HISTORIC AND HOLOCENE FOREST DISTURBANCE

IN SOUTH-CENTRAL UTAH

by

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ABSTRACT

Paleoecological reconstructions provide important information regarding climate affects on vegetation and forest disturbance return intervals. In recent decades, bark beetles (*Dendroctonus* spp.) have rapidly and profoundly altered subalpine forest ecosystems across interior forests in western North America. Disturbance records for bark beetle epidemics extending beyond the most recent few centuries are absent from the paleoecological literature. The research presented here examines sedimentary pollen records from subalpine lake basins to assess both historic and Holocene disturbance by spruce beetle (*D. rufipennis*) and wildfire. It is evident that limited vegetative change has occurred over the last 9,000 years and climate is driving fire disturbance regimes rather than forest composition. As insolation-driven seasonal climate extremes ameliorated from the early to the middle Holocene, annual precipitation regimes transitioned from rain- to snow-dominated with perennial lakes developing in south-central Utah. The early Holocene was characterized by high fire peak magnitude and fire frequency, forced by strong seasonal temperature and moisture contrasts. The middle Holocene was relatively warm, with dry winters and wet summers, facilitating frequent, low-magnitude fire episodes. The late Holocene was relatively cool and wet driven by decreasing summer insolation and increasing amplitude and frequency of El Niño-Southern Oscillation (ENSO) variability. Landscape-scale stand-replacing fire disturbance becomes essentially

absent over the last 3,000 years until the arrival of European settlers to the region. Pollen ratios from host and nonhost trees assessed during the historic period allow us to infer two high-severity spruce beetle epidemics during the Holocene at ca. 4,000 and 8,200 cal yrs BP.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

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CHAPTER 1

INTRODUCTION

Forest disturbances, such as wildfire and bark beetle outbreaks, are integral components of healthy, functioning ecosystems. When severe disturbance episodes do occur, they cause considerable financial expense to society (Romme and Despain, 1989; Raffa et al., 2008). In high elevation ecosystems in western North America, the return interval for landscape-scale disturbance often exceeds the window of Euro-American settlement in these regions and uncertainties exist regarding the natural range of variability. Land cover alteration and land use change following settlement also confound observations made over the last few centuries. During the AD 1980s and 1990s, catastrophic fire (Romme and Despain, 1989) and bark beetle events (Logan and Powell, 2001) suggest that the ecological legacies of timber harvesting and fire suppression have profound consequences on the severity and spatial extent of subsequent disturbance events. This research provides long-term context for disturbances observed during the 20^{th} century in western North America.

Paleoecological studies using lake sediments seek to reconstruct how past climates modify ecosystem composition and disturbance regimes. These data are useful to land management agencies in understanding how presettlement landscape conditions existed when influenced by climate. Recent research has focused on understanding how disturbance regimes might be modified by projected changes in climate over the 21st century and how disturbance might interact with land cover alterations and land use changes, and anthropogenic modification of the earth's atmosphere. Paleoecological data provide a baseline of understanding to contextualize and interpret future climate change.

The economic and ecological legacies of wildfire are significant (Romme and Despain 1989) and have driven many advances in paleoecological research, particularly for sedimentary charcoal. Recent advances include improved understanding of postfire charcoal deposition (Whitlock and Larsen 2001), the development of a global charcoal database (Power et al., 2009), and availability of quantitative software tools that enable robust interpretations of past fire occurrence assessed from sedimentary charcoal (Long et al., 1997; Higuera et al., 2009). Across much of western North America beginning in the late 1980s, eruptions of bark beetle (*Dendroctonus* spp.) equaled (Logan and Powell, 2001) or exceeded (Baker and Veblen, 1990) the economic and ecological impact of wildfire. Surprisingly little is known about the long-term ecological role and recurrence of these insect outbreaks (centuries to millennia), and by historic measures, the spatial extent and severity was unprecedented, at least historically (*sensu* Bentz et al., 2009). In Utah during the 1990s, subalpine forests experienced devastating spruce beetle epidemics (*D. rufipennis*) where >95% (over 81,000 ha) of mature Engelmann spruce (*Picea engelmannii*) were killed (Dymerski et al. 2001; Matthews et al. 2005; DeRose and Long, 2007). In the wake of these insect outbreaks, concerns over catastrophic fire events resulting from elevated forest fuel loads in beetle-affected forests prompted an evaluation how these disturbances are known to interact.

The research presented here addresses the vital need to improve the understanding of the relationship between fire and bark beetle disturbances. In south-central Utah, little information exists regarding long-term ecological history and essentially nothing is known about long-term disturbance. Six subalpine basins in spruce-fir forests across south-central Utah were selected for sediment coring to examine the subfossil charcoal, pollen, and insect remains to assess how severe bark beetle disturbances are recorded in lake sediments. The ultimate objective of this project is to generate data from the historic disturbance records to assist in the interpretation of Holocene-length reconstructions (last ~10,000 years). As previously stated, analytical methodologies for counting and examining sedimentary charcoal are already established. However, in order to address bark beetle disturbances, the development of a new methodology was required.

Recent work documented the presence of bark beetle carcasses in lake sediments contemporaneous with historic outbreaks (Brunelle et al., 2008). However, other studies indicate that the taphonomy and preservation of bark beetle remains during a severe outbreak event is influenced by lakewater chemistry and diagnostic bark beetle remains in lake sediments may not be present (Morris et al., 2010). However, high-resolution pollen sequences from historic beetle outbreaks reproduced known changes in stand structure following beetle disturbance (Morris et al., 2010). A further examination of this methodology is presented and discussed here (Chapter 2). One of the first applications of the historic pollen data to Holocene sediment records was performed on a 9,000 yr record from Purple Lake, located on the Aquarius Plateau (Chapter 3). Charcoal-derived fire histories from three sites were then developed to better understand the long-term climate controls on wildfire disturbance in the study area (Chapter 4). These chapters will be submitted to the following peer-reviewed journals for potential publication: The Holocene (Chapter 2), Quaternary International (Chapter 3), and the International Journal of Wildland Fire (Chapter 4).

The goals of this research are to provide useful and meaningful data to land managers to better contextualize bark beetle disturbances and to understand the disturbance history over longer timescales and different climate regimes as compared to modern. Until this study, wildfire recurrence in this region was essentially unknown beyond the most recent few centuries (Brown et al., 2008). Uncertainties as to how climate warming over the 21st century might force fire and insect disturbances into new trajectories and interactions are a key theme to this research. Therefore, climate periods of the Holocene, both warmer and drier and warmer and wetter periods than present, were of interest.

CHAPTER 2

POLLEN RECORDS OF HISTORIC SPRUCE BEETLE (*DENDROCTONUS RUFIPENNIS)* DISTURBANCE FROM SOUTH-CENTRAL UTAH

Introduction

Pollen and charcoal preserved in lake sediments are useful in reconstructing the influence of past climate on landscape disturbance. Sedimentary charcoal provides valuable information about wildfire variability across local, regional, and global scales (Whitlock and Millspaugh, 1996; Long et al., 1998; Higuera et al., 2007; Power et al., 2009). Sedimentary pollen and macrofossils are used to infer nonfire disturbances such as phytophagus insect epidemics and fungal blights (Davis, 1981; Anderson et al., 1986; Brunelle et al., 2008; Morris et al., 2010). In eastern North America, sedimentary pollen records enabled the reconstruction of a mid-Holocene outbreak of two defoliators: spruce budworm (*Choristoneura fumiferana*) and hemlock looper (*Lambdina fiscelaria*) (Allison et al., 1986; Fuller, 1998; Shuman et al., 2005). Similarly, the decline of American chestnut (*Castanea dentata*) beginning in AD 1904 from a nonnative pathogen (chestnut blight; *Endothia parasitica*) is well-documented in sedimentary sequences (Anderson, 1974; Brugam, 1978; Davis, 1981). In Europe, declines of elm pollen (*Ulmus* spp.) during the mid-Holocene are attributed to infection from a fungal pathogen

(*Ophiostoma ulmi*) and possibly an epidemic of elm bark beetle (*Scolytus scolytus*) concomitant with widespread forest clearance for agriculture (Watts, 1961; Fossit, 1994; Innes et al., 2003; Rasmussen, 2005).

Spruce beetle (SB; *Dendroctonus rufipennis*) and mountain pine beetle (MPB; *D. ponderosae*) account for the most significant numbers of tree mortality in higher elevation forests (Fettig et al., 2007; Raffa et al., 2008) and damage from these insects equal (Baker and Veblen, 1990) or exceed (Logan and Powell, 2001) the ecological and economic impacts of wildfire in the western United States. It is therefore surprising that only recently have paleoecological studies explored the long-term dynamics of these insects in disturbance reconstructions using lake sediments (Brunelle et al., 2008; Morris et al., 2010; Anderson et al., 2010).

Dendroecological records suggest that SB outbreaks recur at ca. 120 year intervals based on datasets in Colorado and Utah (Veblen et al., 1994; DeRose and Long, 2007). These records essentially encompass two climatic periods: 1) the cool and dry Little Ice Age (Bradley and Jones, 1993; Petersen et al., 1994; Crowley and Lowery, 2000) and 2) the 19th and 20th centuries which are characterized by anthropogenic climate warming (Mann et al., 1999; IPCC, 2007) and the ecological impacts of logging (Baker, 1992) and fire suppression (Romme and Despain, 1989). A significant amount of research suggests that historic eruptions of bark beetle populations may be unprecedented in scale and severity (Bentz, 2009) due to interacting mechanisms of climate warming, prolonged drought, and increased stand density (Logan and Powell, 2001; Breshears et al., 2005; Hicke et al., 2006; Raffa et al., 2008; Bentz et al., 2010).

Furthermore, recent research suggests that Pacific climate modes such as the Pacific Decadal Oscillation (PDO) (Mantua et al., 1997) and El Nino-Southern Oscillation (ENSO) (Diaz and Markgraf, 2000) have influenced the recurrence and severity of bark beetle populations over the last few centuries (Macias Faria and Johnson, 2009; Sherriff et al., 2011). Persistent states of ENSO and PDO over the Holocene (Clement et al., 2000; Moy et al., 2002; Koutavas et al., 2002) occurred from changes in insolation due to alterations in the earth's orbit (Berger and Loutre, 1991; Kutzbach et al., 1998). These long-term variations created moisture and temperature regimes different to those of the last several centuries that are reflected in the Colorado tree ring records (Veblen et al., 1994). The absence of a methodology for reconstructing of bark beetle disturbances over the Holocene indicates that our current understanding of these disturbances and potential relationships with wildfire is based on a limited assessment of climate conditions.

The two existing paleoecological studies from SB-affected forests demonstrate that in response to an epidemic, spruce pollen declines while fir pollen increases (Morris et al., 2010; Anderson et al., 2010). This tradeoff between spruce and fir pollen mirrors host/nonhost stand conditions consistent with ground surveys (Dymerski et al., 2001), stand age reconstructions (DeRose and Long, 2007), and growth patterns observed in tree rings (Sherriff et al., 2011). Vegetation surveys suggest that other understory components, including shrubs and herbs, are more successful following the loss of canopy-dominant spruce (Schmid and Hinds, 1974). The purpose of this study is to examine pollen sequences from lake basins affected by 20th-century SB outbreaks to determine how SB events are associated with pollen accumulations in lake sediments.

Study Area

The Colorado Plateau is punctuated at its western margin in central and southwestern Utah by a series of subalpine plateaus that traverse the eastern Great Basin (Wannamaker et al., 2001). These plateaus rise steeply from the surrounding desert valleys and the towering relief of these landforms facilitates the development of convectional and orographic-induced precipitation gradients where moisture receipt is controlled by altitude, with greater amounts of precipitation received at higher elevations. In the subalpine zone (2,700 m to 3,300 m), most moisture is received as snowfall during winter and spring months with a secondary peak in precipitation during late summer from convective storms. The study area lies on the transition zone of summer-dominant (monsoon) and winter-dominant (Pacific) moisture regimes (Mitchell, 1976; Mock, 1996) and south of the ≈42° N ENSO dipole boundary (Wise, 2010), resulting in variable seasonal and annual precipitation accumulation (Cayan, 1996; Mock, 1996; Hidalgo and Dracup, 2003; Shinker, 2010). The forests on the summits of these plateaus are composed of Engelmann spruce/subalpine fir (*Picea engelmannii* / *Abies lasiocarpa*). Unlike subalpine ecosystems at comparable elevations in Colorado and northern Utah, lodgepole pine (*Pinus contorta*) are absent in south-central Utah.

Wasatch Plateau

The Wasatch Plateau (WP) is oriented north/south and covers an area of 2,477 km^2. Elevations average 3,350 m across the summit of the plateau. The WP is capped by limestone, causing surface water to be alkaline (9+) in pH (Morris et al., 2010). The WP was glaciated during the Pleistocene with alpine-style glaciers eroding numerous cirques and depositing moraine and till features that are conspicuous on north-facing aspects (Osborn and Bevis, 2001). Land-use changes following settlement ca. AD 1850 included lumber harvesting and livestock grazing in subalpine meadows (Ellison, 1954; Hall, 2001). Many meadows were so severely denuded of vegetation that erosion removed the 'A' soil horizon, increasing drought susceptibility (Klemmedson and Tiedemann, 1998; Gill, 2007).

A landslide in AD 1984 facilitated establishment of SB populations in downed spruce (Hebertson and Jenkins, 2007). A landscape composed of susceptible hosts coupled with warm and dry conditions during the 1990s were favorable for the development of a SB epidemic that killed >95% of mature Engelmann spruce (Dymerski et al., 2001). Blue Lake (39° 3'20.33"N, 111°30'17.43"W) and Emerald Lake (39° 4'26.72"N, 111°29'50.964"W) (Fig. 1, Table 1) occupy north-facing cirque basins with average elevations of 3,129 m and 3,090 m, respectively. Both lakes are surrounded by dead Engelmann spruce from the 1980-90s SB outbreak. Residual subalpine fir are both abundant in both watersheds. Limber pine (*Pinus flexilis*) is occasionally present at rocky, exposed locales and isolated blue spruce (*Picea pungens*), a less preferred host for SB, can be found in particularly mesic sites. Aspen (*Populus tremuloides*) are absent in both basins but are found at similar elevations on the WP.

<u>Aquarius Plateau</u>

The Aquarius Plateau (AqP) is the highest elevation landform in the study area with a mean elevation of 3,355 m, covering an area of 2,330 km^2. The summit of the AqP exhibits rolling tabletop topography and is composed of andesitic basalt that

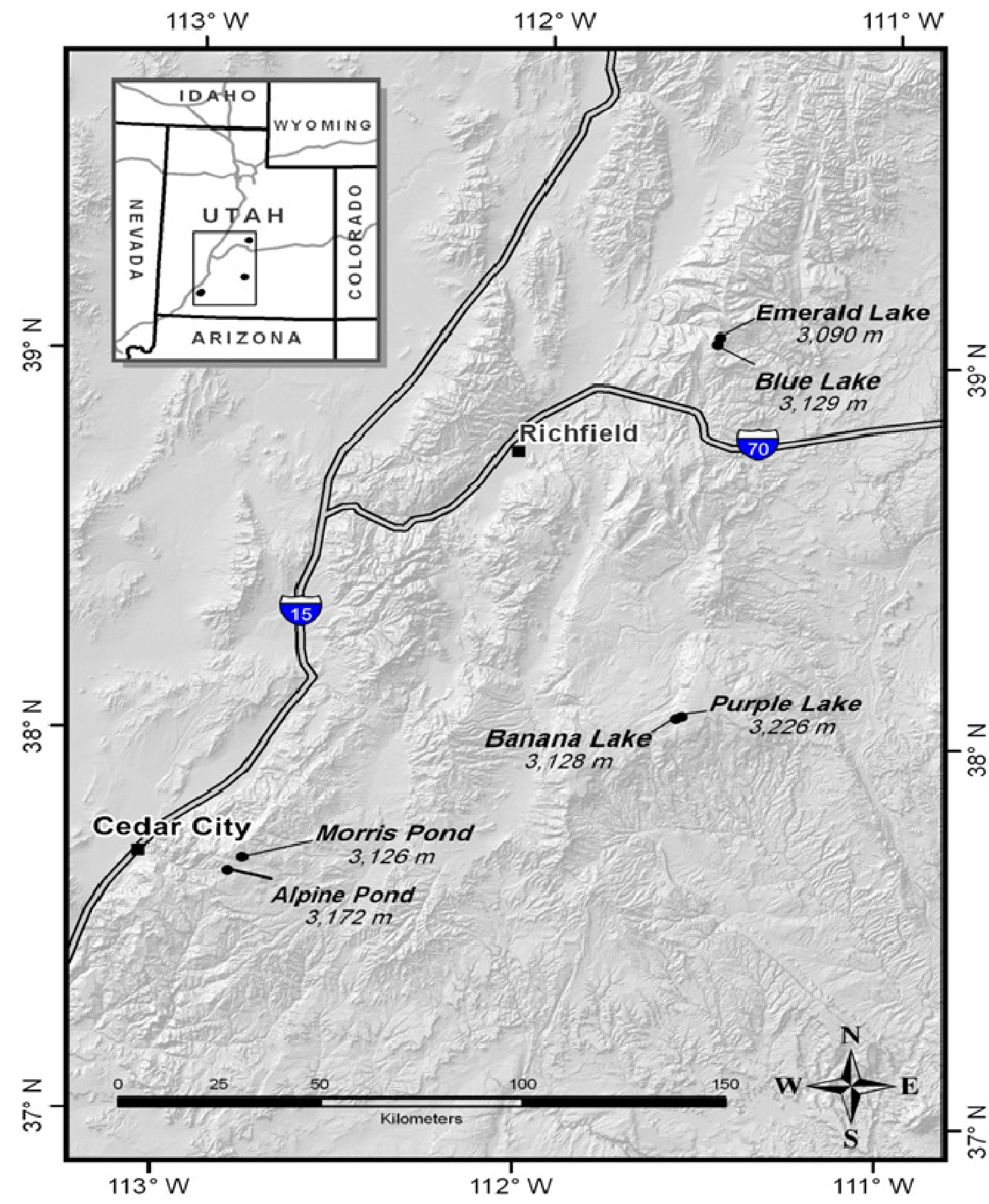


Figure 1. Location map of south-central Utah showing the six basins in the study area.

Table 1. Summary of location and elevation data for lake basins analyzed in the study.

Coring Site	High Plateau	Stewardship	Coordinate		Elevation (m)
Blue Lake	Wasatch Plateau	Manti-LaSal NF	N 39.05526	W 111.50464	3 129
Emerald Lake	Wasatch Plateau	Manti-LaSal NF	N 39.07403	W 111.49749	3 089
Banana Lake	Aquarius Plateau	Dixie NF	N 38.06745	W 111.58758	3 128
Purple Lake	Aquarius Plateau	Dixie NF	N 38.07740	W 111.57162	3 226
Alpine Pond	Markagunt Plateau	Cedar Breaks NM	N 37.63653	W 112.82412	3 172
Morris Pond	Markagunt Plateau	Dixie NF	N 37.67392	W 112.78072	3 126

originated during the Oligocene Marysvale Volcanic episode (Flint and Denny, 1958). The AqP was occupied by a ≈200 m thick ice cap during the Pleistocene (Flint and Denny, 1958; Osborn and Bevis, 2001) and glacigenic features on the AqP are generally erosional that include roche moutonnées, thin soils, and glacial abrasions (striations, chatter marks) (Marchetti et al., 2005). The AqP is dominated by spruce-fir forests with the highest elevations consisting of pure Engelmann spruce stands with interspersed grasslands (Schmid and Hinds, 1974). Other arboreal species include subalpine fir, limber pine, aspen, blue spruce, and bristlecone pine (*Pinus longaeva*). A SB epidemic beginning around AD 1916-1918 persisted into the 1930s killing >80% of mature Engelmann spruce (Dixon, 1935; Mielke, 1950). Banana Lake (38° 4'0.29"N, 111°35'12.21"W) and Purple Lake (38°4'28.33"N, 111°34'16.47"W) (Fig. 1, Table 1) are kettle lakes occurring at 3,128 m and 3,226 m, respectively. Both basins are surrounded by dense stands of Engelmann spruce, subalpine fir, and blue spruce with occasional aspen patches. Subalpine fir is rare at Purple Lake when compared to the other watersheds discussed here. Snags from the AD 1920s SB outbreak are visible in both watersheds.

Markagunt Plateau

The Markagunt Plateau (MP) trends north-south and covers an area of 2,100 km^2 with an average elevation of 3,320 m. Holocene-age lava flows dating to ≈1,200 years ago overlay limestone creating a volcano-karst landscape that drains rapidly, increasing drought susceptibility (Wilson and Thomas, 1964). A thin ice sheet occupied the top of the MP during the Pleistocene and occasional examples of depositional features are present, including moraines and till (Osborn and Bevis, 2001). The MP experienced a severe SB outbreak beginning in the 1990s with eruptive SB populations building in remnant logging debris and windthrow developing into a severe outbreak that killed >93% of Engelmann spruce across all class sizes (DeRose and Long, 2007). Alpine Pond (37°38'11.22"N, 112°49'26.75"W) and Morris Pond (37°40'25.48"N, 112°46'49.75"W) (Fig. 1, Table 1) have elevations of 3,171 m and 3,124 m, respectively. Alpine Pond and Lowder Creek Bog were cored in paleoecological studies conducted prior to the outbreak (Mulvey et al., 1984; Anderson et al., 1999). Morris Pond is a moraine-dammed lake located 1.5 km north of Lowder Creek Bog. Alpine and Morris Ponds are surrounded by ghost forests of dead Engelmann spruce, with abundant residual subalpine fir and occasional aspen and limber pine. Bristlecone pine occurs in the Alpine Pond watershed.

Methods

Characteristics of lakes selected for this study included USDA Forest Service documentation of a severe 20th-century SB outbreak (Hebertson and Jenkins, 2008), the presence of spruce-fir forest with visually detectable SB-caused mortality, limited inflow/outflow of surface water, basins unmodified by significant impoundments, absence of stand-replacing 20th-century wildfire, and no evidence of large-scale salvage logging to remove beetle-killed trees. Based on these criteria, six basins were selected and cored using modified piston devices between 2005 and 2009. Information regarding bark beetle outbreaks is inherently qualitative, even during the historical period. Unlike fire, historical detection of the onset and collapse of bark beetle eruptions are often difficult to assess (Hebertson and Jenkins, 2008). Detection of insect disturbances on public lands are observed and mapped from fixed-wing aircraft to generate aerial sketchmaps of defoliation and mortality, which are subjective according to each individual observer (McConnell, 1999).

Chronology for the six cores discussed here was achieved using ^{210}Pb and ^{137}Cs analysis (Table 2). The upper 24 cm of each core was sampled, weighed, and dried in a muffle furnace at 100°C to remove water. Dehydrated samples were submitted to Dr. James Budahn at the USGS Laboratory in Denver, CO for analysis. The ^{210}Pb record was interpreted using 1963 as the peak in ^{137}Cs associated with the climax of atmospheric detonation of nuclear test weapons. Though the dated sediment records presented here extend to the 19th century, only data from the 20th century to the year of coring are presented.

Pollen samples (1 cc) were processed at 1 cm intervals for the upper 24 cm for each core. Each sample was processed to isolate pollen following methods established by Faegri et al. (1989). *Lycopodium*, an exotic spore, was introduced to each sample during processing as a tracer. Slide-mounted pollen samples were examined using light microscopy at 500x and counted to a minimum of 300 terrestrial grains. Identification of grains was aided by laboratory reference collections and relevant dichotomous keys and literature (Erdtman, 1952; Bassett et al., 1978; Kapp et al., 2000).

