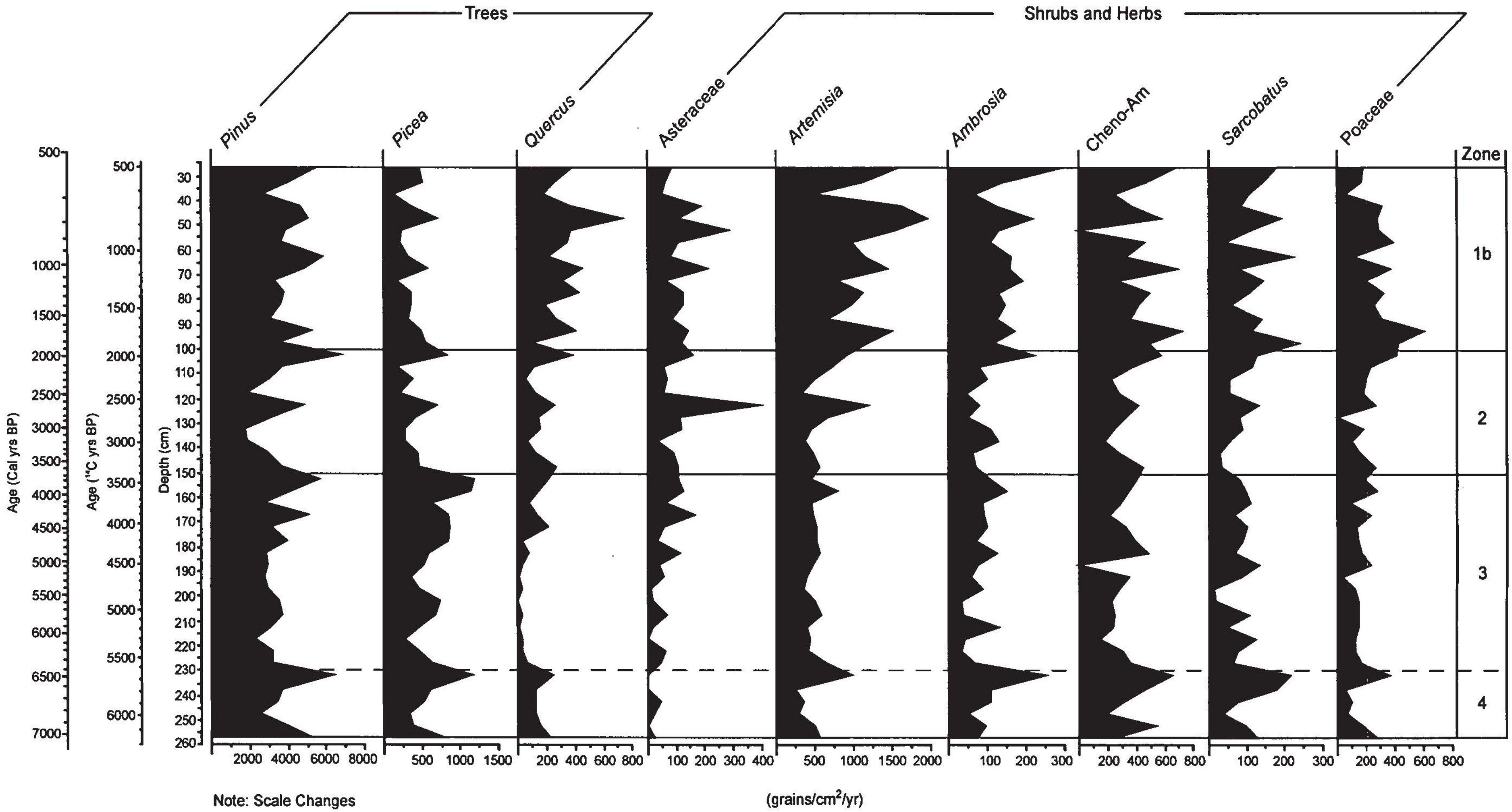

Figure 8. Pollen accumulation rates (PAR) for selected taxa from the Bear Lake core (BL 06-1).