Though numerous species were identified and counted, pollen data presented here focus on subalpine taxa that would be most likely to respond to SB-caused mortality. Pollen records are described in terms of percent, influx, and ratios. Pollen percent provides information about relative vegetation composition (interrelatedness of taxa),

Table 2. Age-depth relationships for historic sediments from six basins presented in this study.

Depth (m)[ab]	Wasatch Plateau				Aquarius Plateau				Markagunt Plateau			
	Emerald Lake (Year A.D.)	+/-	Blue Lake (Year A.D.)	+/-	Banana Lake (Year A.D.)	+/-	Purple Lake (Year A.D.)	+/-	Alpine Pond (Year A.D.)	+/-	Morris Pond (Year A.D.)	+/-
0,00	2007	0	2005	0	2007	0	2007	0	2007	0	2008	0
0,02	2004	2	2002	2	2003	2	2003	4	2002	5	2003	2
0,04	1997	2	1995	4	1994	3	1994	5	1992	6	1993	2
0,06	1987	2	1986	5	1985	3	1983	6	1982	7	1983	3
0,08	1977	3	1978	8	1975	4	1971	7	1972	9	1973	3
0,10	1965	4	1970	8	1963	5	1963	9	1959	11	1967	4
0,12	1950	5	1962	9	1945	7	1958	9	1947	14	1964	5
0,14	1933	7	1955	9	1923	10	1953	9	1937	15	1960	6
0,16	1919	9	1949	9	1911	12	1944	10	1927	17	1956	9
0,18	1908	9	1938	10	1899	13	1927	12	1918	17	1953	10
0,20	1900	9	1926	11	1876	18	1911	14	1904	19	1950	11
0,22	1888	8	1914	12	1843	26	1896	14	1878	23	1948	12
0,24	1857	7	1894	12	1815	22	1851	18	1839	24	1884	15

[a] Depth below mud-water interface, uppermost sample assigned to year core was collected.
[b] Bulk sediment samples were submitted for all ^{210}Pb dates to US Geologic Survey in Denver, Colorado by James Budahn.

influx provides information about individual taxa abundance, and ratios allow for consideration of single taxon versus a group of taxa, or another single taxon. Pollen ratios were calculated using the formula (a-b)/(a+b) (Maher, 1963, 1972) which is useful in assessing ecological change from both climate and disturbance (Mensing et al., 2008). In all instances 'a' represents spruce pollen and 'b' represents various combinations of arboreal and non-arboreal pollen. Ratio data are presented in standard units (SU). Higher (lower) ratio values reflect greater (lesser) abundance of spruce pollen relative to other taxa.

Samples for charcoal and macrofossil analysis (5-10 cc) were collected and analyzed for the upper 24 cm of each core and were prepared following methodologies discussed by Whitlock and Millspaugh (1996). Sediments samples were screened using 125 µm and 250 µm nested sieves. Retrieved materials were placed on gridded petri dishes and then examined and counted using light microscopy at 40x. Raw charcoal counts were then converted to charcoal concentration (particles/cm^3). Insect macrofossils meeting general criteria of bark beetles (*Dendroctonus* spp., *Ips* spp.) were submitted to Dr. James Pitts at Utah State University in Logan, UT for identification. No bark beetle remains were identified in any of the six cores presented here.

Results

The Wasatch Plateau pollen assemblages (Blue and Emerald lakes) have similar arboreal components throughout the AD 1900s, featuring abundant spruce (20-30%) and pine (20-25%) pollen, with fir (10%) and aspen (≤5%) also at both sites (Figs. 2a and 2b). Conifer pollen influx is greater at Emerald Lake (e.g. spruce averages 4,000 grains/cm^3

a)

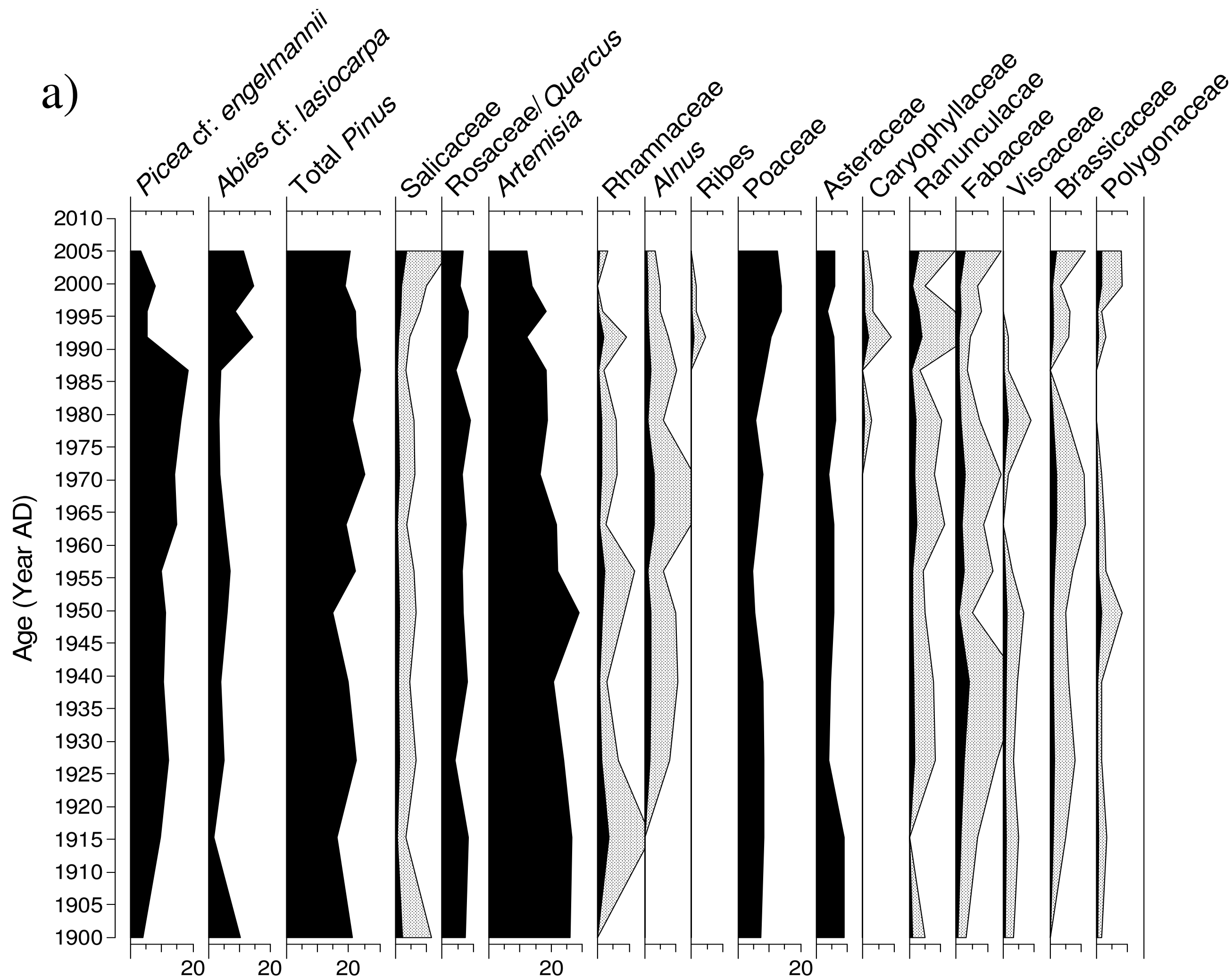


Figure 2. Wasatch Plateau pollen percent data for the 20th century at a) Blue Lake and b) Emerald Lake. A spruce beetle epidemic killed at least 95% of the spruce beginning in AD 1984. A spatially small, endemic spruce beetle outbreak occurred near Emerald Lake around AD 1905.

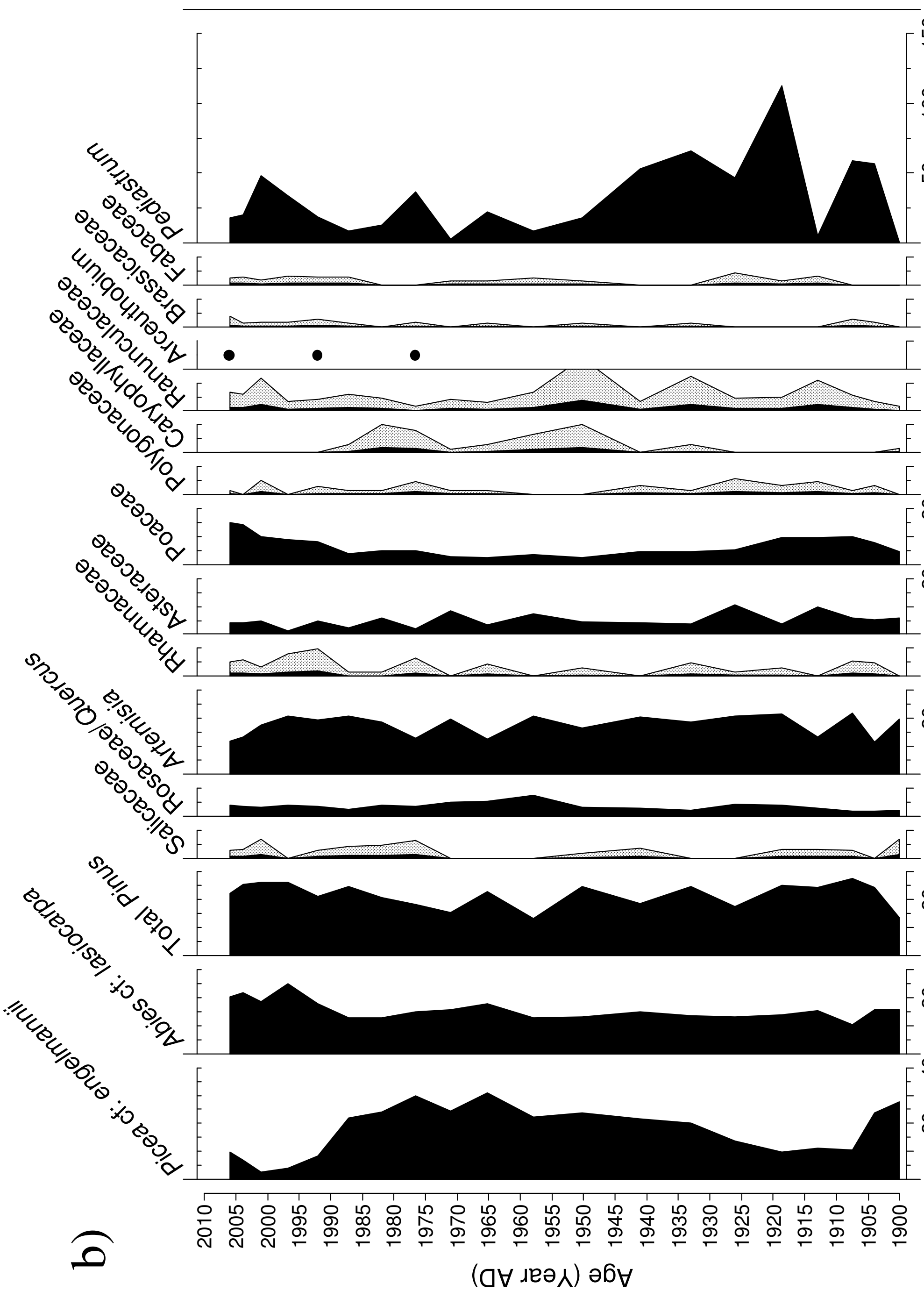


Figure 2. Continued

versus 800 grains/cm^3 at Blue Lake) (Figs. 3a and 3b). The shrub community at both lakes is dominated by sagebrush (*Artemisia*) (20-23%) with rose/oak (Rosaceae/*Quercus*) (3-4%) and buckbrush (Rhamnaceae) also present (1-2%). Shrub pollen influx averages are similar between both sites for sagebrush (1,500 grains/cm^3), rose/oak (950 grains/cm^3), and buckbrush (150 grains/cm^3). Herbaceous taxa are dominated by grasses (Poaceae) (9-10%) and members of the sunflower family (Asteraceae) (3-4%) with influx averages of 750 and 2,000 grains/cm^3 for Blue and Emerald, respectively. Other herbaceous components are present at low values (e.g., 1-2%; <100 grains/cm3) including smartweed (Polygonaceae), buttercup (Ranunculaceae), and bean families (Fabaceae). The ratio assemblage at both lakes displays similar trends where spruce pollen is reduced relative to other taxa early in the 20th century (ca. AD 1910), becomes dominant through the midcentury, and declines again before ca. AD 1990 (Fig. 4a-f).

The arboreal Aquarius Plateau assemblages are dominated by spruce (30-40%) and pine (15-20%) with fir pollen more abundant at Banana Lake (8%) than at Purple Lake (<3%) (Figs. 5a and 5b). Aspen pollen is greater at Purple (20%) than at Banana Lake (7%). Pollen influx of all tree species except fir is higher at Purple Lake (Figs. 6a and 6b). Shrub pollen at both lakes are composed largely of rose/oak (5%) and sagebrush (12%) while influx for both taxa is relatively higher at Purple Lake than at Banana Lake. Herbaceous taxa are dominated by grasses (4-5%) and members of the sunflower family (3-4%) and influx averages are greater at Banana Lake than at Purple Lake. Other herbaceous components are present at low values (1-2%; <100 grains/cm3) including mustards (Brassicaceae), smartweed, buttercup, and members of the bean families. The ratio assemblage at both lakes displays similar trends where spruce pollen is decreased

a)

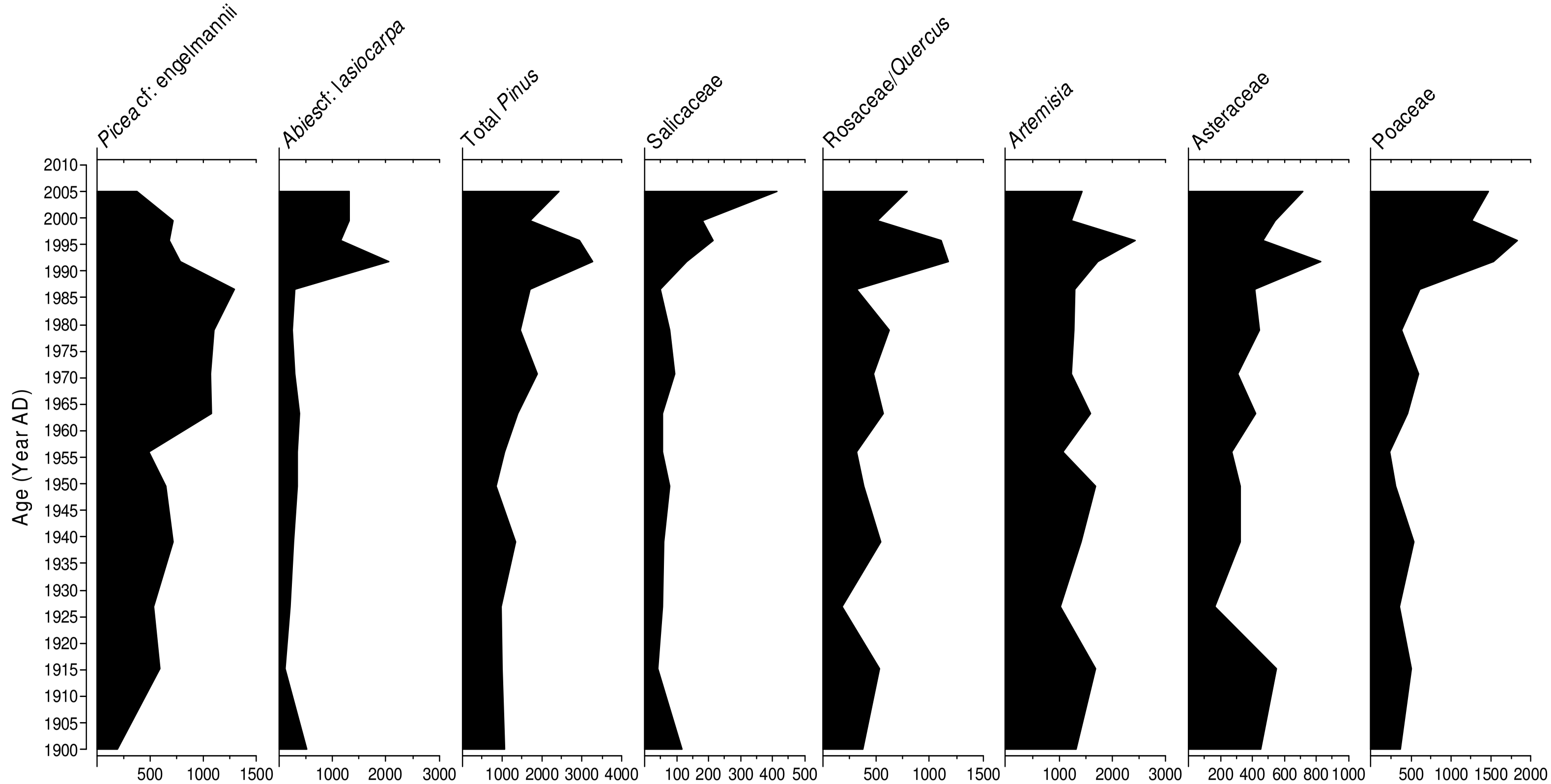
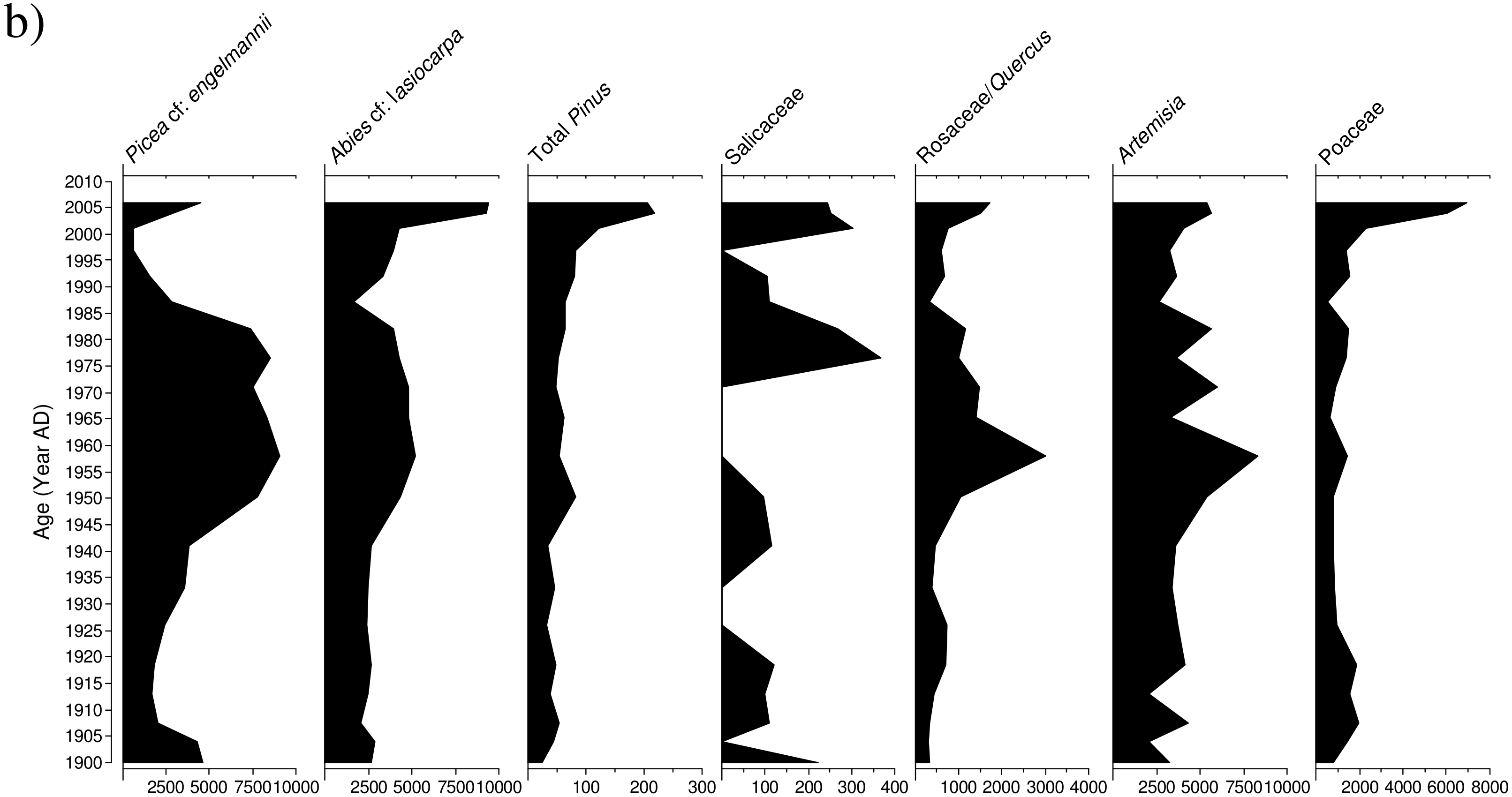


Figure 3. Wasatch Plateau pollen influx data for the 20th century at a) Blue Lake and b) Emerald Lake. A spruce beetle epidemic killed at least 95% of the spruce beginning in AD 1984. A spatially small, endemic spruce beetle outbreak occurred near Emerald Lake around AD 1905.

b)



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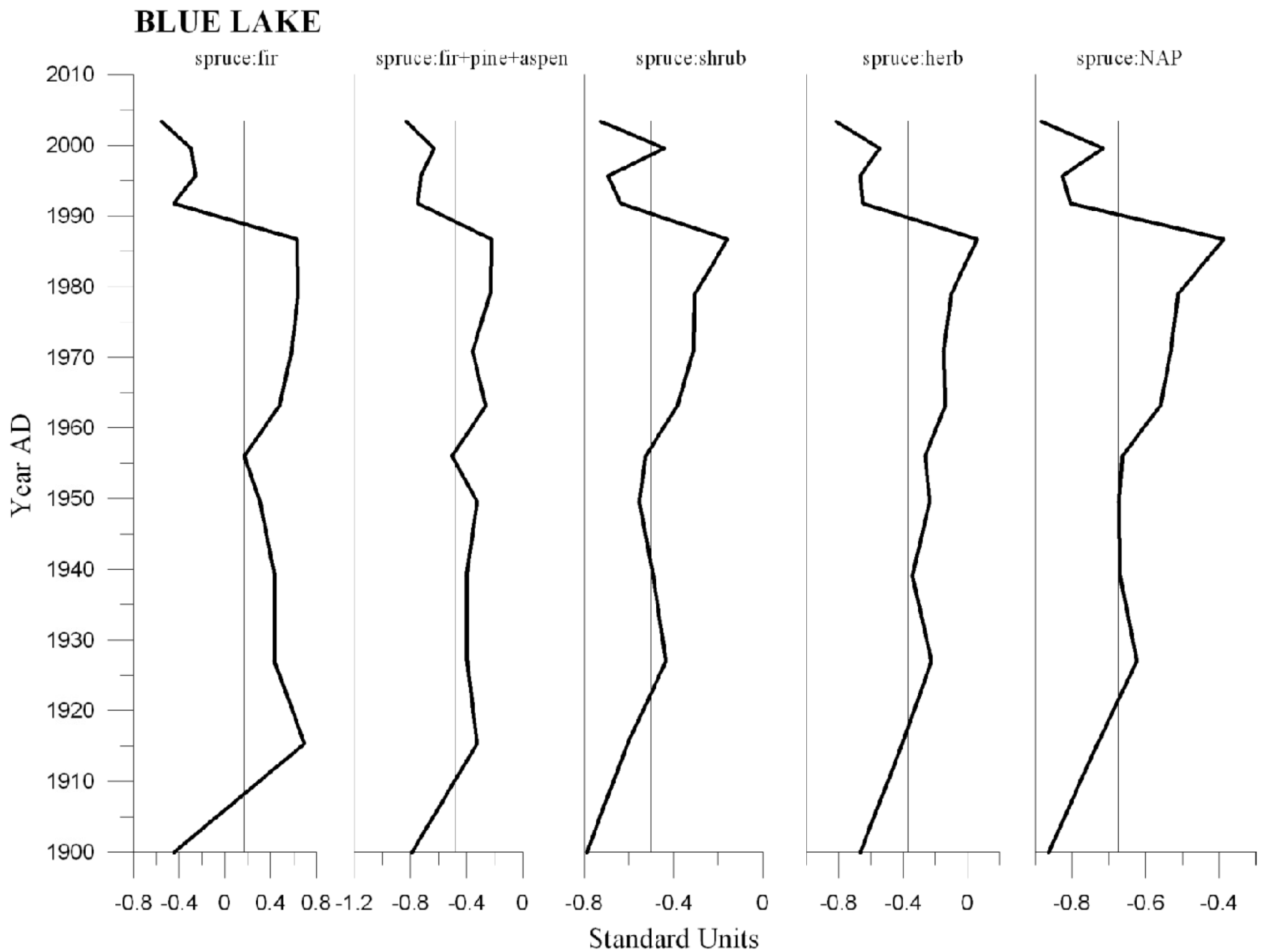
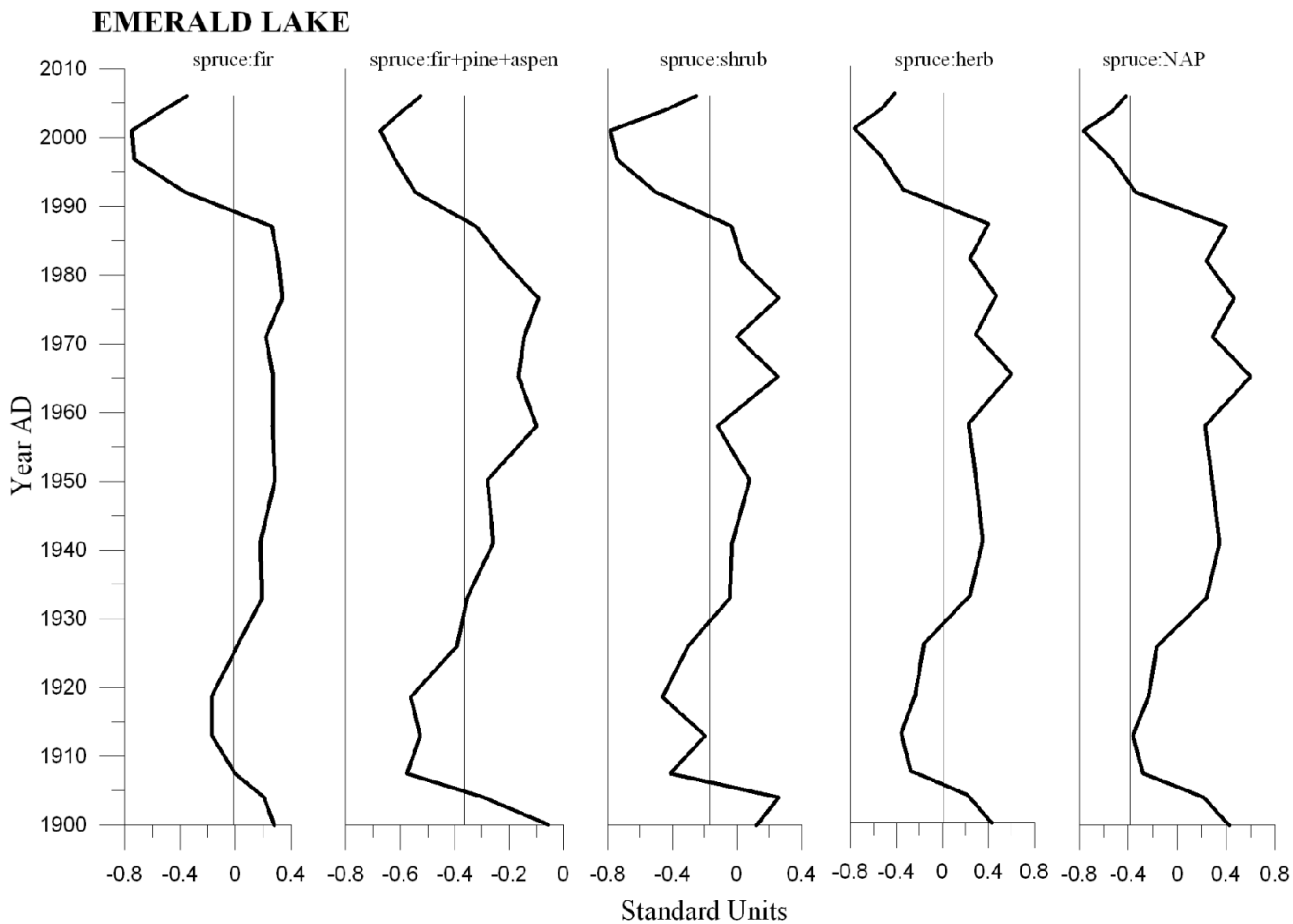


Figure 4. Summary of pollen ratio for the six lake basins in the study area. Higher ratio values indicate greater abundance of spruce whereas lower values indicate less spruce. Low ratio values are coincident with spruce beetle epidemics that occurred on the Wasatch Plateau beginning in AD 1984 until collapsing during the 1990s (4a and 4b), the Aquarius Plateau during the AD 1920s (4c and 4d), and the Markagunt Plateau during the AD 1990s (4e and 4f). The ratio was calculated (a-b)/(a+b) where “a” represents spruce (host) and “b” represents various non-host taxa.



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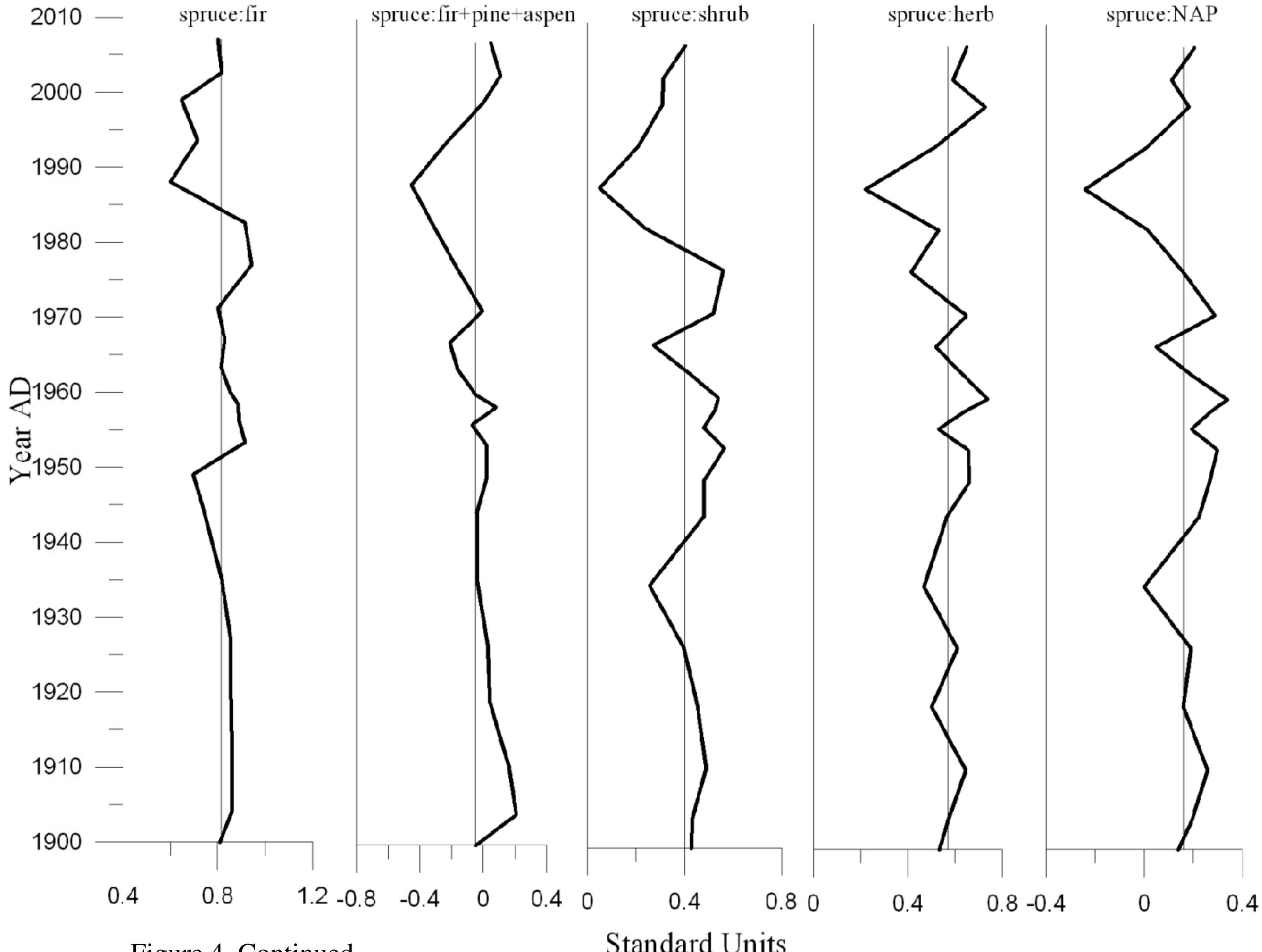
PURPLE LAKE



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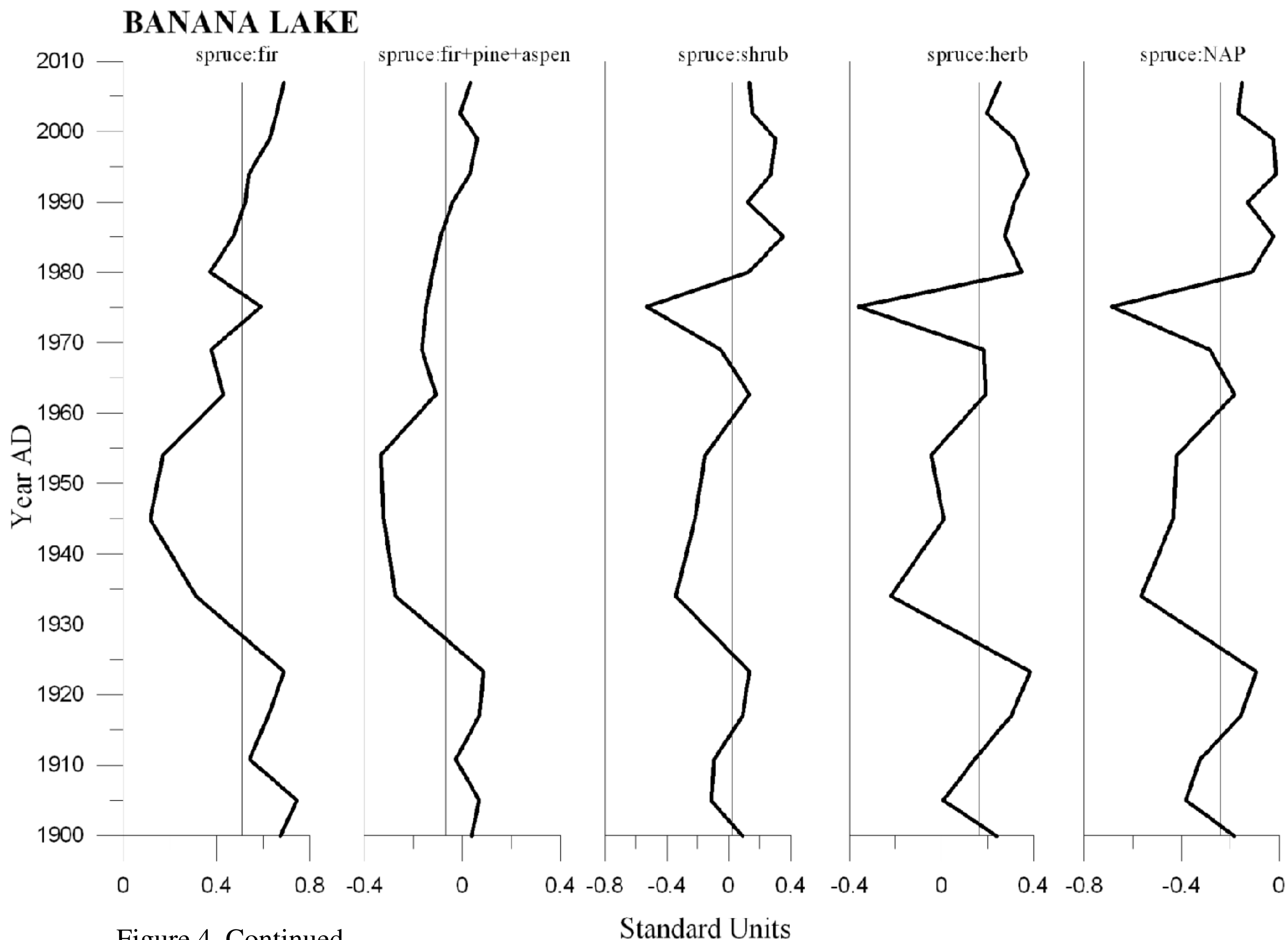

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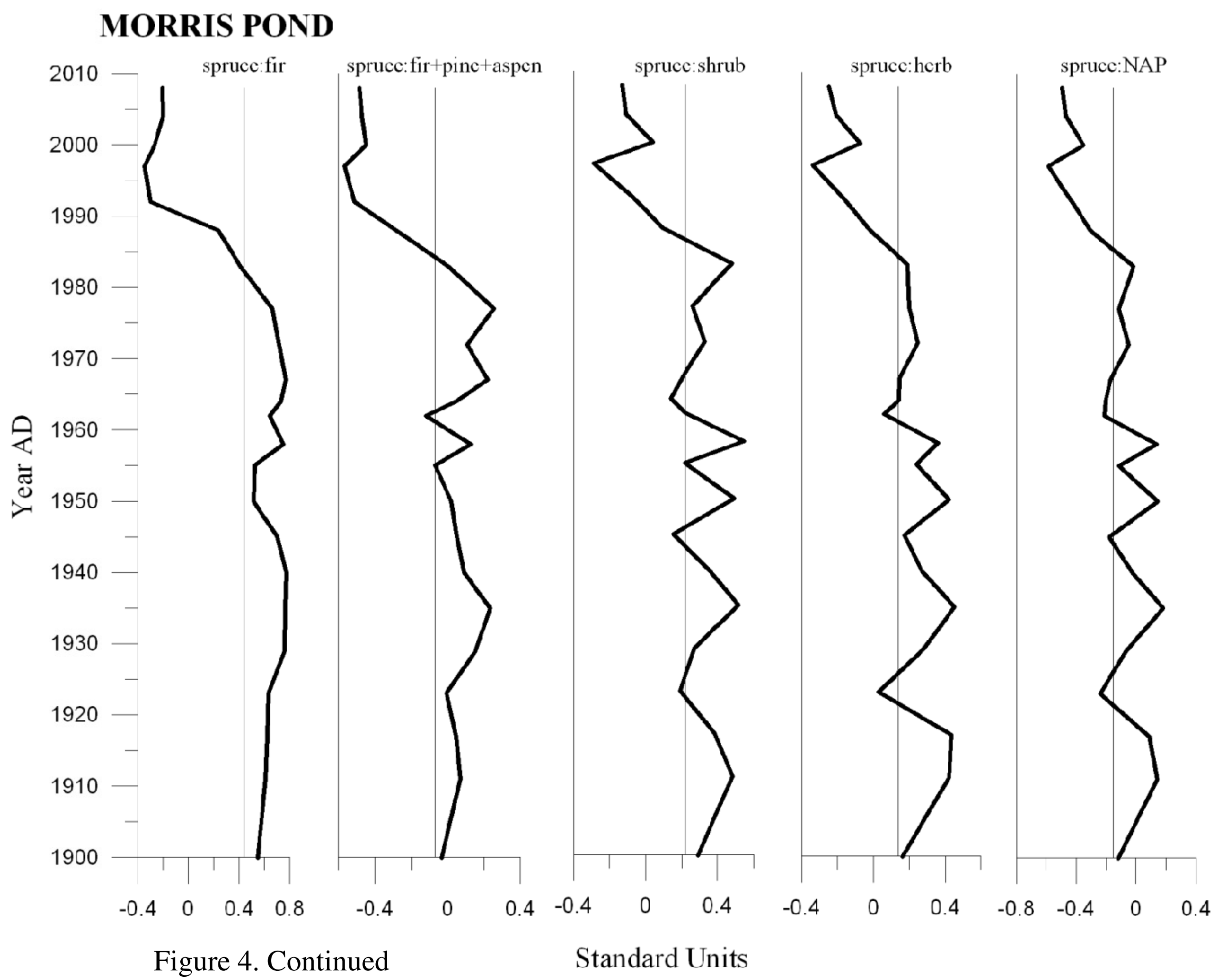

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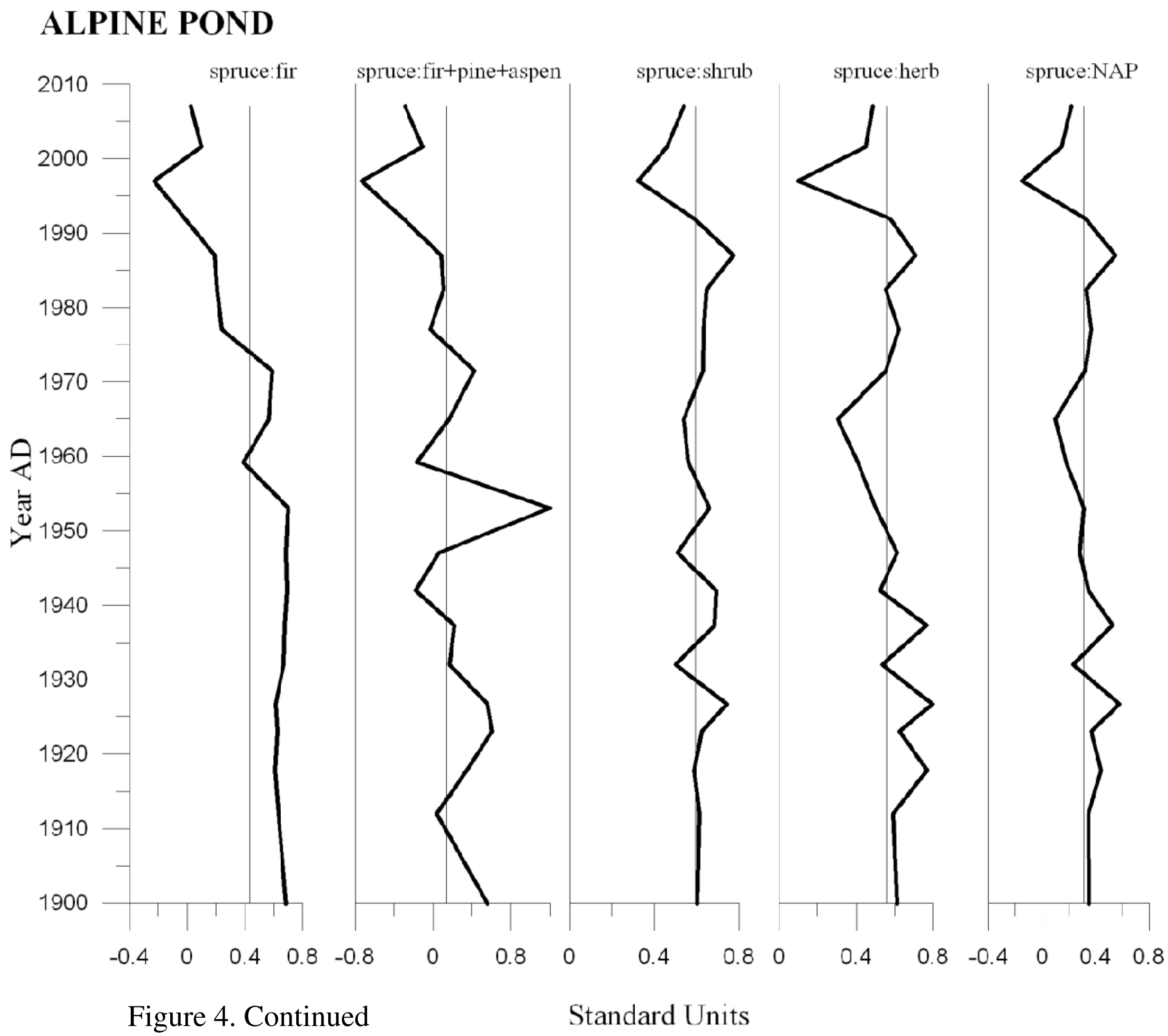

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a)