Lake area which occurred at ca. 1900 A.D. (Lee 1917). The mean fire return interval (FRI) or fire-episode frequency for the BL06-2 core is 219 years (Table 2). The FRI represents the mean time interval between successive fire episodes reconstructed from charcoal peaks. It is not a predictive statistic and one should not infer that another fire in the Bear Lake area is expected in the year A.D. 2219 (based upon the A.D. 1900 fire and the FRI of 219 years).

For the long core (BL06-1), the program identified a total of twenty-four charcoal peaks (Table 2, Fig. 10). In zone 1b there were five peaks identified, with the largest peak (228 pieces cm^{-2} $peak^{-1}$) occurring at ca. 590 cal yrs BP (38 cm depth). The calculated FRI for zone 1b is 318 years. For zone 2, five peaks were documented, with the largest (18 pieces cm^{-2} $peak^{-1}$) occurring at ca. 2200 cal yrs BP (108 cm depth). The mean FRI for zone 2 is 264 years. In zone 3, the program identified at total of eleven charcoal peaks, with the largest (95 pieces cm^{-2} $peak^{-1}$) occurring at ca. 5085 cal yrs BP (188 cm depth). The FRI for zone 3 is 270 years. In zone 4, there were three peaks recognized, with the largest (49 pieces cm^{-2} $peak^{-1}$) found at 6670 cal yrs BP (239 cm depth). The FRI for zone 4 is 248 years.

The charcoal records (Figs. 9 and 10) show three main trends: 1) moderate to high fire activity in the most recent ca. 1900 cal years; 2) low to moderate fire activity in the period between ca. 2000 and 3500 cal years; and 3) increased fire activity during the middle Holocene. The FRIs in all zones identified in this study (Table 2) are within the modern fire regime established for Rocky Mountain National Park (Veblen et al. 1994; Kipfmueller and Baker 2000; Buechling and Baker 2004; and Sibold et al. 2006).

TABLE 2. Fire episodes and fire return intervals (FRI) for Bear Lake sediment cores

Charcoal/Pollen Zone	Fire Episodes (# of peaks)	FRI (cal yrs)	Time Period (cal yrs BP)	Time Period (^{14}C yrs BP)
		BL 06-2 (short core)		
Zone 1a	3	219	Present to ca. 650	Present to ca. 650
		Bear Lake 06-1 (long core)		
Zone 1b	5	318	ca. 530 to 1900	ca. 510 to 1925
Zone 2	5	264	ca. 1900 to 3480	ca. 1925 to 3230
Zone 3	11	270	ca. 3480 to 6450	ca. 3230 to 5670
Zone 4	3	248	ca. 6450 to 7050	ca. 5670 to 6120