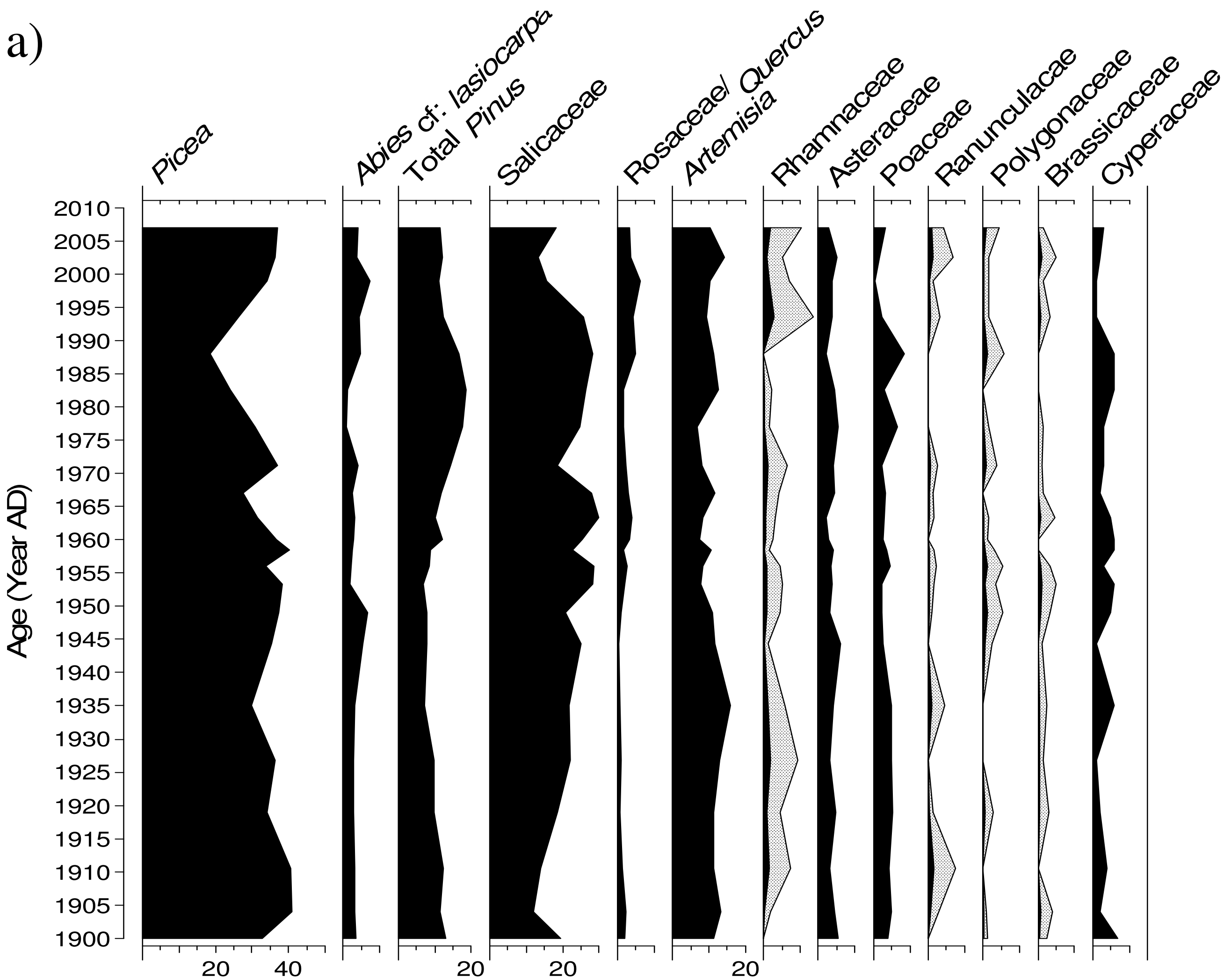
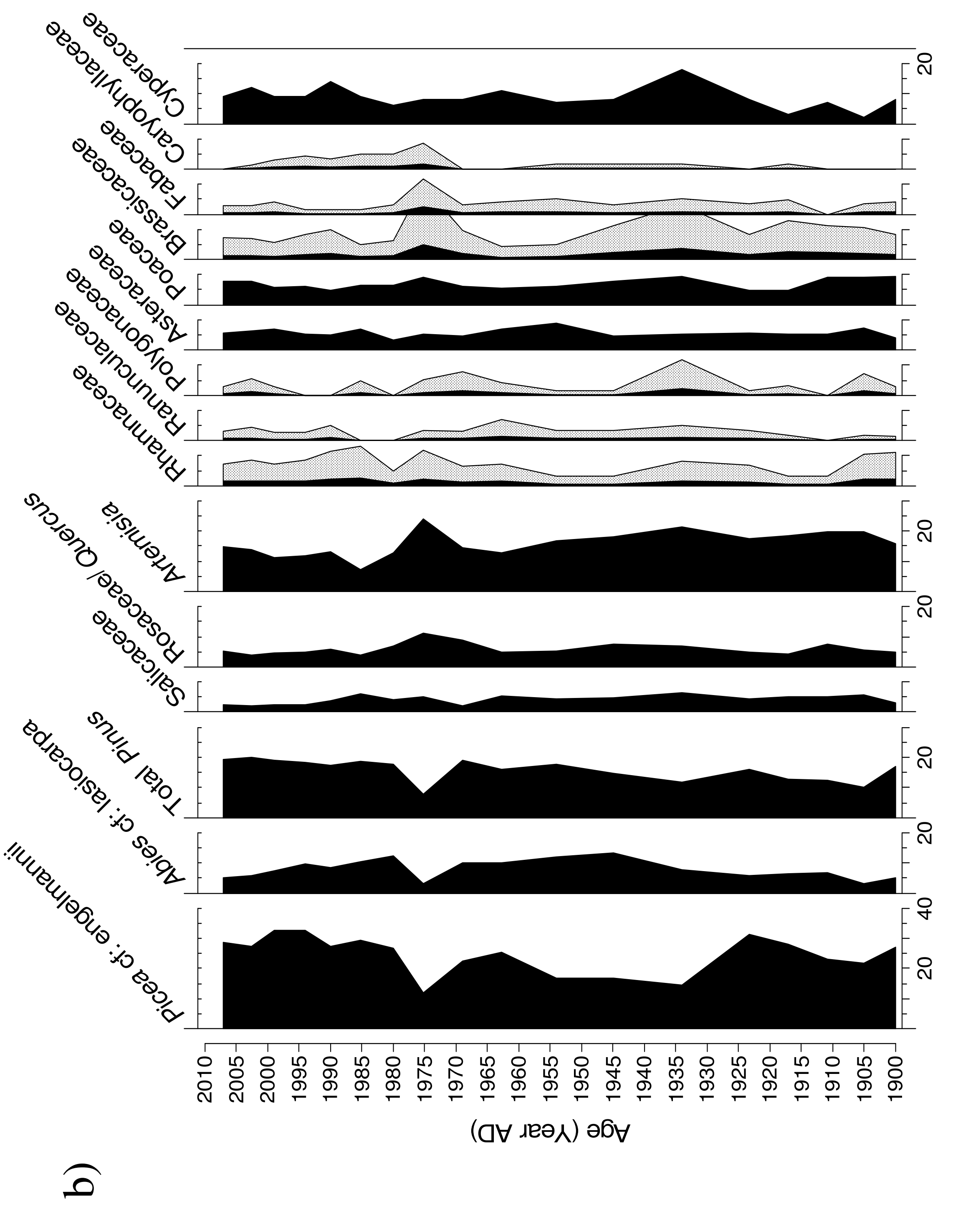


Figure 5. Aquarius Plateau pollen percent data for the 20th century at a) Purple Lake and b) Banana Lake. A spruce beetle epidemic killed most of the spruce component beginning in the late AD 1910s until the outbreak collapsed in the early AD 1930s.



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a)

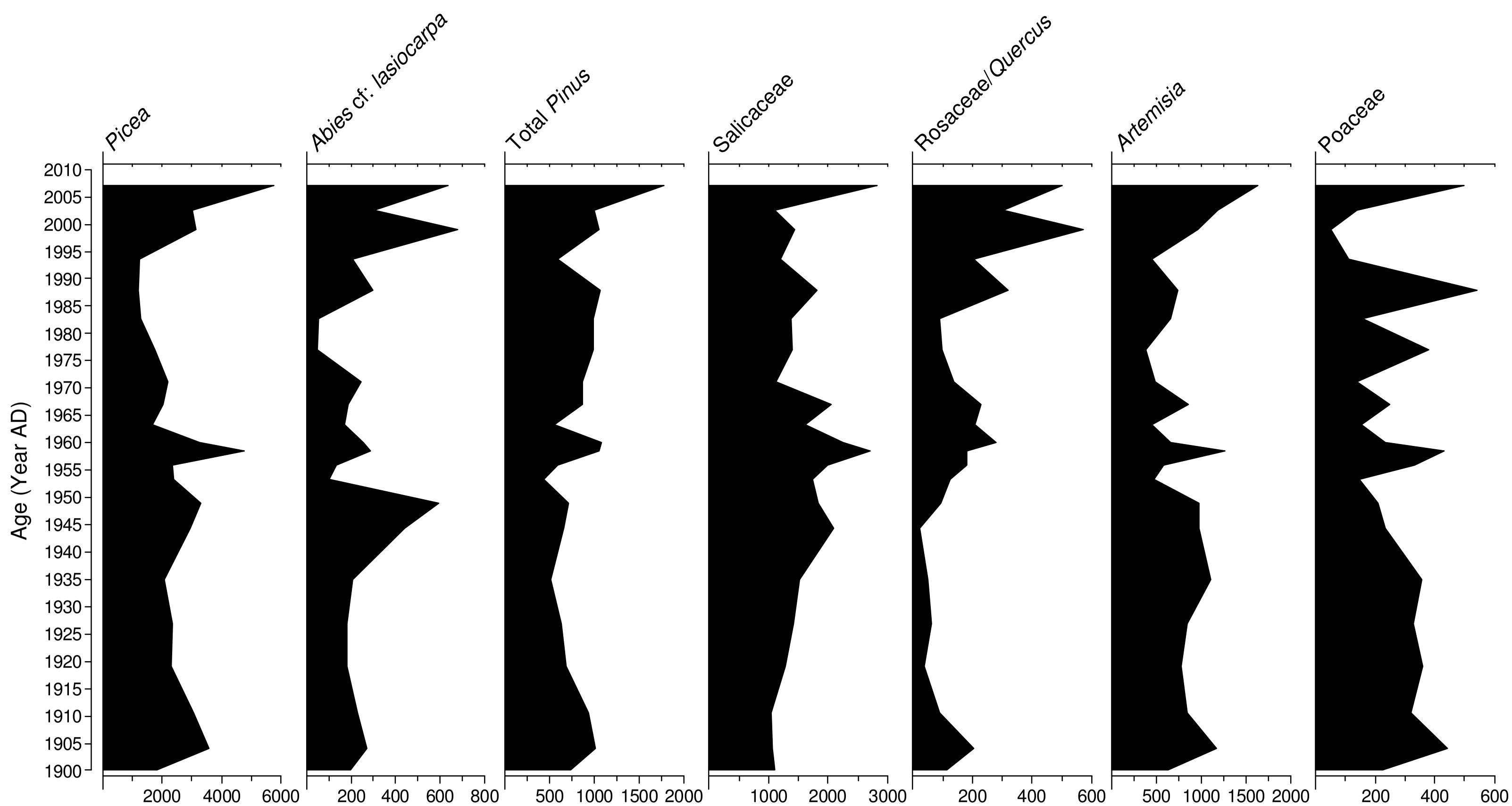

Figure 6. Aquarius Plateau pollen influx data for 20th century at a) Purple Lake and b) Banana Lake. A spruce beetle epidemic killed at least 80% of the spruce component beginning in the late AD 1910s until the outbreak collapsed in the early AD 1930s.

b)

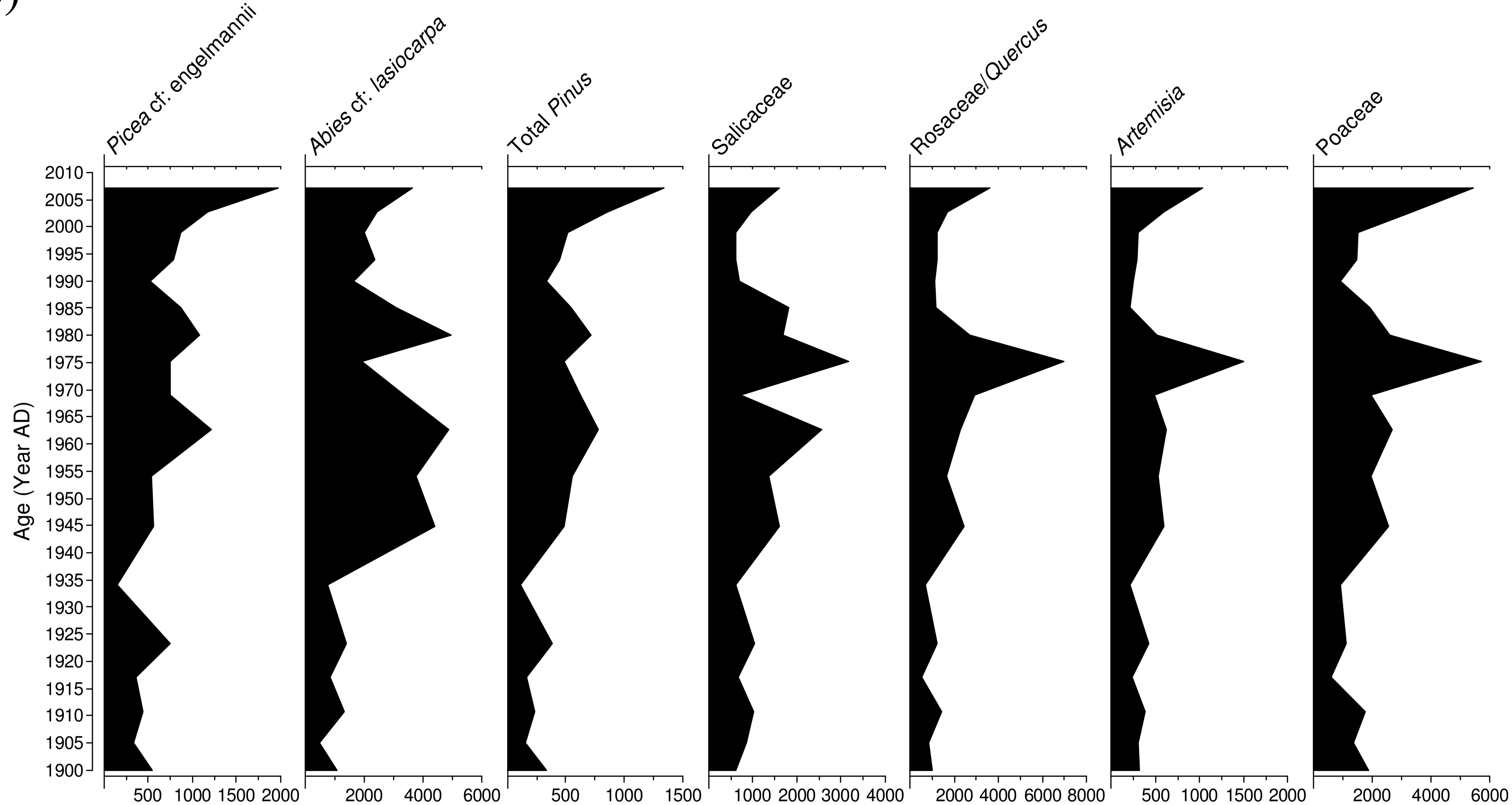

Figure 6. Continued

relative to other taxa between 1930 and 1940, and again between AD 1980 and 1990 (Fig. 4a-f).

Arboreal pollen on the Markagunt Plateau are composed of spruce (37%), fir (10%), pine (20%), and aspen (2-3%) (Figs. 7a and 7b). . Shrubs at both lakes are composed mostly of rose/oak (4-5%) and sagebrush (5-10%) while influx for both taxa are relatively higher at Morris Pond (Figure 8a and 8b). Herbaceous taxa are dominated by grasses (10% at Morris Pond and 4% at Alpine Pond) and members of the sunflower family (≤5%) with average influx averages for herbs also greater at Morris Pond. Other herbaceous components are present at low values (1-2%; <100 grains/cm3) including bell flower (Campanulaceae), pink (Caryophyllaceae), buttercup, and members of the bean family. The ratio assemblage at both lakes displays similar trends where spruce pollen is dominant in the ratio until ca. AD 1980 where it declines through the remainder of the records (Fig. 4a-f).

Discussion

During a SB epidemic, mortality of the generally taller and longer-lived Engelmann spruce creates canopy gaps that increase availability of sunlight, nutrients, and growing space which invigorate understory arboreal and non-arboreal species. The resulting growth release of the understory has been observed in numerous stand surveys during and immediately after SB outbreaks (Schmid and Frye, 1977; Holsten et al., 1995; Dymerski et al., 2001; DeRose and Long, 2007). For example, an SB epidemic in Colorado modified the canopy from 90% Engelmann spruce and 10% subalpine fir to 20% and 80%, respectively (Schmid and Hinds, 1974) and aerial ground surveys indicate

a)

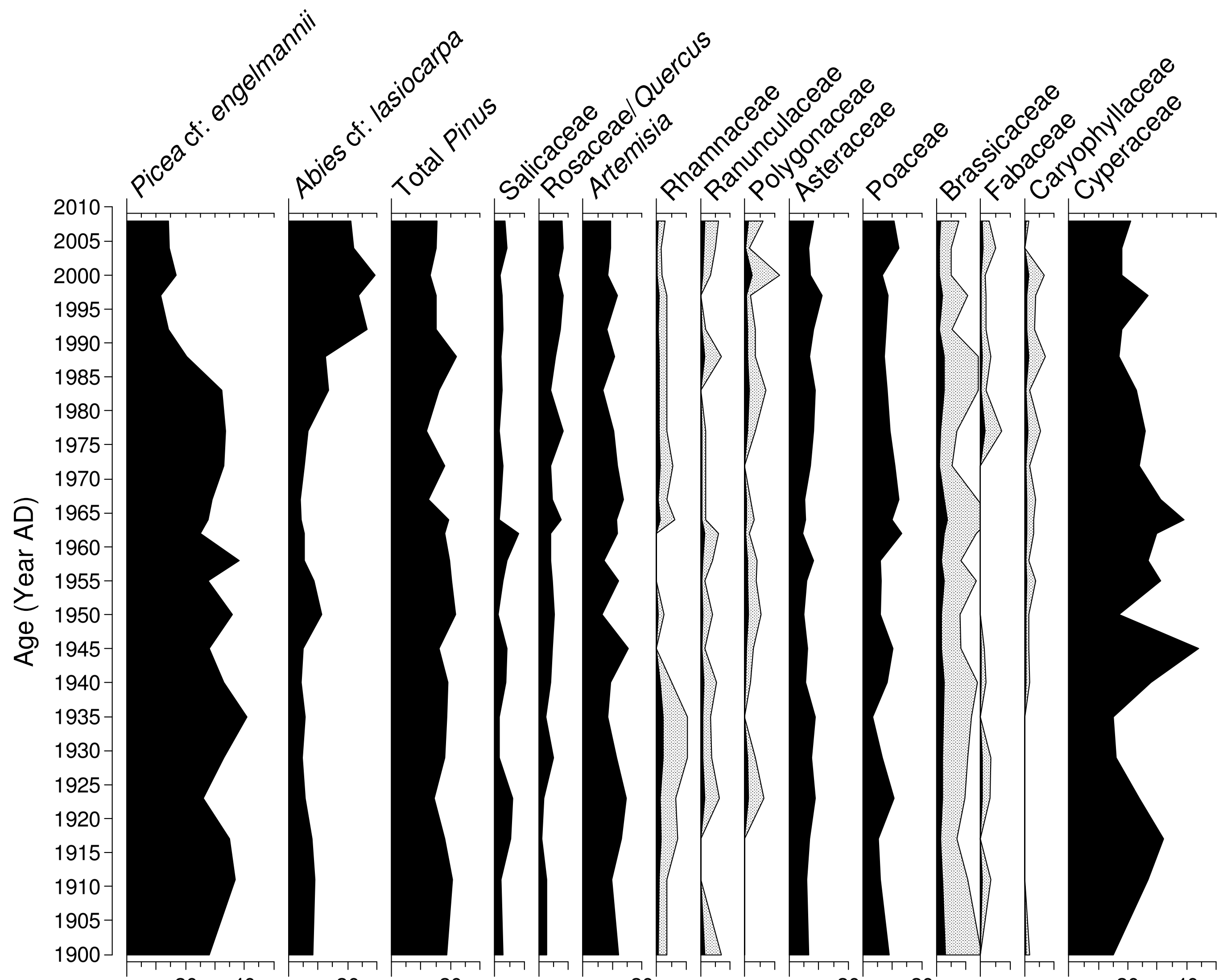

Figure 7. Markagunt Plateau pollen percent data for 20th century at a) Morris Pond. And b) Alpine Pond. A spruce beetle epidemic killed at least 93% of the spruce component during the AD 1990s.

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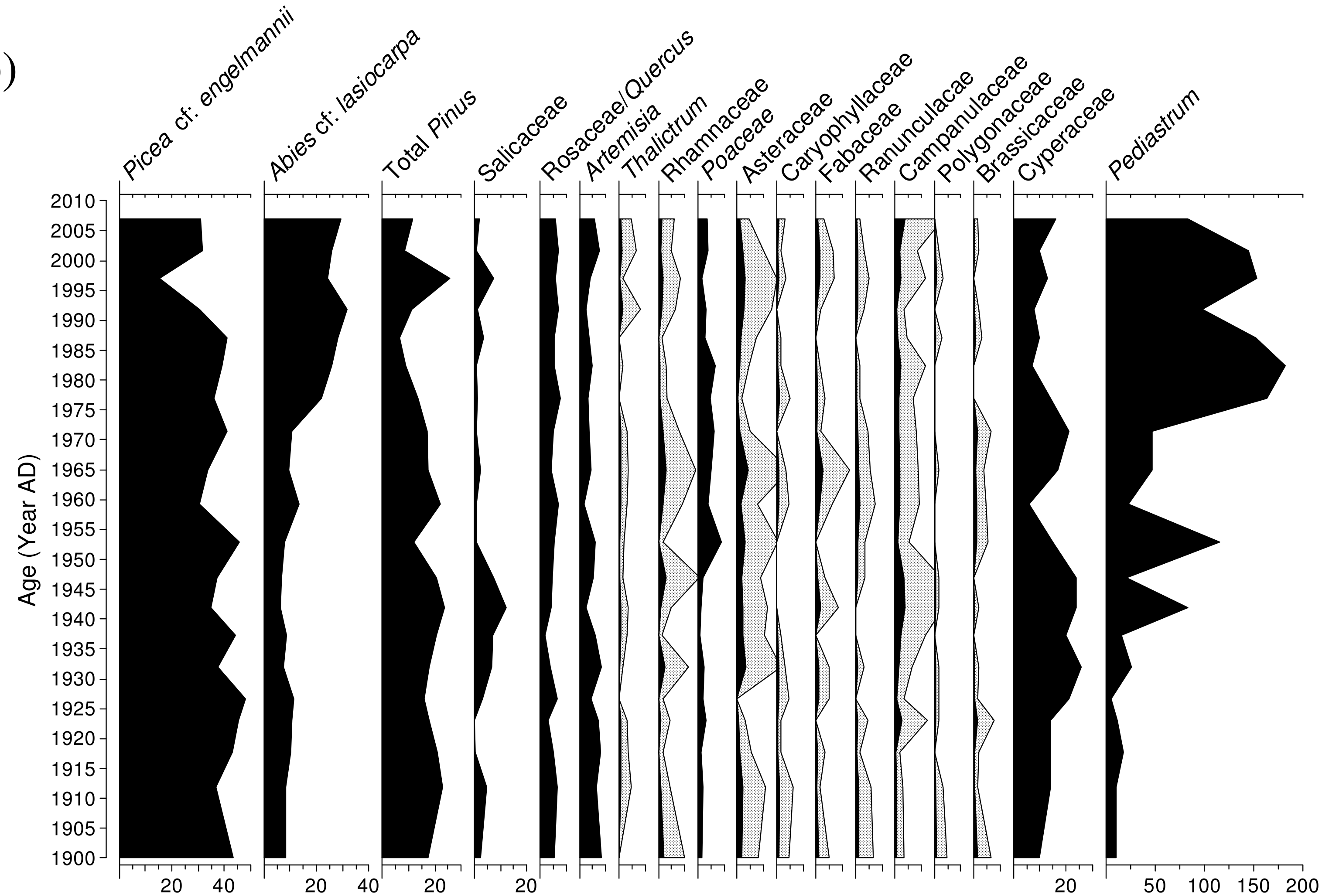

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a)

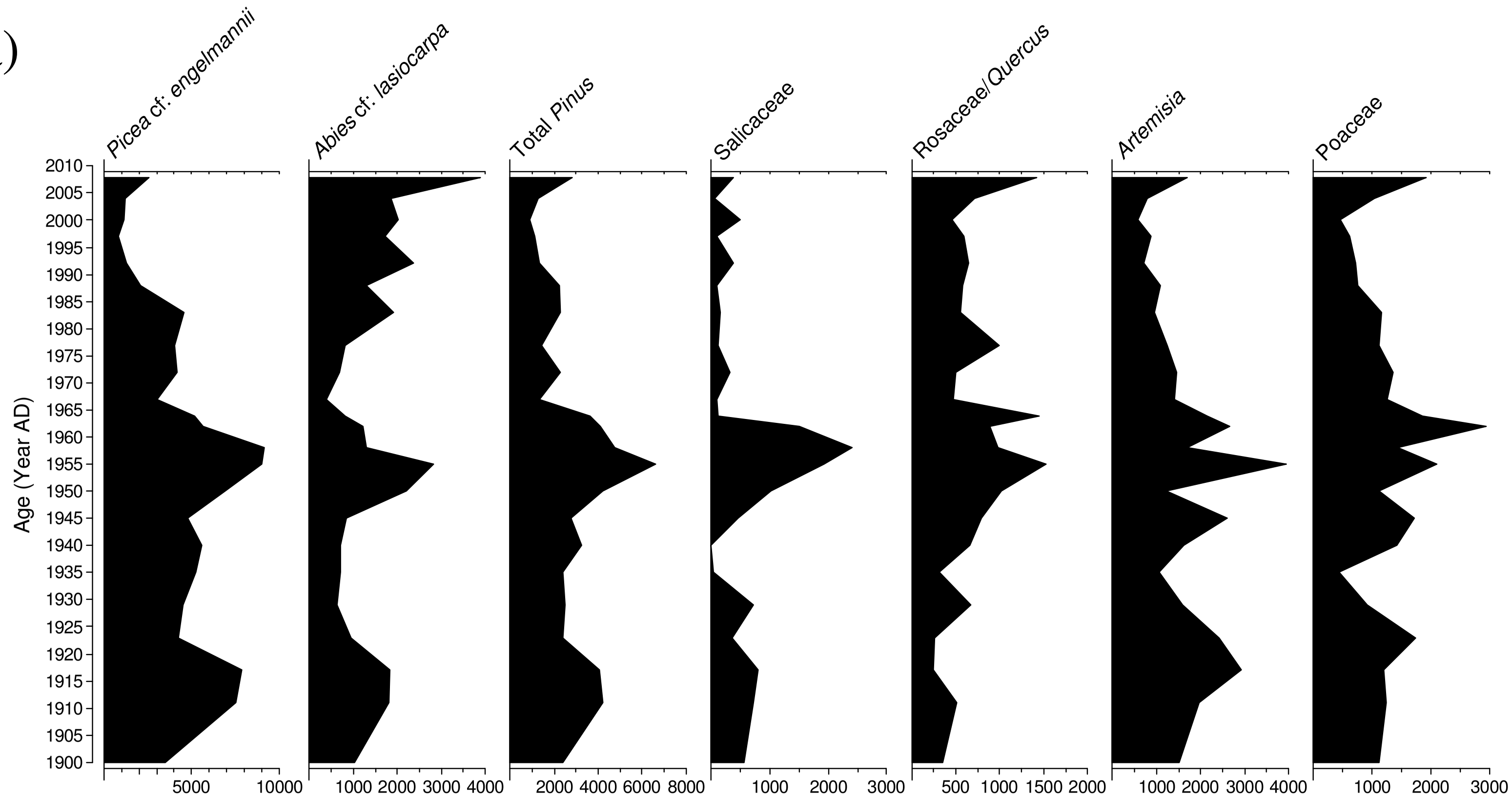

Figure 8. Markagunt Plateau pollen influx data for 20th century at a) Morris Pond. And a)Alpine Pond A spruce beetle epidemic killed at least 93% of the spruce component during the AD 1990s.

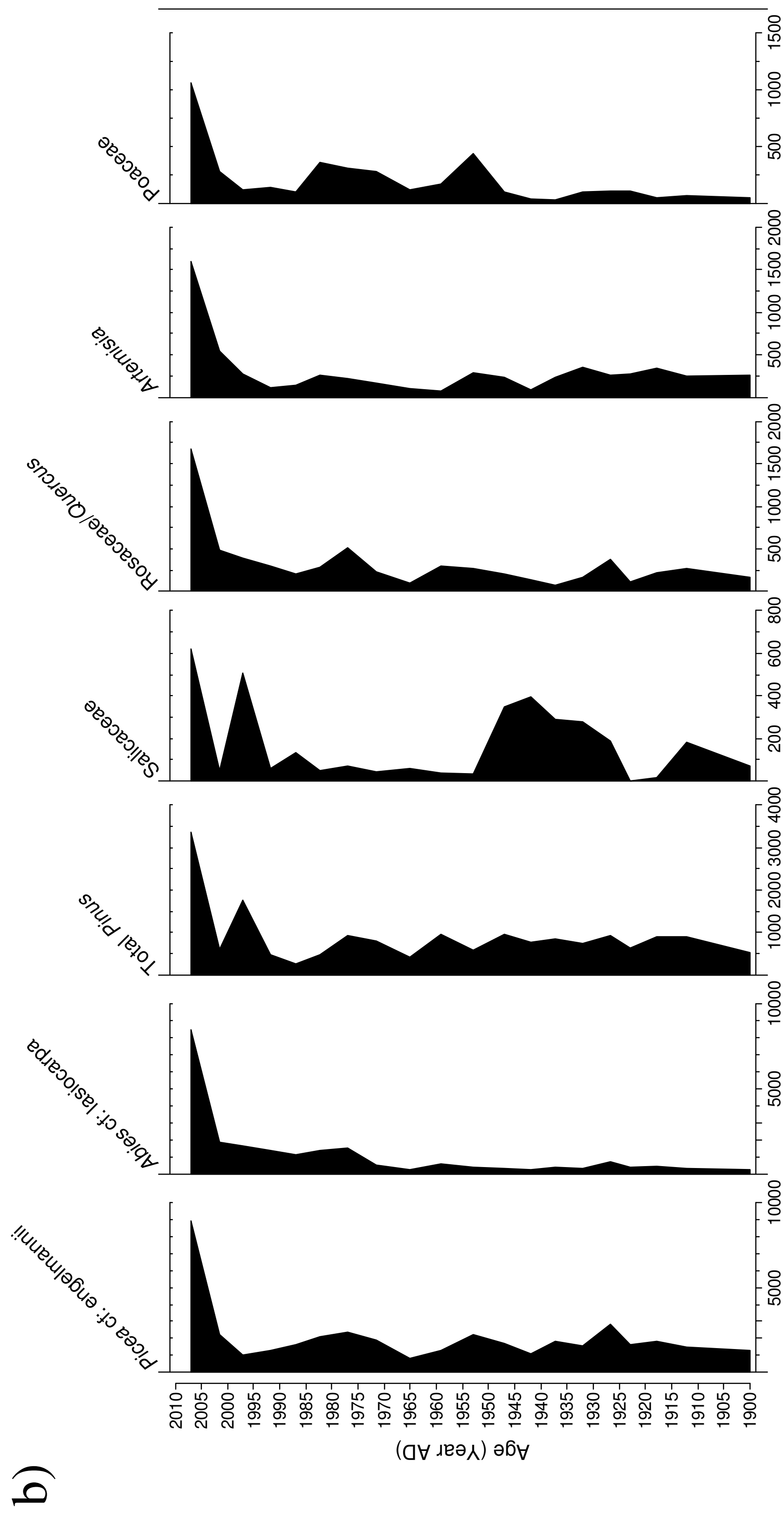

Figure 8. Continued

similar changes in Utah on the Wasatch Plateau (Dymerski et al., 2001). Tree-ring records suggest that elevated ring-width growth in non-host trees may persist for up to 40 years after a SB outbreak (Veblen et al., 1991, 1994). These distinct and ecologically well-documented changes in vegetation composition following a SB outbreak provide the theoretical framework for examining how these vegetation responses are recorded in sedimentary pollen stratigraphies.

Davis (1981) provides the foundation for using sedimentary pollen to reconstruct non-fire disturbances. She examined several Holocene pollen sequences and noted acute declines in the influx and percentage of eastern hemlock from spruce budworm and hemlock looper caused tree mortality which she described as "virtually instantaneous" (Davis, 1981). Fuller (1998) reiterates the magnitude and rapidity of hemlock pollen reductions noted by Davis and subsequent work identified similar outbreak signals in at least 60 pollen records (Bennett and Fuller, 2002). Both Davis and Fuller observed increases in pollen of competitive arboreal species (birch (*Betula*), beech (*Fagus*), and oak) concurrent with the hemlock decline. Davis (1981) reasoned that this event was triggered by an insect disturbance because 1) no charcoal was found coincident with the hemlock decline that would suggest wildfire; 2) climate would exert influence on at least several species, not hemlock alone; and 3) the coherency of the pollen decline is simultaneous across a region suggesting eruptive populations of an organism. Due to the sparse population densities of humans during the middle Holocene (Russel, 1983; Vale, 2002), it appears unlikely that a systematic selection of hemlock occurred, particularly across much of eastern North America (Davis, 1981; Allison et al., 1986). An insect outbreak was later confirmed by secondary physical evidence in lake sediments

(Anderson et al., 1986) including lepidopteron remains that co-occurred stratigraphically with declines of hemlock pollen, supporting Davis' initial interpretation of the disturbance as an insect outbreak.

The foundation for interpreting non-fire disturbance during the mid-Holocene hemlock decline strengthening the case for using pollen to reconstruct bark beetle outbreaks, significant differences exist among the mid-Holocene hemlock decline and bark beetle outbreaks. First, the hemlock decline is attributed to a species introduction, whereas bark beetles are native insects and have been present at least over the Holocene (Brunelle et al., 2008) and likely much longer. Second, the hemlock decline occurred over several centuries; whereas bark beetles are native insects that outbreaks persist for only a few decades. Thus sediment compression and sampling intervals are considerable limitations in reconstructing these short events (even operating under the premise that pollen alone is sufficient to identify outbreaks). Third, in the absence of secondary physical evidence, e.g. macrofossil or geochemical marker, attributing eruptive bark beetle populations to an observed pollen decline is speculative because other insects or pathogens could potentially be responsible.

MPB remains have been retrieved from lake sediments coincident with historic beetle disturbance (Brunelle et al., 2008) which could potentially offer crucial pieces of secondary evidence in bark beetle disturbance reconstructions. However, lake water chemistry is an important factor in SB preservation (Morris et al. 2010). Furthermore, no SB remains were found in any of the cores analyzed for this study. For insect remains to be deposited in lake sediments, the adult beetle must come in contact with surface water which is probably a rare occurrence because SB spend the majority of their life in subcortical chambers of the host tree and emerge for flight briefly (about a week) during their 1-2 yr lifespan (Holsten et al. 1999).

Schmid and Frye (1977) report that during an SB outbreak in July AD 1949, SB carcass accumulations were observed in drifts that accumulated for at least one km on a lakeshore in western Colorado. In this region, SB emergence typically occurs in June when daily maximum temperatures reach ~16°C (Dyer, 1969; Fettig et al., 2007). Interestingly, the National Climate Data Center reports for Colorado Division 4 where the SB epidemic occurred that June 1949 was the single wettest June during the 20th century, suggesting anomalous precipitation during SB emergence adversely affected beetle flight and contributed to the carcass drifts reported in Schmid and Frye (1977).

The six pollen records presented here reflect known ecological conditions contemporaneous with historic SB outbreaks where decreasing spruce and concurrent increases in fir pollen are evident across sites (Figs. 3a, 3b, 5a, 5b, 6a, and 6b). Generally, herb and shrub pollen also increase during outbreaks, although examination of individual percentage and influx data (e.g., Figs. 3a and 6a) is less compelling than an inspection of sums for herbs/shrubs compared to spruce (Fig. 4a-f). To provide context, ratios are plotted against 20th century ratio averages. Ratios are broadly consistent across sites, while ratios of spruce to arboreal species (spruce:fir, spruce:fir+pine+aspen) are more persistent in decades following an outbreak (Fig. 4a-f). The robustness of the spruce:arboreal signal is probably due to the greater longevity of trees relative to shrubs and herbs and eventual canopy closure following the release of understory trees that excludes herbs and shrubs. Therefore, in the context of Holocene pollen records, examining host pollen to other arboreal pollen (or groups of arboreal pollen) is advantageous compared to shrub and herb sums.

Because Purple Lake is surrounded by palynologically indistinguishable species of spruce with only a minor fir component, ratios of spruce to nonarboreal taxa best coincides with the known outbreak dates. A fire occurred during AD 1993 in the Purple Lake watershed (discussed in Chapter 3) which registers conspicuously across all ratios, though mostly clearly in the shrub and herb ratios. While spruce pollen declines (Figs. 5a and 6a), colonization by herbaceous taxa was more rapid than other arboreal species, which require more time to mature and produce pollen, suggesting that a ratio of arboreal pollen to herbaceous pollen may be useful in detecting fire disturbance.

Conclusions

While the results of this study represent a significant compilation of data and multiple high-resolution historical assessments, this study is not a rigorous statistical analysis. Even with every centimeter of the core analyzed there are not enough samples for the historic period to produce a large enough n-value for a robust statistical analysis. What is presented instead are qualitative pollen representations that include percentages, influx, and ratios reflecting the loss of host spruce and growth release of non-host taxa for all six lakes analyzed in this study. These results offer a practical method to assess other palynological records.

In five of the six cores we examined for this study, the spruce:fir ratio decreases with the known SB outbreak which provides guidelines for detecting SB disturbance using pollen. Determining a single quantitative threshold on ratios is problematic for 20th century outbreaks because of the low sample size (n=14 to 20) despite an analysis being conducted every contiguous cm. Statistical approaches among multiple sites are also inherently problematic because of differences in forest composition, successional stage, and lake surface area which influence pollen taphonomy. However, the palynological signal of SB epidemics is clear and provides a framework for identifying large magnitude outbreaks over the Holocene. The assessments will of course become more robust with the addition of secondary and or supporting lines of evidence, such as beetle remains (Brunelle et al., 2008), geochemical markers, and paired studies with tree-rings. Overlapping high-resolution pollen analysis with tree ring studies may offer more temporally extensive datasets that would facilitate rigorous statistical application. Using host/non-host pollen ratios is effective at describing known ecological conditions, but without secondary indicators interpreting bark beetle activity provides a conservative estimate and likely only captures high magnitude events. Sediment compression (more time per centimeter), shifts in climate regimes and insolation dynamics, and no-analog vegetative communities (Williams and Jackson, 2007) are considerable challenges that could potentially be overcome by analyzing for a suite of ratios for host versus non-host taxa and/or groups in concert with a supporting line of physical evidence.

CHAPTER 3

CLIMATE CONTROLS ON VEGETATION AND FIRE REGIMES FROM THE AQUARIUS PLATEAU, UTAH

Introduction

Climate forecasts suggest as much as a 4˚ C global warming over the next 100 years (Sokolov et al., 2009; Cayan et al., 2010), leading to increased occurrence of drought and changes in moisture seasonality and availability in the American west (Sewall and Sloan, 2004; MacDonald et al., 2010). Drought conditions and warming temperatures are intuitively and quantitatively linked to increased incidence of natural forest disturbances, including wildfire and eruptive insect infestations (Westerling and Swetnam, 2003; Westerling et al., 2006; Fettig et al., 2007; Hebertson and Jenkins, 2008; Raffa et al., 2008; Bentz et al., 2010). Alterations to temperature and hydrological regimes will drive modifications of species range, including instances of local extirpation and nonnative invasion at regional and continental scales (Bentz et al., 2010). Changes in temperature and moisture regimes can also increase the severity, frequency, and spatial synchrony of disturbance, which in turn hastens ecosystem reorganization (Turner et al., 2010). Anticipated warming and related changes in precipitation seasonality and moisture availability require better understanding of the range of variability in climate-vegetation interaction and ecosystem resilience to disturbance (Logan and Powell, 2001;

Westerling et al., 2006; Raffa et al., 2008).

Variations in El Nino-Southern Oscillation (ENSO) and Pacific Decadal Oscillation (PDO) over the Holocene exhibit a considerable range of frequency and intensity (Clement et al., 2000; Moy et al., 2002; Koutavas et al., 2006; Barron and Anderson, 2011) and evidence suggests that pervasive El Niño or La Niña states have persisted over millennial timescales (Tudhope et al., 2001; Koutavas et al., 2002, 2006; Shin et al., 2006; Marchitto et al., 2010; Asmerom et al., 2011). Climate forecast models for the 21st century acknowledge uncertainties as to how ENSO will respond as some research suggests sustained El Niño-like conditions (Wara et al., 2005) similar to the warmer-than-modern Pliocene (~4.5-3.0 million years ago), while other research suggests persistent La Niña circulation patterns (Seager et al., 2007). In western North America, the ≈42° parallel delineates the boundary of the ENSO winter precipitation dipole (Ropelewski and Halpert, 1986; Dettinger et al., 1998; Cayan et al., 1999; Brown and Comrie, 2004; McCabe and Dettinger, 2008; Wise, 2010). The dipole boundary is approximate and has probably migrated from its present day orientation in the past (Cayan et al., 2002). ENSO status is described as positive (negative) indicating warm (cool) sea surface temperatures (SSTs) in the eastern Pacific Ocean. During a moderate to strong El Niño episode, the SW generally receives greater than average winter precipitation, whereas the Pacific Northwest (PNW) experiences decreases in winter precipitation. The opposite occurs during La Niña winters. The ENSO periodicity is generally 2-7 years, which include years of neutrality (Diaz and Markgraf, 2000). The PDO is somewhat similar in terms of climate and circulation response, though exhibiting 20-30 year periods (Mantua et al., 1997) and is similarly described as positive (negative) in reference to warm (cool) SST conditions in the northern Pacific Ocean. Given the comparatively low temporal frequency of PDO, its status can enhance (constructive) or suppress (destructive) winter precipitation in western NA during El Niño and La Niña events (Gershunov and Barnett, 1998; McCabe and Dettinger, 1999; Biondi, 2001; Gray, et al., 2003).

Understanding the influence of Pacific Ocean teleconnections on local and regional synchronization of forest disturbance has benefitted from recent studies using tree ring records (Schoennagel et al., 2005, 2007; Brown et al., 2008; Heyerdahl et al., 2008; Macias Fauria and Johnson, 2009; Sherriff et al., 2011). Tree rings are advantageous because they are annually resolved and can therefore be closely compared with historic climate indices. Currently, records of climate teleconnections and wildfire exist for the last several centuries in the Sierra Nevada, Cascade, and U.S. Rocky Mountains (hereafter Rocky Mountains). Climate/fire dynamics are perhaps best understood in the Rocky Mountains where tree-ring records span topographic and vegetation gradients, including fuel-limited, low-elevation ponderosa pine (*Pinus ponderosa*) parklands that are characterized by frequent, low-severity burning (Swetnam and Betancourt, 1998; Westerling and Swetnam, 2003; Sherriff and Veblen, 2008). In comparatively high elevations of the Rocky Mountains, fuel-abundant Engelmann spruce/subalpine fir forests that experience stand-replacing wildfires only once over hundreds of years (Kipfmueller and Baker, 1990; Buechling and Baker, 2004; Sibold et al., 2006). Despite the fire/climate information provided by dendrochronlogy, tree ring records are generally limited by the lifespan of the tree, especially in areas where fire disturbances are typically stand-replacing (e.g., spruce-fir forests).

Lake sediment records are useful in understanding climate, vegetation, and disturbance dynamics over longer timescales (centuries to millennia). During the Holocene, changes in insolation due to variations in the earth's orbital pathway modified climate, and therefore vegetation distributions and disturbance regimes (Webb et al., 1993; Kutzbach et al., 1998; Whitlock and Bartlein, 1997). Some examples include climate controls on vegetation and disturbance such as migration of upper and lower timberline (Fall, 1997), shifts in wildfire regimes (Long et al., 1998, 2007; Gavin et al., 2006), and frequency of insect epidemics and/or the presence/abundance of pathogens (Brunelle et al., 2008). Additionally, several advances over the last decade in understanding charcoal taphonomy (Whitlock and Millspaugh, 1996; Gardner and Whitlock, 2001), the development of a global charcoal database (Marlon et al., 2006; Power et al., 2009), and the availability of analytical software tools (Long et al., 1997; Higuera et al., 2009) now enable robust interpretations of past climate-fire relationships using sedimentary charcoal. Lake sediment records may underrepresent low-severity fire disturbance compared to tree-rings reconstructions. However, general changes in fire regime and catastrophic fire episodes are well-recorded in lake sediments (Gardner and Whitlock, 2001).

Here we present a ~9,000 yr assessment of climate-driven wildfire disturbance using lake sediments from an isolated subalpine plateau dominated by spruce-fir forests. This site is located in the SW ENSO realm (El Niño wet/ La Niña dry). Fire-prone taxa are known to influence fire severity and recurrence in coniferous forests (Lynch et al., 2004; Higuera et al., 2009; Seppä et al., 2009; Ohlson et al., 2011); however, our record is significant because the relatively stable vegetation community offers an opportunity to explore climate controls on stand-replacing fire frequency irrespective of forest composition.

Study Area

The transition between Great Basin and Colorado Plateau in south-central Utah is topographically complex with precipitation and temperature gradients (and therefore plant communities) related to elevation, as noted elsewhere in the region (Anderson et al., 1999; Weng and Jackson, 1999). The subalpine plateaus and mountain ranges in south-central Utah have been referred to as 'High Plateaus' (Dixon, 1935) because these landforms rise dramatically above the surrounding sagebrush steppe and pinyon-juniper woodland (Fig. 9). These plateaus are important snow accumulation zones that supply tributaries of the Colorado River, including the Escalante, Fremont, and Virgin rivers. Within this region of Utah, seasonal precipitation maxima are heterogeneous and elude broad classification (Pyke, 1972; Houghton, 1975; Mock, 1996; Shinker, 2010).