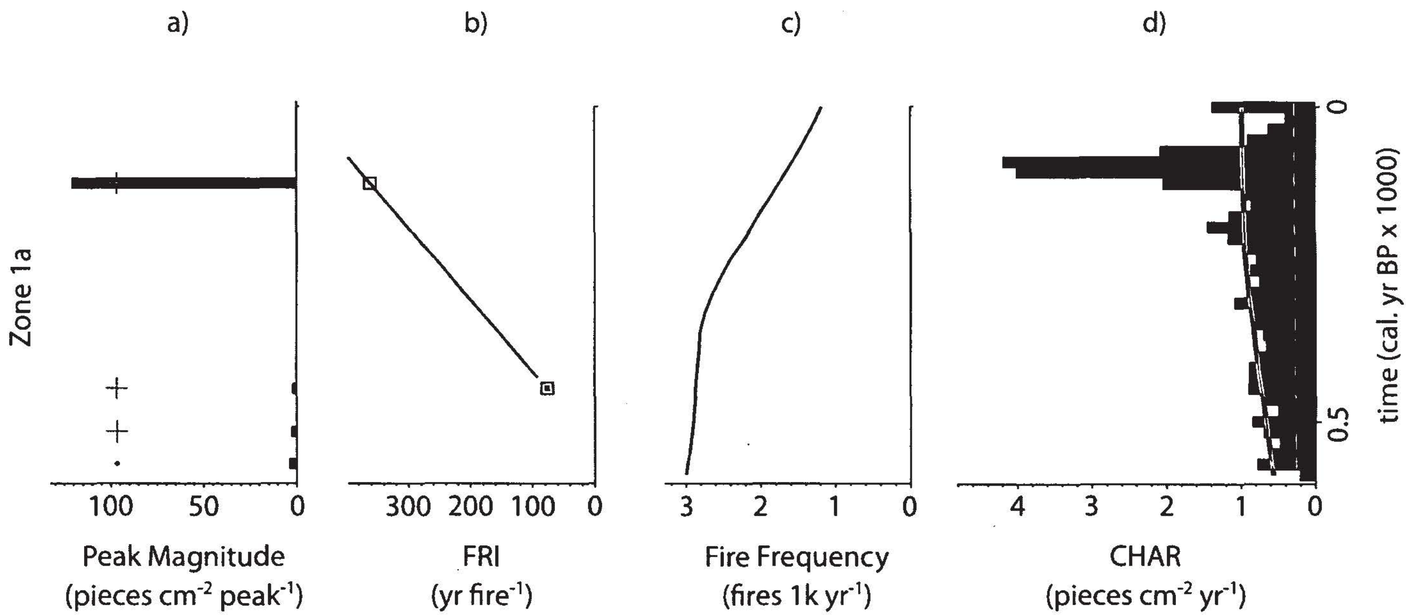

Figure 9. Bear Lake (BL 06-2) continuous fire history: a) Peak magnitudes (bars) and charcoal peaks (+). Peaks that fail to pass the Poisson minimum count triterion are displayed as gray dots; b) Fire return intervals (FRI); c) Fire frequency (# of fires per 1000 years); and d) $Char_{Acc}$ - interpolated charcoal accumulation rate (bars) and $CHAR_{Bkg}$ - low frequency background trend (solid line). Note: this figure was produce by the CharAnalysis program (available at http://CharAnalysis.googlepages.com).