The Aquarius Plateau (AqP) has the largest subalpine area (~2,000 km^2) and highest mean elevation (3,355 m asl) of the High Plateaus (Fig. 9). The AqP is the headwaters of the Escalante River and an important contributor to the Fremont River, that both enter the Colorado River at Glen Canyon (Lake Powell Reservoir). The summit of the AqP exhibits rolling tabletop topography and is composed of andesitic basalt that originated during the Oligocene Marysvale Volcanic episode (Flint and Denny, 1958). The AqP was glaciated during the Pleistocene and an ice cap ≈200 m thick occupied its summit with glacial tongues spilling off the northeastern margin at Boulder Top (Flint and Denny, 1958; Osborn and Bevis, 2001). Glacigenic features on the AqP are largely

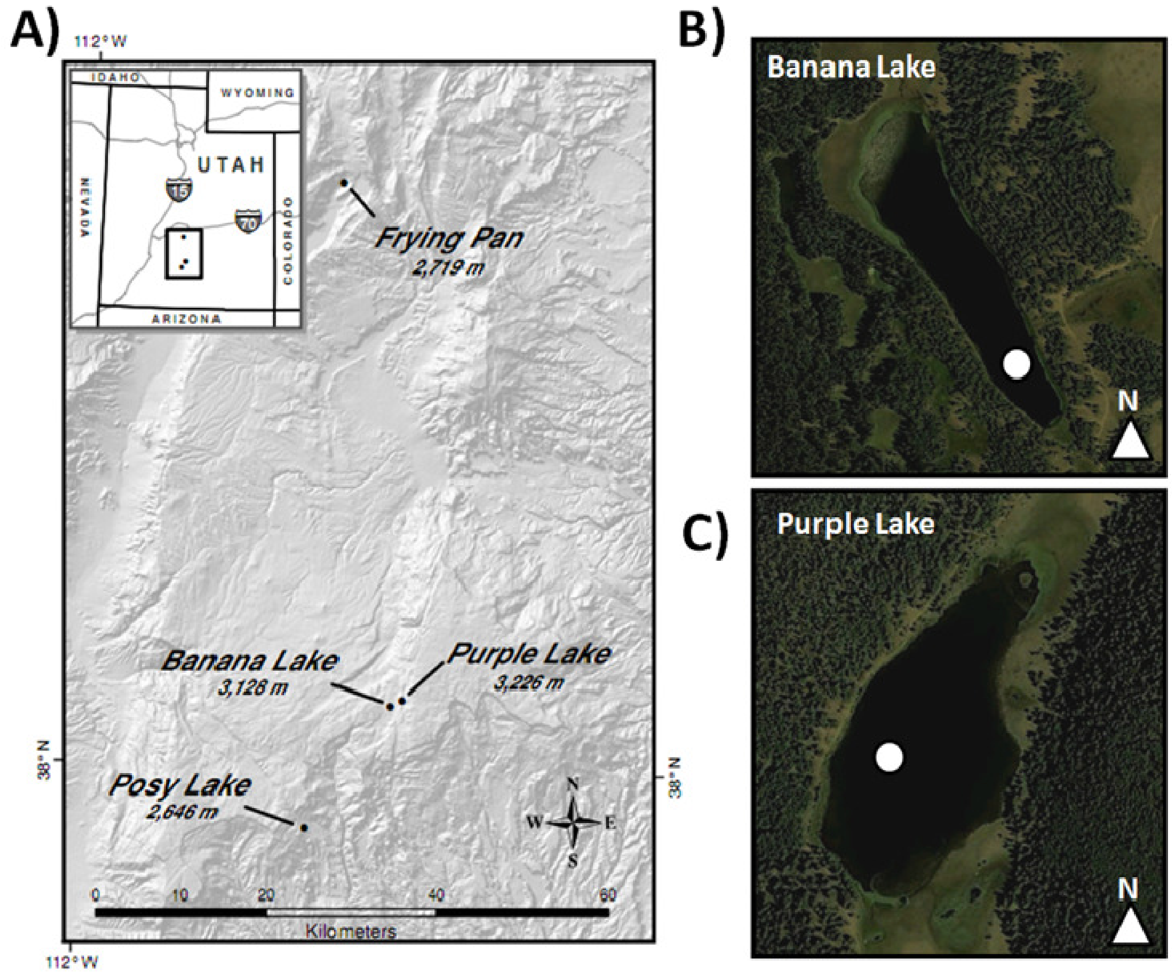

Figure 9. Location map of study sites located on the region. Features include the Aquarius Plateau (A) discussed in text, B) Banana Lake (B) and C) Purple Lake (C). White circles indicate approximate coring location.

erosional and include numerous kettle lakes, whalebacks, roche moutonnées, and glacial abrasions such as striations and chatter marks. Thin soils are common across the AqP and no physical evidence exists suggesting a glacial re-advance following the last glacial maximum (Marchetti et al., 2005).

The subalpine forest zone of the AqP is composed predominantly of Engelmann spruce and subalpine fir, with quaking aspen and blue spruce also present. Bristlecone pine and limber pine are present, though generally limited to rocky, well-drained sites. A landscape-scale spruce beetle (SB) outbreak developed in AD 1916 or 1918, eventually collapsing in the AD 1930s (AD 1920s outbreak hereforward; Dixon, 1935; Mielke, 1950). This outbreak resulted in ≥80% mortality of mature Engelmann spruce (≥ 8 cm diameter at breast height) across the AqP (Mielke, 1950; Schmid and Frye, 1977). Repeat photographs from the Purple Lake watershed document forest regeneration following the 1920s SB epidemic (Fig. 10).

Banana Lake (38° 4'0.29"N, 111°35'12.21"W; 3,128 m elevation), Purple Lake (38°4'28.33"N, 111°34'16.47"W; 3,226 m elevation), and Posy Lake (37° N, 57’ W; 2,646 m elevation) (Fig. 9) are small kettle lakes with surface areas of 5, 3, and 2 ha, respectively. Banana Lake and Purple Lake are surrounded by dense stands of Engelmann spruce, whereas Posy Lake is partially encircled by a subalpine meadow dominated by grasses (Poaceae) and members of the sunflower family (Asteraceae). Engelmann spruce snags from the AD 1920s SB outbreak are visible across the AqP and are abundant in all watersheds discussed here. The forest composition at Banana Lake and Posy Lake is composed of Engelmann spruce, subalpine fir, and blue spruce with aspen clones found in isolated patches. Purple Lake is surrounded by Engelmann spruce

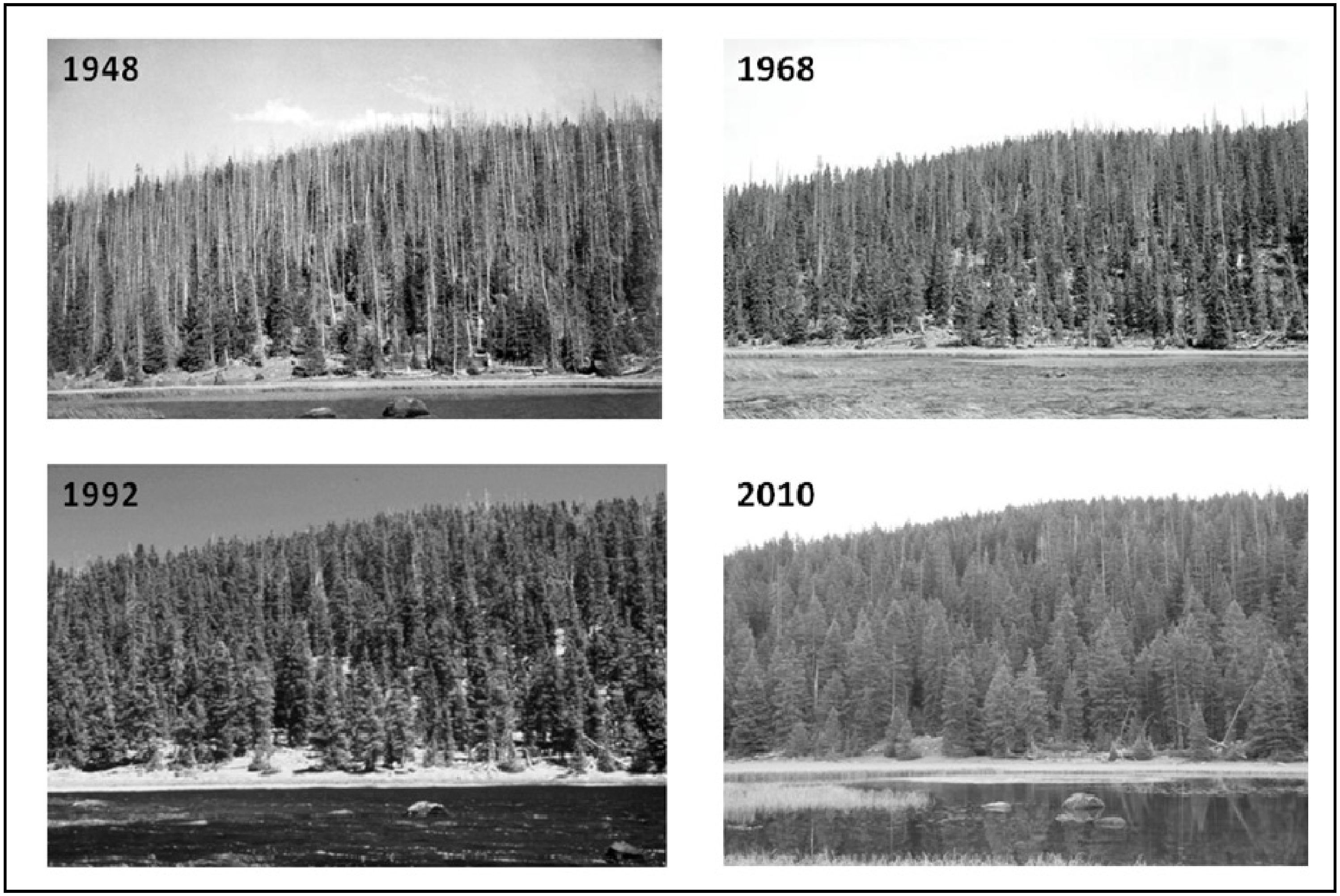

Figure 10. Repeat photographs of the north-facing slope above Purple Lake on the Aquarius Plateau, UT. The first photo was taken shortly after an epidemic spruce beetle outbreak which caused extensive mortality in the Engelmann spruce. Subsequent photographs show the forest regeneration and re-establishment of the forest canopy.

and blue spruce, with aspen present in areas of windthrow disturbance, and in one conspicuous fire-disturbed area located on the northeast slope of the watershed that burned in AD 1993 (USFS, unpublished data). Subalpine fir is rare in the Purple Lake watershed. Livestock grazing was observed around all lakes during the AD 2007 and 2010 field campaigns. Examination of historical photographs from Purple Lake reveals a severely denuded landscape in AD 1902 (Fig. 11), suggesting that the summer rangelands on the AqP experienced heavy domestic and wild ungulate grazing similar to other High Plateaus in Utah (Hall, 2001; Gill, 2007). Small-scale logging activities occurred during the 1970s around Banana Lake where Engelmann spruce was harvested for mining props (USFS, unpublished data).

The Donkey Reservoir SNOTEL station (38˚ 13' N, 111˚ 29' W, 2987 m elevation) provides a continuous temperature and precipitation record for the subalpine zone of the AqP since AD 1985 (Fig. 12). The AqP experiences a considerable annual range of temperatures with cold winters averaging -7 C˚ and brief, mild summers averaging 15 C˚. Precipitation is bimodal with a peak in late summer precipitation from convective thunderstorms enhanced by orographic uplift and a second peak in the spring from Pacific frontal storms (Mock, 1996; Shinker, 2010). Summer precipitation in this region has been described as 'monsoonal,' (Shafer, 1989; Anderson et al., 1999), with enhanced moisture as elevation increases (Tang and Reiter, 1984). The AqP occurs south of ≈42˚ ENSO precipitation dipole and is anomalously wet (dry) during El Niño (La Niña) events. La Niña episodes on the AqP are associated with more frequent fire occurrence (Brown et al., 2008). Modeled conditions for La Niña and negative-phase PDO in south-central Utah suggests extreme droughts (high Palmer Drought Severity

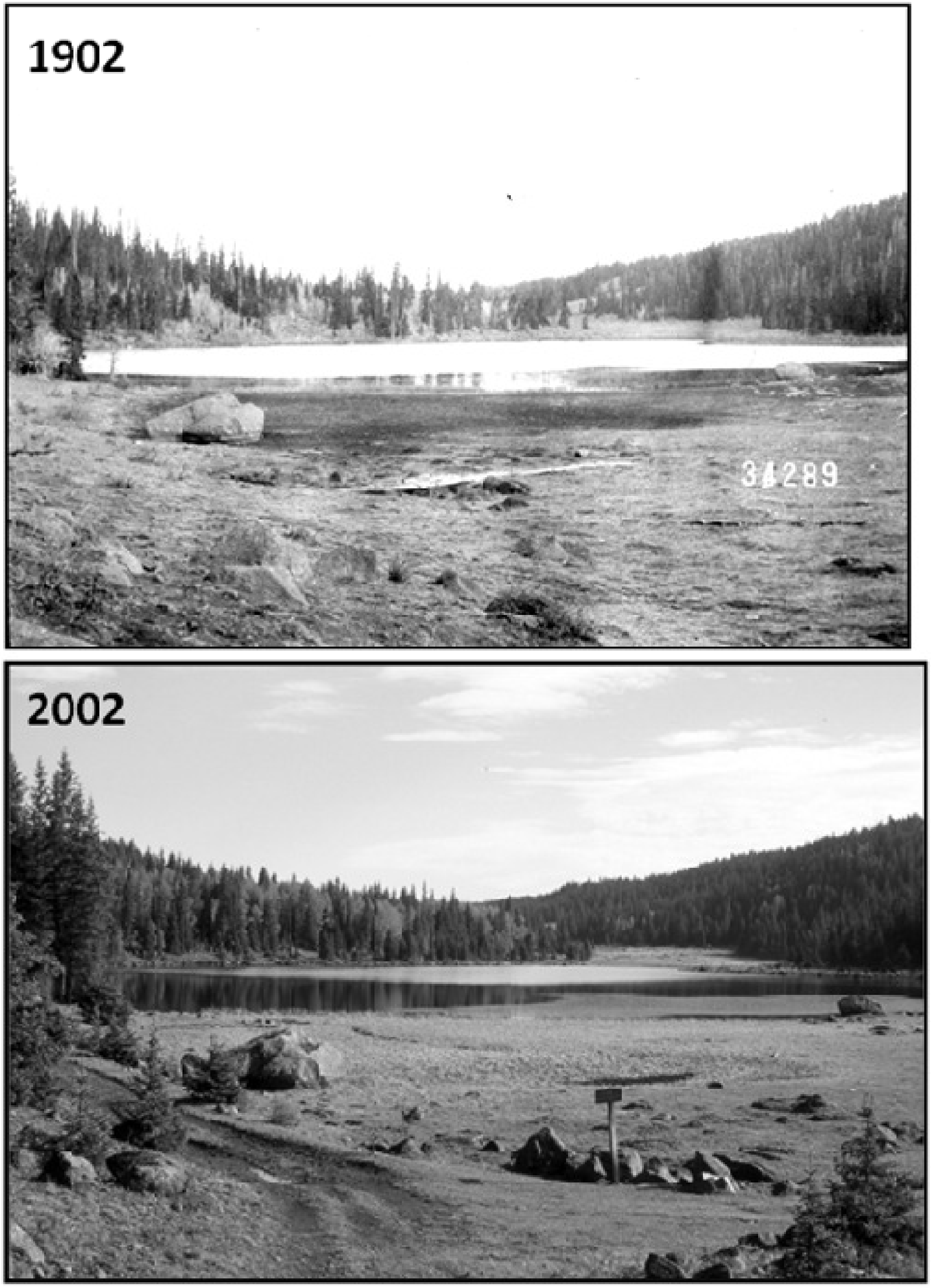

Figure 11. Repeat historical photos of Purple Lake looking to the northeast in 1902 and 2010. The lake margin in the early photograph depicts removal of vegetative cover from livestock grazing and recovery of the herbaceous community in the latter photo.

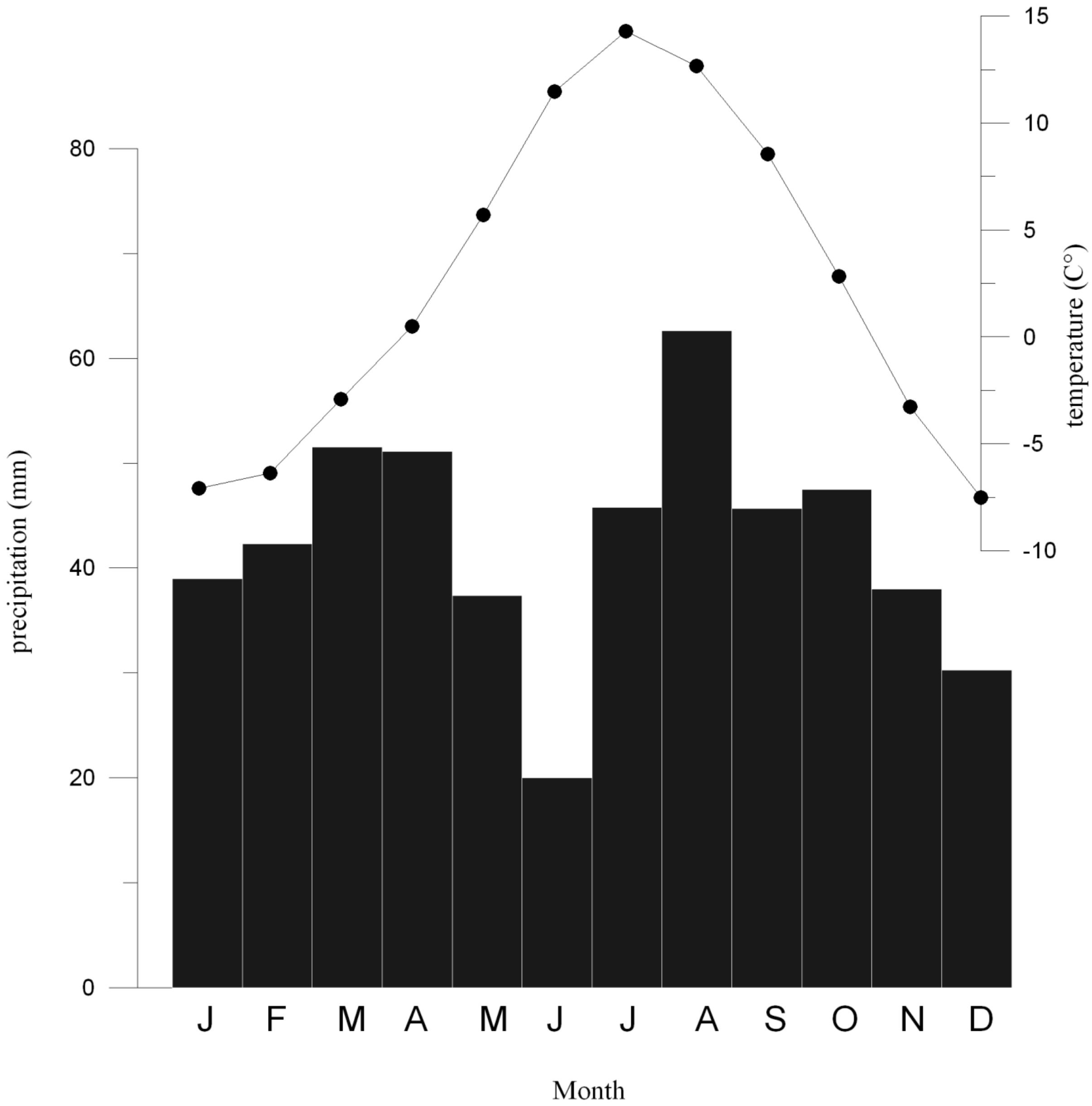

Figure 12. Climagraph constructed from the Donkey Reservoir SNOTEL station depicting mean monthly precipitation and temperature data since AD 1985. The Aquarius Plateau exhibits a bimodal precipitation regime with a late summer peak and a secondary peak in the spring.

Index (PDSI)) and large potential for increased fire occurrence (Schoennagel et al., 2005). This La Niña-fire relationship is generally indicative of the climate-fire relationship at low-elevations in the SW (Westerling and Swetnam, 2003) and in the subalpine zone of the central Rocky Mountain (Schoennagel et al., 2007).

Forest disturbance is an important consideration in hydrology, though it is often overlooked. Forest disturbances change hydrologic cycles through the removal of tree canopy, which in turn affects snow storage. In the western US, climate variability is often of paramount interest because of the clear implication for regional water budgets. The Colorado River is recharged annually by melting snowpack which accumulates in the subalpine zones of western Colorado and Utah. These subalpine areas represent only 15% of the surface area of the Colorado River basin yet contribute 85% of the total streamflow (Stockton and Jacoby, 1976; Hidalgo and Dracup, 2003). Landscape-scale fire and bark beetle disturbances in this region are historically infrequent, but are often severe when they do occur (Romme and Despain, 1989; Veblen et al., 1994; Dymerski et al., 2001; Matthews et al., 2005; DeRose and Long, 2007) and alter streamflow and water quality (Troendle and Bevenger, 1996). Elevated suspended sediment loads (Clark, 1998; Benavides-Solorio and MacDonald, 2001, 2005) increase annual water yield by 25-35% (Love, 1955; Potts, 1984), and peak streamflow is advanced by two to three weeks (Bethalamy, 1974, 1975) following landscape-scale disturbances in the subalpine zone. Bark beetle epidemics are currently occurring at historically unprecedented spatial scale (Logan and Powell, 2001). Wildfire and insect outbreaks are projected to increase in frequency and severity over the coming century on susceptible landscapes (Westerling et al., 2006; Raffa et al., 2008; Bentz et al., 2010; Turner et al., 2010). Thus, disturbance/hydrology relationships, specifically in critical watersheds, should be thoroughly evaluated.

Methods

Field Methods

Sediments used in this study were collected from Banana and Purple Lakes in August 2007. Both lakes were cored from a platform anchored over the deepest area of the lake to ensure maximum sediment focusing. Short cores were collected with a plexiglass tube outfitted with a piston to capture the unconsolidated sediment-water interface, which were then subsampled in the field at 1 cm increments. Long cores were collected with a modified Livingstone piston coring device and cores were extruded, wrapped in plastic wrap and aluminum foil, and then secured in wooden boxes for transport to the lab. One 87 cm short core (BaL07A) and one 2.4 m long core (BaL07B) were retrieved from Banana Lake in 3 m of water. Data from the upper 24 cm of BaL07A represent the historic period (AD 1850 to present) and are presented here. One 71 cm short core (PL07A) and one 2.87 m long core (PL07B) were collected from Purple Lake in 5 m of water. Data from the upper 24 cm of BaL07A and PL07A represent the historic period (AD 1850 to present) and are presented here. Data covering the last 8,600 cal yr BP from PL07B are also presented and discussed. Sedimentary pollen sequences from Posy Lake were analyzed by Shafer (1989), who then submitted pollen data to the North American Pollen Database (NAPD) (Grimm et al., 2000; www.ncdc.noaa.gov/paleo/napd.html). The Posy Lake data were accessed and downloaded in January 2011.

<u>Laboratory and Analytical Methods</u>

Chronologies for the historic sediments were achieved by analyzing the upper 24 cm of the short core profiles for ^{210}Pb / ^{137}Cs (Table 3). Samples were weighed and then dried in a muffle furnace at 100° C to remove water. Dehydrated samples were submitted for analysis to Dr. James Budahn at the USGS Laboratory in Denver, CO. The ^{210}Pb record was interpreted using 1963 as the peak in ^{137}Cs associated with climax of atmospheric detonation of nuclear test weapons. The upper cm was assigned to the year of core retrieval. Short core sediments were linked to long core segments by matching discrete peaks in charcoal accumulation. Accelerator mass spectrometry (AMS) ^{14}C dates were obtained from four shultzed pollen samples for PL07B and submitted to the Center for Applied Isotope Studies at the University of Georgia for analysis. AMS results were converted from ^{14}C years to Calendar Years before Present (Cal yr BP) using the Calib 6.0 software package (Reimer et al., 2009). Depth-age relationships for Purple Lake and Posy Lake were developed using smoothing spline, calculated in "R" using a script developed by Dr. Patrick Bartlein at the University of Oregon (Fig. 13).

Magnetic susceptibility (MS) data were collected for every contiguous cm of PL07A and PL07B to assess ferromagnetic mineral content of the sediments. Peaks in MS are associated with increased runoff and erosion from landscape disturbances like logging and fire (Gedye et al., 2000). MS properties of PL07A sediments were assessed using 10cc cups in the Bartington coil sensor and MS was performed on PL07B by placing long cores end to end and analyzed using a Bartington ring sensor.

Table 3. Uncalibrated and calibrated ages for Purple, Banana, and Posy Lake sediment cores.

Depth (m)[a]	Assigned age (cal yr BP)[b,c] Banana Lake	Purple Lake	Upper age range (cal yr BP)	Lower age range (cal yr BP)	^{14}C age (^{14}C yr BP)	+/-	Material dated	Analysis[d,e]
0,00	-57	-57					sediment	^{210}Pb
0,02	-53	-53					sediment	^{210}Pb
0,04	-44	-44					sediment	^{210}Pb
0,06	-35	-33					sediment	^{210}Pb
0,08	-25	-21					sediment	^{210}Pb
0,10	-13	-13					sediment	^{210}Pb
0,12	5	-8					sediment	^{210}Pb
0,14	27	-3					sediment	^{210}Pb
0,16	39	6					sediment	^{210}Pb
0,18	51	23					sediment	^{210}Pb
0,20	74	39					sediment	^{210}Pb
0,22	107	54					sediment	^{210}Pb
0,24	136	99					sediment	^{210}Pb
0,68		2141	2186	2096	2160	25	pollen	^{14}C AMS
1,19		4355	4424	4285	3920	25	pollen	^{14}C AMS
1,97		7740	7799	7680	6920	30	pollen	^{14}C AMS
2,76		8650	8721	8579	7852	27	pollen	^{14}C AMS

[a] Depth below mud-water interface.
[b] ^{210}Pb dates were adjusted to reflect a 2007 coring date (from 1950).
[c] ^{14}C ages were calibrated (two sigma error) using Calib 6.0 (Reimer et al. 2009) and ages assigned as upper/lower range midpoint.
[d] ^{210}Pb ages from US Geologic Survey in Denver, Colorado by James Budahn.
[e] ^{14}C AMS dates provided by the Center for Applied Isotope Studies at the University of Georgia by Douglas Dvoracek.

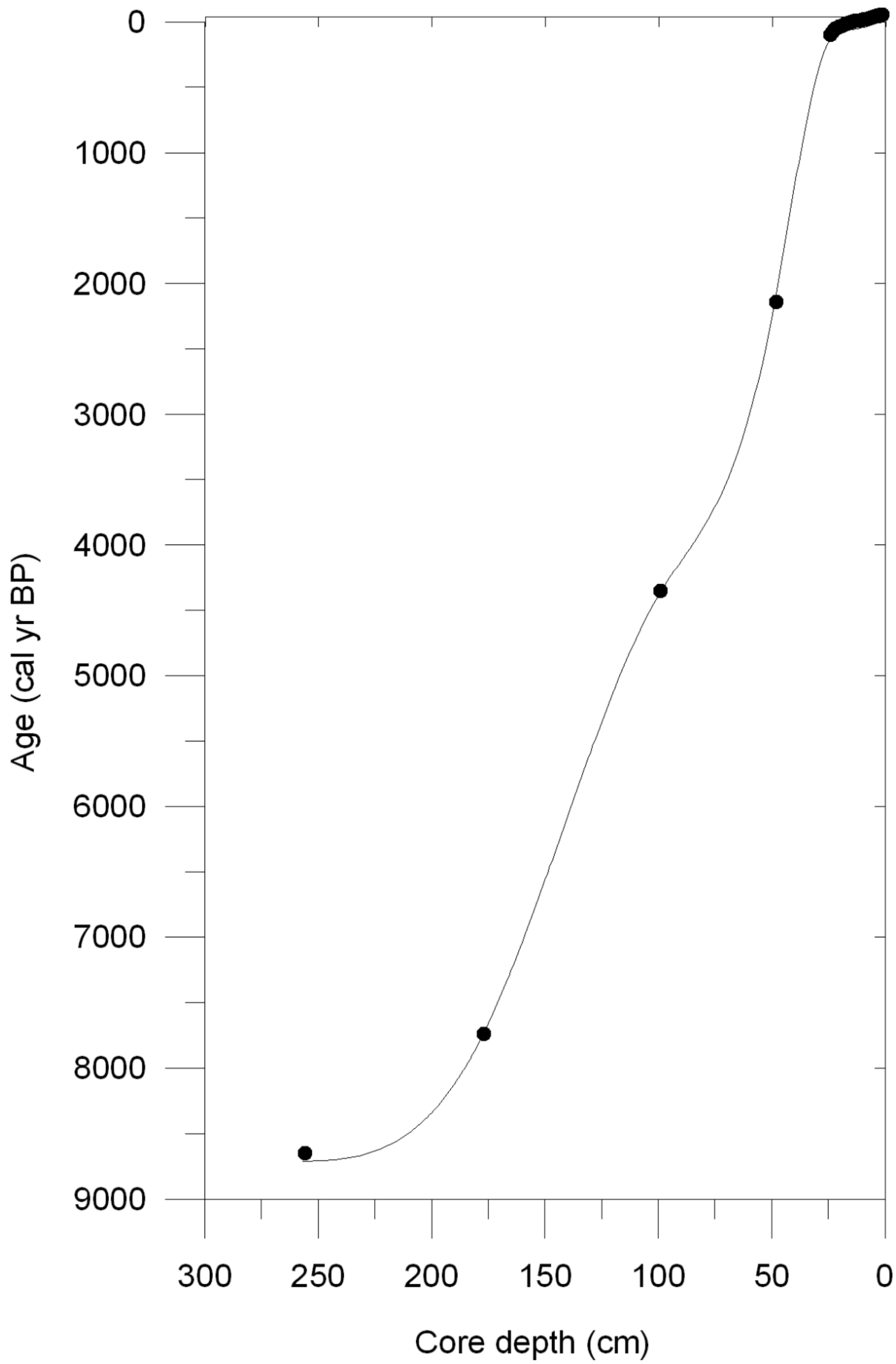

Figure 13. Age/depth relationship for Purple Lake.

Loss-on-ignition (LOI) analysis was performed on 1 cc samples collected from every contiguous cm from PL07A and at 8-cm intervals for PL07B to calculate organic and carbonate ($CaCO_3$) content of the sediment. Determination of organic and carbonate content was achieved by ignitions at 550° and 900° C, respectively, for 2 hours (Dean, 1974).

Pollen samples (1 cc) were processed at 1 cm intervals for the upper 24 cm for Purple Lake and Banana Lake following methods described by Faegri et al. (1989). *Lycopodium*, an exotic spore, was introduced to each sample during processing as a tracer. Slide-mounted pollen samples were examined using light microscopy at 500 X and counted to a minimum of 300 terrestrial grains. Grain identification was aided by laboratory reference collections and relevant dichotomous keys and literature (Erdtman, 1952; Bassett et al., 1978; Kapp et al. 2000).

Ratios of spruce to fir, sagebrush to saltbush plus greasewood (AC ratio, *Artemisia*: Chenopodiaceae+*Sarcobatus*), and sagebrush to ragweed (ArtAm ratio, *Artemisia*:*Ambrosia*) were calculated using a technique applied by Maher (1963, 1972) and others (Mensing et al., 2008). AC ratio and ArtAm ratio are useful in assessing general moisture conditions (positive AC ratio suggests wetter annual conditions) and precipitation seasonality (positive ArtAm ratio suggests greater summer moisture).The formula used here is (a-b)/(a+b) and ratio data are presented in standard units (SU). The ratio of spruce (host) to fir (nonhost) was useful in characterizing known changes in stand conditions during historic SB epidemics on the Wasatch Plateau, UT (Morris et al., 2010) and the White River Plateau, CO (Anderson et al., 2010). The spruce:fir ratio is robust across numerous sites in Utah during historic SB outbreaks (Chapter 2).

Samples for charcoal and macrofossil analysis (5-10 cc) were collected and analyzed for the upper 24 cm of each core and using techniques described by Whitlock and Millspaugh (1996). Sediments samples were screened using 125 µm and 250 µm nested sieves. Retrieved materials were placed on gridded petri dishes and then examined and counted using light microscopy at 40x. These size fractions were selected because modern studies have shown that large particles do not travel far from their source and most likely represent a local, watershed-scale fire history (Clark, 1988; Gardner and Whitlock, 2001).

Charcoal counts for each sample were converted to concentration (particles cm-1) and then calculated as influx. To minimize variations in the record that might arise due to changes in sediment deposition rates, the concentrations were binned using the median sediment deposition time (27 years). Newly binned concentrations were then converted to charcoal accumulation rates (CHAR, particles cm-1 yr-1) and decomposed into background and peak components (Higuera et al., 2009; http://CharAnalysis.googlepages.com). Background is defined as the slowly varying trend in CHAR as a primary result of changes in fuel abundance and vegetation composition (Marlon et al., 2006). Peaks, which are positive deviations from the background CHAR, are interpreted as input of charcoal originating from a fire episode. Peaks were determined using a Lowess smoother which is robust to outliers within a 500-year window width (Higuera et al., 2010). The background values for each time interval were then subtracted from the total CHAR accumulation for each interval. The peaks in the charcoal record (i.e., intervals with CHAR values above background) were tested for significance using a Gaussian distribution, where peak CHAR values that exceeded the

95th percentile were considered significant. This procedure was applied for every 500-year overlapping portion of the CHAR record producing a unique threshold for each sample. Once identified, all peaks were screened to eliminate those that resulted from statistically insignificant variations in CHAR (Gavin et al., 2006). If the maximum count in a CHAR peak had a >5% chance of coming from the same Poisson distribution population as the minimum charcoal count within the proceeding 75 years, then the peak was rejected (Higuera et al., 2010).

Results and Discussion

Early to Middle Holocene (9,000-6,000 cal yr BP)

The pollen assemblage of the AqP suggests forests dominated by spruce (25%) and pine (30%), with fir also locally present (4%) (Figs. 14a and 14b). Aspen pollen is low (1-2%) and herbaceous pollen is high during this period, including grasses (17%) and sedges (4%), as well as mustard (Brassicaceae) (2%), bean (Fabaceae) (2%), and buckwheat families (Polygonaceae) (1-2%). Mesophytic shrubs, including cattails (*Typha*), willows (*Salix*), and meadow rue (*Thalictrum*) are similarly abundant (2-3%) within the record. The abundance of these herbaceous and shrub components suggest ample available growing season moisture and openings within and between the forest canopy (Thompson et al., 1999). Corresponding increases in organic content at Purple Lake are evident in the LOI data (Fig. 15). Higher organic LOI values support growing season conditions conducive to plant growth (adequate moisture). Pollen and packrat midden data from the Colorado Plateau generally support interpretations indicating

a)

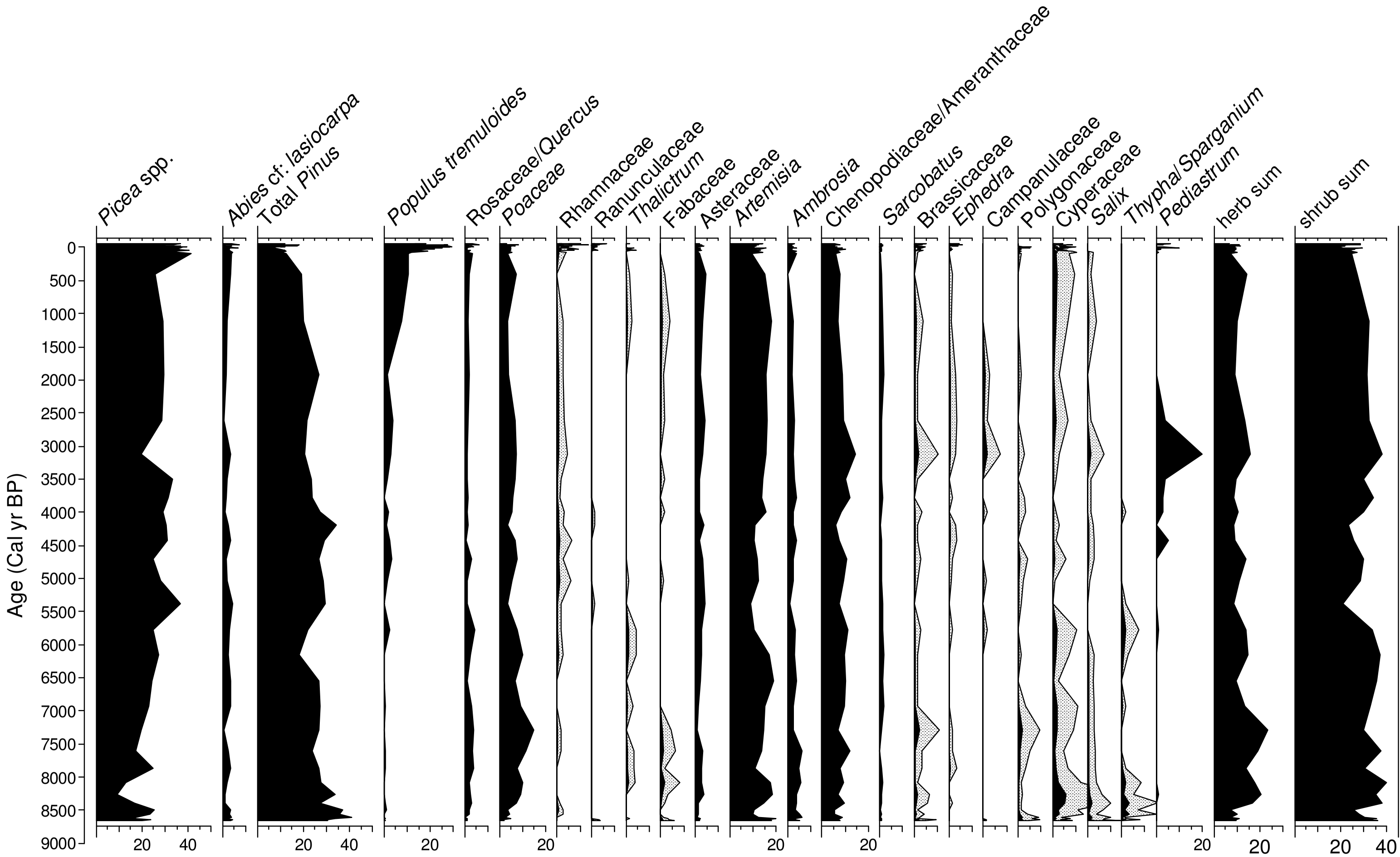

Figure 14. Pollen percentage sequence for a) Purple Lake and b) Posy Lake covering the last 9,000 cal yr BP.

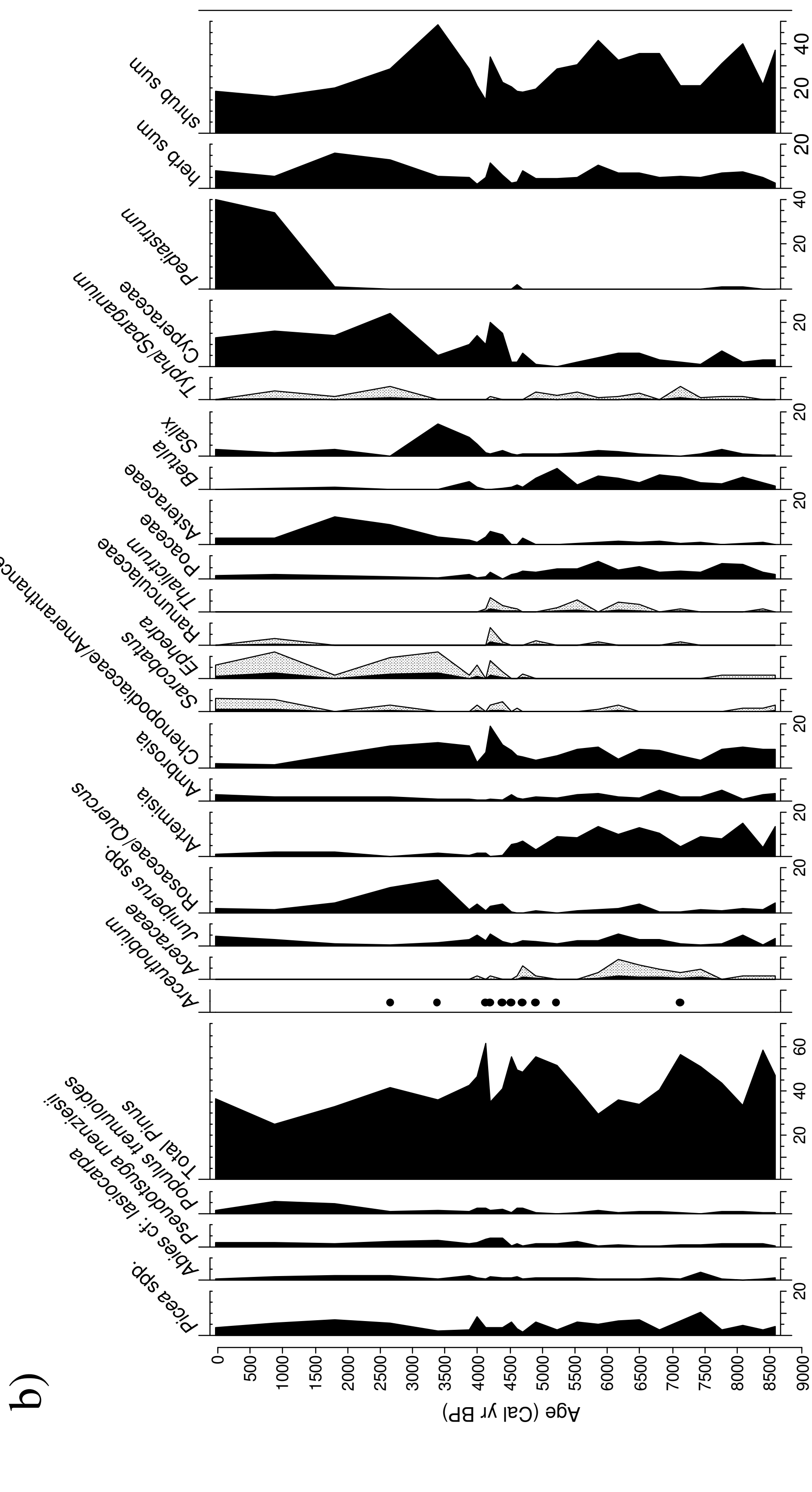

Figure 14. Continued

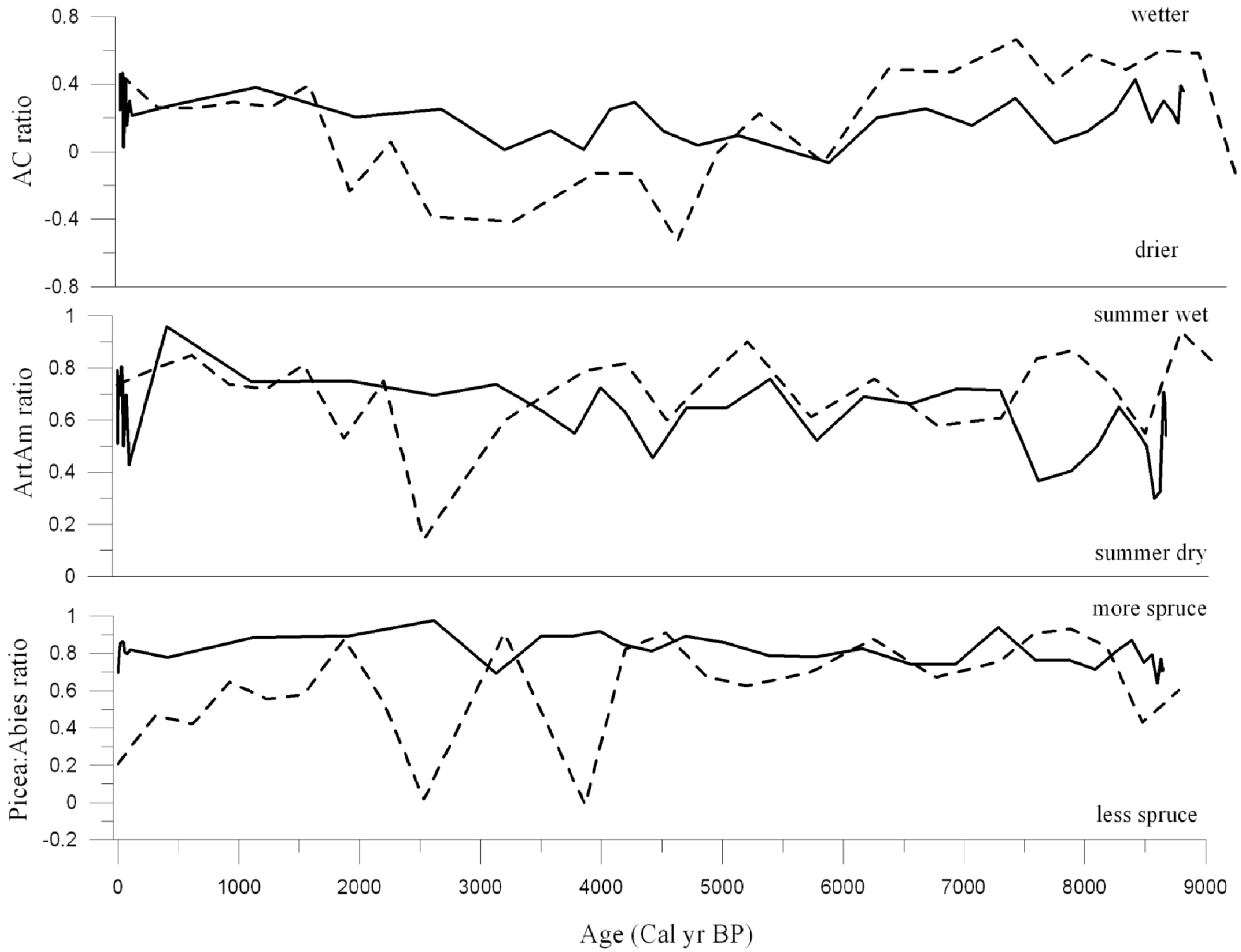

Figure 15. Pollen ratios for key taxa suggesting for Purple Lake (solid line) and Posy Lake (dashed line).

additional growing-season moisture region at 9,000 cal yr BP (Mock and Brunelle-Daines, 1999)as do lake records from the eastern Great Basin (Anderson et al., 1999; Weng and Jackson, 1999).

Seasonal temperature extremes were amplified during the early Holocene, driven by insolation anomalies (Berger and Loutre, 1991; Kutzbach et al. 1998), with summers in western North America generally warmer-than-present and winters cooler-than-present. Proxy and model data suggest that annual temperatures were 1-2° C warmer than modern across western North America and that summer temperature anomalies were greater than winter (Diffenbaugh and Sloan, 2004). Greater-than-present summer heating would cause early snow melt with spring and fall precipitation occurring as rain instead of snow, and supporting convective thunderstorm activity during summer months. At ca. 8,600 ka, perennial lakes developed on the southern margin of the AqP indicated by roughly coincident bottom dates for Purple and Posy lakes (Table 3). Because lake level is driven by snowpack (Friedman et al., 2002; Dutton et al., 2005), winter snowfall amounts probably started to increase around this time compared to the late Pleistocene/earliest Holocene.

Because the ArtAm and AC ratios reflect moisture availability, positive values for ArtAm and AC ratios at both AqP sites (Fig. 15) suggest generally abundant annual and growing season moisture. Greater-than-previous summer moisture throughout the SW was probably due to enhanced convective and orographic storms triggered by high summer insolation (Kutzbach et al., 1998; Mock and Brunelle-Daines, 1999). Ample growing season moisture is also implicated in altitudinal migration of conifers in western

Colorado where lower timberline migrated downslope (Petersen and Mehringer, 1976; Fall, 1997). Lower timberline boundary is limited by available growing season moisture and moves down in elevation in response to increasing moisture. The spruce:fir ratio at both Purple and Posy Lakes indicates spruce was abundant in both watersheds.