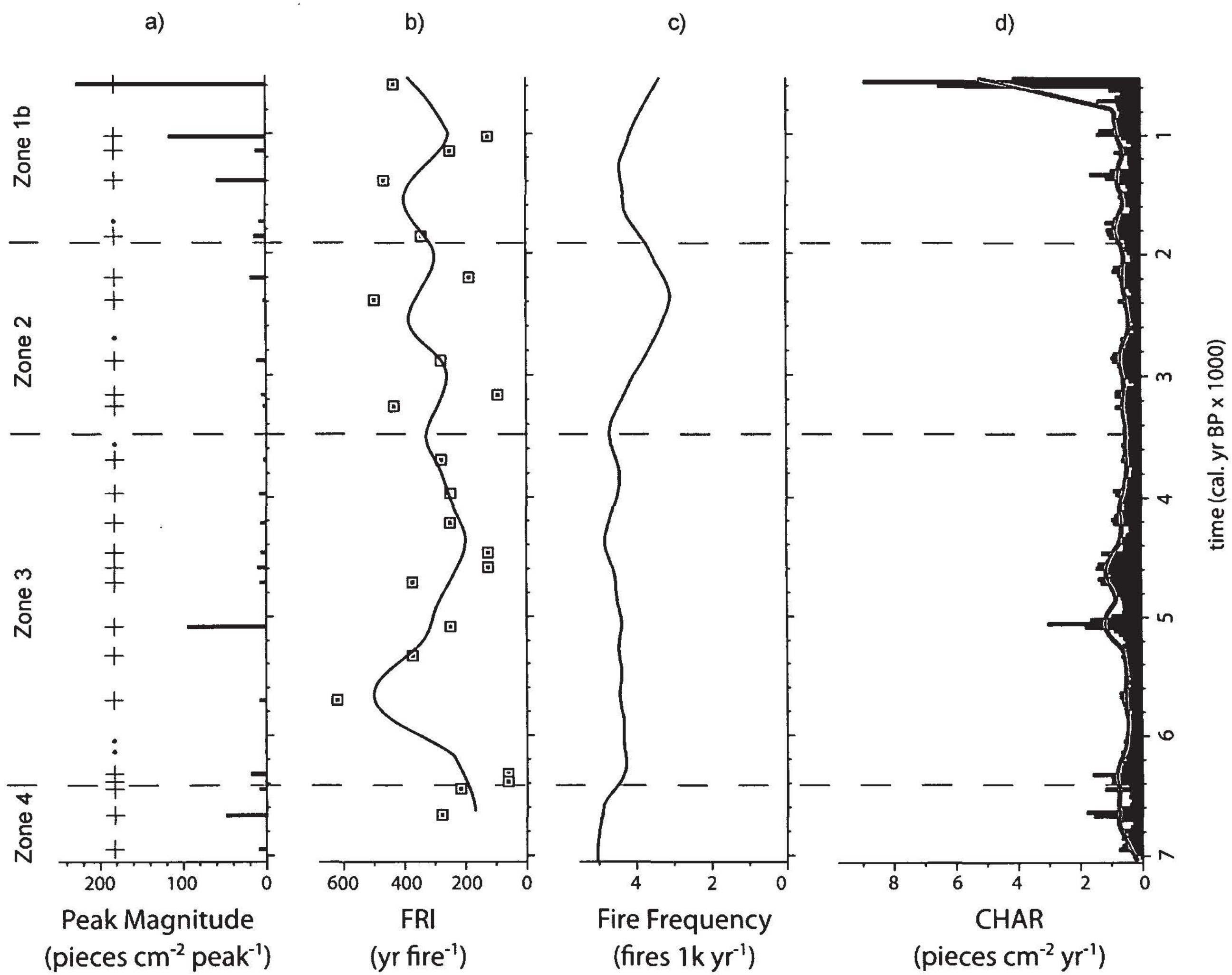

Figure 10. Bear Lake (BL 06-2) continuous fire history: a) Peak magnitudes (bars) and charcoal peaks (+). Peaks that fail to pass the Poisson minimum count triterion are displayed as gray dots; b) Fire return intervals (FRI); c) Fire frequency (# of fires per 1000 years); and d) $Char_{Acc}$ - interpolated charcoal accumulation rate (bars) and $CHAR_{Bkg}$ - low frequency background trend (solid line). Note: this figure was produce by the CharAnalysis program (available at http://CharAnalysis.googlepages.com).

DISCUSSION

Middle Holocene (ca. 6120 to 5670 ^{14}C yrs BP)

The Bear Lake pollen spectra in the middle Holocene indicates that the climate was warmer than the modern climate. Tree pollen dominates and non-arboreal pollen (NAP) types have their lowest values in the cores. Conifers are the prevailing vegetation cover and a dense spruce–pine forest likely surrounded the lake. Fire episode frequency is the highest here averaging between 4 to 5 events/1000 years (Fig. 10c). The Beaver Meadows site recorded higher temperatures and lower effective precipitation which resulted in increased alluvial deposition and the disappearance of wetlands from valley floor (Doerner et al. 2001). At the Lawn Lake fen warmer summers and longer growing seasons resulted in rapid peat formation (Doerner et al. 2002). Short (1985) working in the La Poudre Pass area to the north of Rocky Mountain National Park found that this period represented the time of maximum Holocene temperatures as pines expanded into the lower subalpine forest. Doerner (2005) also working in La Poudre Pass area found that higher temperatures at this time resulted in conditions more favorable for the build-up of organic matter in wetland deposits.

Middle to Late Holocene (ca. 5670 to 3230 ^{14}C yrs BP)

The transition from the middle to the late Holocene is characterized by cooler and drier conditions but temperatures likely remained warmer than the present. During this period pine and spruce continue to dominate the pollen rain but sagebrush and other NAP types increased (Figs 6, 7, and 8). The increase in non-tree taxa suggests that conditions were becoming drier and/or that greater vegetation disturbance was occurring. Data from the Mt. Ida and La Poudre Pass also support this interpretation that the regional climate was becoming cooler and drier (Doerner 2004, 2005). Fire frequency remains high during this time (4 to 5 events/1000 years; Fig. 10c). Magnetic susceptibility averages peak in this zone (Fig. 7, zone 3) indicating a greater influx of mineral sediment into the lake. This suggests that drier conditions contributed to more fires thus reducing the vegetation cover which contributed to increased erosion. Millspaugh and Whitlock (1995) found that peaks in magnetic susceptibility in Yellowstone lakes corresponded well with charcoal peaks, suggesting that they were fire related erosion events. However, in other studies in Yellowstone, the Coast Range, the Sierra Nevada and the Klamath Mountains there was no direct relation between CHAR peaks and magnetic susceptibility peaks even when the possibility of a time lag was considered (Brunelle 1997; Millspaugh 1997; Long *et al.* 1998; Millspaugh *et al.* 2000; Mohr *et al.* 2000).

Late Holocene (ca. 3230 ^{14}C yrs BP to present)

The climate during the early portion of this period was colder relative to the middle Holocene. The decline of spruce and the increase in sagebrush suggest that colder conditions existed at the lake. Low PAR (Figs. 7 and 8; zone 2) shows low pollen productive in the period between ca. 3230 and 1925 ^{14}C yrs BP. This time is also characterized by a decrease in fire activity as the number of fire episodes decrease to 3 to 4 events per 1000 years (Fig. 10c). Cooler conditions results in fewer and lower magnitude fire events (Fig. 10a).

Beginning about ca. 1925 ^{14}C yrs BP the pollen spectra indicates a warming trend (Fig. 7). At this time there is an increase in oak pollen. This suggests that temperatures were increasing, at least, at lower elevations in the Front Range. This taxon is not local and it likely represents the upslope transport of pollen into the Bear Lake basin. Its expansion probably represents a change to more favorable environmental conditions (warmer) in the foothills to the east of the Park. The increase in PARs is also interpreted as a signal of increased temperatures at this time. Drier conditions are also indicated by the increase in non-arboreal pollen (i.e. sagebrush). The magnitude and frequency of fire increased in response to these warmer and drier conditions.

Doerner (2004) found that the climatic warming in the Park occurred sometime after ca. 2500 ^{14}C yrs BP. This warming resulted in peat formation in the Mt. Ida area and the development of a wetland at the Trail Ridge Game Drive site. Modern vegetation associations and climate conditions were likely established by around ca. 1800 ^{14}C yrs BP.

CONCLUSIONS

Previous paleoecological investigations in the Rocky Mountain National Park have identified multiple periods of climate variability during the Holocene (Elias 1983, 1985; Short 1985; Doerner 2004, 2005). The long-term climate and fire history reconstructed for Bear Lake indicates three distinct environmental periods. During the middle Holocene (ca. 6120 to 3230 ^{14}C yrs BP) the pollen data indicates that climate was warmer than the present. Fire activity was high during this time. Early in the late Holocene (ca. 3230 to 1925 ^{14}C yrs BP) climatic deterioration (cooling) was accompanied by a decrease in fire activity. After ca. 1925 ^{14}C yrs BP the climate gradually warmed and conditions became slightly drier. In response to this change fire activity also increased.

Climate plays a significant role in the long-term fire history in RMNP. Fire activity increases as the climate becomes warmer. When the climate is cooler the magnitude and frequency of fire decreases. These results are consistent with the findings from tree-ring studies that show a strong regional climatic influence on the fire regimes in the Park (Sibold et al. 2006). Buechling and Baker (2004) and Sibold and Veblen (2006) showed that widespread burning of the subalpine forests in the Park is strongly dependent on drought. The results presented here can be used by managers to assess the potential response of ecosystems to future climate change. It is likely that global climate change will result in higher temperatures and longer summers in RMNP in the near future (Hobbs et al. 2003). Under this scenario it is reasonable to expect an increase in the magnitude and/or the frequency of fire activity in RMNP.

RECOMMENDATIONS

The macroscopic charcoal record from Bear Lake is a local reconstruction; to infer landscape, regional, or larger-scale patterns requires a network of sites, conducted at a similar high-resolution standard (Whitlock and Larsen 2001). It is uncertain if the results presented here are regional or local in extent. This suggests the need for additional research from a wide-range of environments (high and low elevation sites; wet and dry sites). Future research efforts should include sites that contain records that span the entire Holocene and extend to the late Pleistocene. These studies would help clarify the controls on vegetation and fire that operate on different spatial and temporal scales in RMNP.

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