Fire activity during this period suggests lengthening of fire season from high summer insolation triggering rapid spring snow melt and warm summer conditions. Anderson (2011) suggests greater abundance of rain relative to snow during this period and Mock and Brunelle-Daines (1999) indicate greater-than-modern growing season moisture at 9,000 cal yr BP. Convective storms in late summer increase potential for lightning-ignited fire occurrence (Westerling et al., 2006). Fire return intervals from 9,000-6,000 cal yr BP are the lowest of the record (most frequent fires), averaging ca. 200 years between fire episode peaks (Fig. 16). Background CHAR exhibits variability over the Purple Lake record (between 0.25 to 0.0 pieces/cm-2/yr-1) and the early to middle Holocene period ranges between 0.2 and 0.1 cm-2 yr-1. Peak magnitudes are the highest during this period, ranging between 40 and 15 pieces-2/peak-1. Magnetic susceptibility appears unresponsive to fire over the Holocene and might be indicative of soil development processes (Fig. 17).

High pine pollen at Purple and Posy lakes is probably related to fire activity during this period. Pollen sequences from Purple and Posy lakes indicate that pines (probably limber pine, but possibly bristlecone) was a large forest component in these watershed (32%) during the early-middle Holocene, albeit only slightly greater than the Holocene average (27%). In the Purple Lake record, an abundance of limber pine would

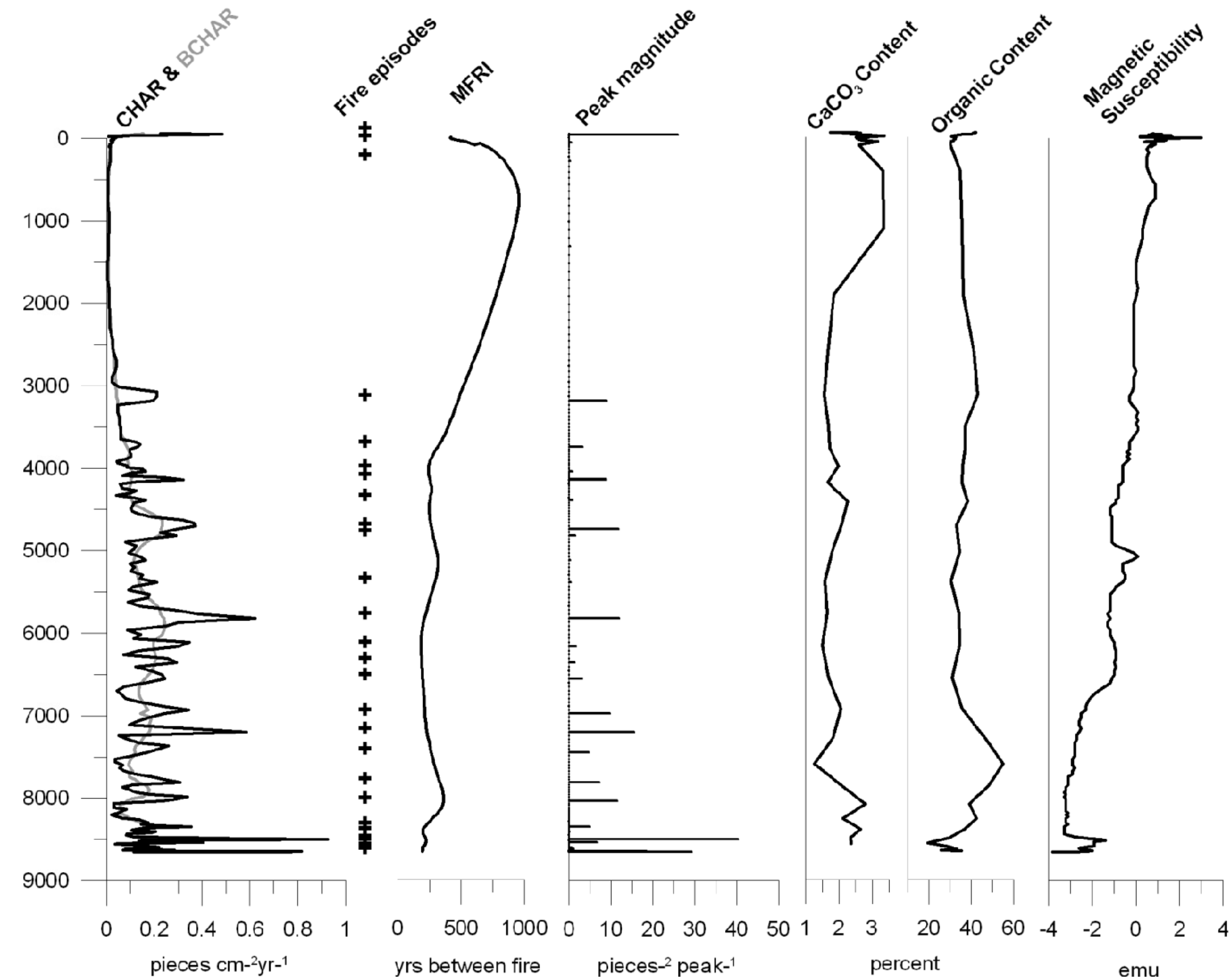

Figure 16. Charcoal, magnetic susceptibility and loss-on-ignition data for Purple Lake.

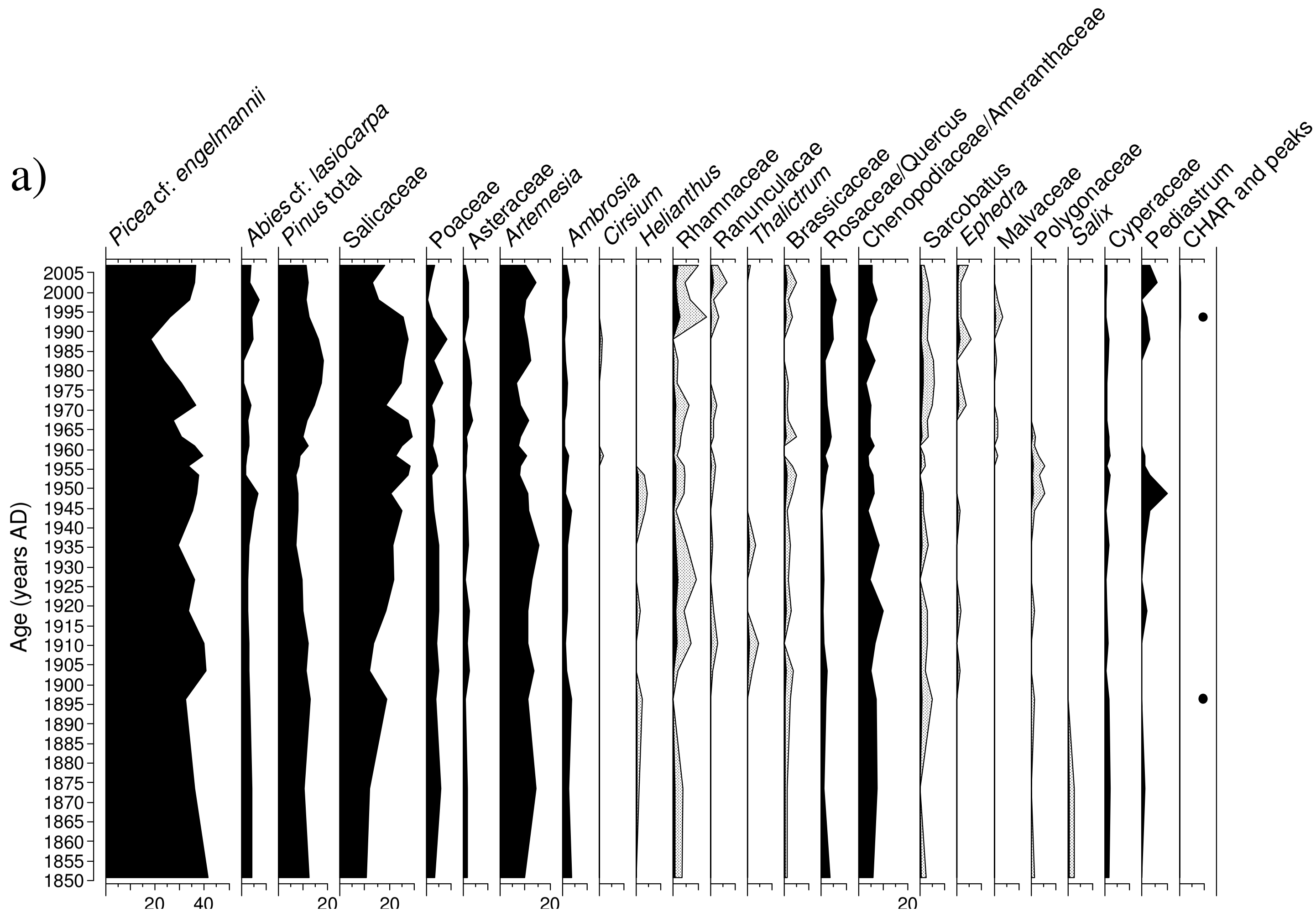

Figure 17. 20th century pollen sequence for Purple Lake and Banana Lake . A spruce beetle outbreak occurred in the watershed during the AD 1920s and 1930s. A fire also occurred on the northeast slope (south-facing) in AD 1993.

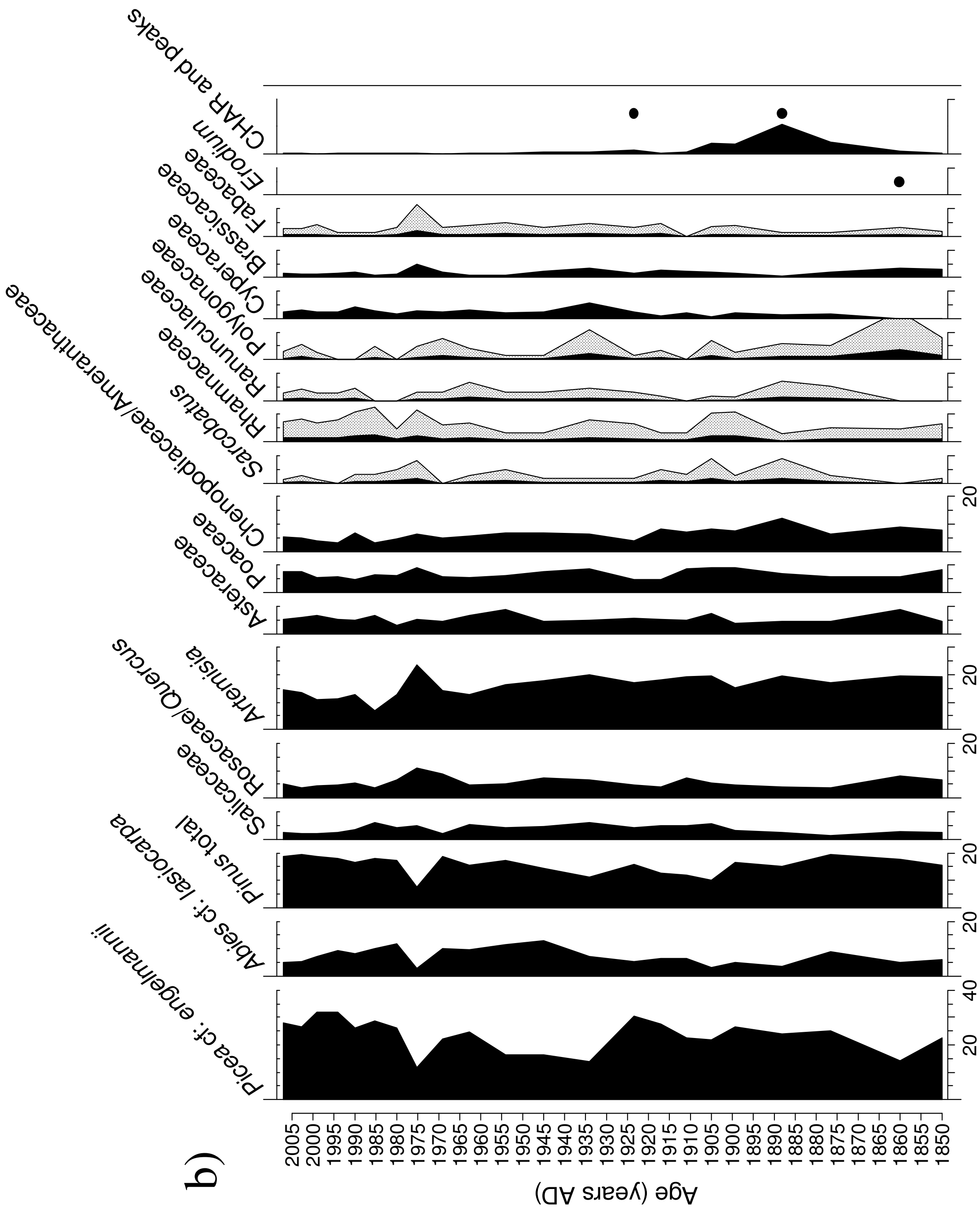

Figure 17.Continued

be consistent with fire disturbance because limber pine establishes more readily than other subalpine competitors following fire (Peet, 1981), whereas limber pine is a poor competitor in closed canopy forests when fire is infrequent (Peet, 1981; Youngblood and Mauk, 1985).

Examining spruce pollen and using spruce:fir pollen ratios provides evidence of nonfire disturbances (SB) (Chapter 2) known to affect forests on the Aquarius Plateau (Mielke, 1950). Spruce and fir were present in these watersheds during the early to middle Holocene; however, spruce pollen exhibits an abrupt decline at 8,200 cal yr BP, decreasing from 27% to10% (Fig. 14a). The spruce:fir ratio is complacent, which is probably due to the residual spruce (blue and/or Engelmann spruce) abundance Purple Lake over fir at this site. This distinctive decrease in spruce percentages is consistent with modern palynological representations of a large-scale spruce beetle epidemic (Morris et al., 2010; Anderson et al., 2010). Feiler et al. (1997) and Anderson et al. (1999) discuss the possibility of a landscape-scale spruce beetle outbreak in western Colorado at this time and Brunelle et al. (2008) note mountain pine beetle presence in the north Rockies around 8,200 cal yr BP. The AqP records suggest a synchronous climate forcing mechanism for a bark beetle infestation for the interior subalpine ranges of western North America at this time.

<u>Middle Holocene (6,000-3,000 cal yr BP)</u>

The mid-Holocene pollen sequence at Purple and Posy lakes indicates continued local dominance of spruce and fir with a pine component (Figs. 15a and 15b). Percentage values of spruce and fir are essentially unchanged from the early to middle Holocene, though spruce pollen increases slightly to 35% and remains near this percentage throughout the remainder of the record. Aspen pollen also rises to 3-5%, indicating that it is locally present. The spruce:fir ratio becomes more negative (i.e., less spruce) at Purple and Posy lakes than elsewhere in the record, which is consistent with observation from historic beetle outbreaks (Chapter 2) but could be indicative of spruce mortality from drought (Fig. 15) (Bigler et al., 2009). Mistletoe (*Arceuthobium*) is present a Posy Lake during this period (Fig. 14b) so it is plausible that a disturbance complex (*sensu* Whitlock et al., 2010) could be responsible for the spruce declines; however, more supporting evidence is required to strengthen this interpretation.

Beginning at ca. 6,000, the Purple Lake and Posy Lake herb and shrub pollen assemblages declined in response to decreasing water table levels from increasing winter aridity (Figs. 15a and 15b). Percentage of organic material in the lake also decreases as indicated in the LOI profile (Fig. 17). Mesophytic herbaceous pollen, including grass and sedges decrease, and shrubs and aquatic taxa preferring moist soil conditions, such as meadow rue, sedge, and cattail become absent or rare. Pollen of drought-tolerant subalpine shrubs, such as buckbrush (Rhamnaceae), becomes more prominent and desert shrub taxa including sagebrush, mormon tea (*Ephedra* spp.), and goosefoot are similarly elevated (Figs. 15a and 15b) (Thompson et al., 1999). AC ratio suggest that annual conditions were generally drier, while AA ratio suggests that summer precipitation was ample and growing season conditions were similar to the early to middle Holocene (Fig. 16). The AC ratio is decreased in response to persistent La Niña circulation patterns (Shin et al., 2006), causing low snow pack yields (Hidalgo and Dracup, 2003). Pollen reconstructions in the eastern Great Basin and central Rocky Mountains generally have been interpreted as reflecting warm and dry conditions during the middle Holocene (Madsen and Currey, 1979; Fall, 1997; Feiler et al., 1997; Weng and Jackson, 1999).

Other records suggest that effective moisture was essentially unchanged (Mock and Brunelle-Daines, 1999) and that summers were warm and wet during this period (Anderson et al., 1999). Our record supports the latter interpretation. Annual hydrological conditions were probably drier than both the early and late Holocene. However, summer conditions were wet due to convective summer storm activity promoted by peak temperature, as noted in the eastern Great Basin (Reinnemann et al., 2009). Changes in mid-Holocene winter precipitation affected lake levels on the Aquarius Plateau because lake level is controlled by snowpack (Dutton et al., 2005). *Pediastrum* increases to its highest values observed during the middle Holocene at Purple Lake (Fig. 15a) though high *Pediastrum* values do not occur until around 3,000 cal yr BP at Posy Lake (Fig. 15b). *Pediastrum* is responding differently to hydrological conditions in these basins which probably reflect incongruence in water depth and bathymetry among the basins. The decline of some mesophytic taxa in the mid-Holocene pollen assemblages at Purple Lake (Fig. 15a) is particularly evident in aquatic plants (sedge, willow, and cattail) and herbaceous taxa (meadow rue) that prefer saturated soils, suggesting that their declining values are probably related to decrease water table height which is ultimately controlled by winter snowpack (Dutton et al., 2005) rather than growing season precipitation. However, the fact that Purple Lake and Posy Lake did not desiccate during the mid-Holocene (as they both did prior to 8,600 cal yr BP) suggests winter precipitation in mid-Holocene was sufficient to recharge these lakes (albeit at lower lake levels). Persistent La Niña conditions in the Pacific Ocean between 6,000 to 4,000 cal yr BP were probably responsible for decreases in winter precipitation and therefore lower water table and lake levels on the Aquarius Plateau (Moy et al., 2002; Shin et al., 2006; Asmerom et al., 2011; Barron and Anderson, 2011).

Considering inferred low snowpack yields during winter (Shuman et al., 2009) and peak temperature in the region (Reinnemann et al., 2009), in order for growing season proxy data to suggest unchanged effective moisture (Mock and Brunelle-Daines, 1999), summer precipitation had to be considerably higher. The Escalante River, with its headwaters on the Aquarius Plateau, experienced large magnitude flood events during the middle Holocene (Ely, 1997). Though interpretations of seasonality are problematic in many paleo-flood reconstructions, historic observations of flood events in the Escalante River drainage are attributed to intense late summer thunderstorms (Ely, 1997), suggesting that episodes of summer precipitation during the mid-Holocene was particularly intense on the AqP. Fire and bark beetle disturbances are known to decrease interception of precipitation which enhances surface runoff and erosion during intense storm events (Troendle and Bevenger, 1996). The paucity of charcoal during the mid-Holocene suggests that fire episodes were infrequent with relatively small peak magnitudes (Fig. 17) which is consistent with particularly intense summer rainfall that would bring ignition (lightning) but also considerable moisture. Alternatively, the spruce:fir ratio at Posy and Purple lakes (Fig. 16) between 4,000 and 3,000 suggests SB or a similar nonfire disturbance, which would enhance surface runoff and down gradient flood events observed by Ely (1997; Troendle and Bevenger, 1996).

Summer insolation (Kutzbach et al.,1998) and temperature (Reinnemann et al., 2009) continued to decline towards the end of the mid-Holocene. In western Colorado, cooling summer temperature forced upper timberline to move downslope (Petersen and Mehringer, 1976; Fall, 1997). Beginning after 4,000 cal yr. BP, increases in winter snowpack are suggested at Bison Lake in western Colorado (Anderson, 2011) probably due to increasing frequency and amplitude of El Niño events (Clement et al., 2000; Moy et al., 2002; Barron and Anderson, 2011). On the AqP, the AC ratio indicates annual conditions are still relatively dry in the context of the record, despite high (or at least similar to the early to middle Holocene) summer precipitation inferred by the ArtAm ratio (Fig. 16). These pollen ratios suggest that snow accumulation was still relatively low and summer precipitation high.

Over the entire Purple Lake record, fire return interval, fire peaks, background CHAR, and peak magnitude generally decrease towards modern. Through the middle Holocene, 200-300 years between fire episodes are typical, though an increasing interval between fire episodes initiates at ca. 4,000 cal yr BP. Background CHAR ranges between 0.1 and 0.2 and similarly declines to 0.0 over this period. Peak magnitude does not exceed 10 pieces-2 peak-1, though several episodes do reach this magnitude. The middle Holocene fire record is similar to the early to middle Holocene period in terms of frequency, though peak magnitudes are not as great. This could be due to more frequent, intense summer precipitation events during the mid-Holocene summers which provide greater incidence of ignition only to be suppressed by intense rainfall. The rise in aspen pollen in the mid-Holocene suggests that aspen clones became established and probably played a greater role in postdisturbance forest succession. No spruce beetle outbreaks were inferred during this period for Purple Lake; however, one potential outbreak is evident in the Posy Lake record ~3,800 cal years BP.

Late Holocene (3,000 cal yr BP – AD 1850)

At Purple and Posy lakes during the late Holocene, spruce and fir pollen are broadly consistent with previous periods (25% and 4%; 11% and 3%, respectively), while declining pine percentages (30% to 10%; 40% to 20%, respectively) and increasing aspen percentages (to ca.10% at both sites) are apparent. Mesophytic taxa including sedges, meadow rue, and willows return to similar values observed during the early-middle Holocene, suggesting rising water tables from increasing snowpack. Increasing snowpack is supported by the AC ratio indicating an increasing trend to wetter annual hydrological conditions during this period (Fig. 16). Similarly, the long-term gradual, declining trend in spruce:fir ratio at Posy Lake probably reflects greater abundance of and more persistence snowpack (Alexander, 1984; Fall, 1997). Buckbrush pollen gradually declines, approaching near zero values ca. 800 cal yr BP. Grass pollen increases slightly and remains around 10% (3% at Posy), while the bell flower family and mustards increase slightly (1-3%) at Purple Lake. Desert shrub taxa exhibit little variability and remain at or near middle Holocene values at Purple Lake, though both goosefoot and sagebrush decrease towards modern at Posy Lake. The late Holocene pollen assemblage at Purple Lake record suggests elevated growing season soil moisture because grass, sedges, and meadow rue percentages increase. Similarly, increases of sedges, cattail, alders, and willows at Posy Lake suggest moist soil conditions consistent with an interpretation of a rising water table.

The late Holocene at Purple Lake is noteworthy for the absence of background CHAR and peak episodes (Fig. 16). Subdued fire activity is probably due to an interaction of variables that adversely affect conditions associated with wildfires. This may include snowpack persisting into summer months, greater effective moisture from higher water table, fuel and soil moisture conditions that are inadequate to promote fire, and weather conditions not suitable for stand-replacing wildfire (Bessie and Johnson, 1995; Baker, 2000; Veblen, 2003). Knight et al. (2009) using tree-ring records from mid-montane (≈2,000 m) forests on the Tavaputs Plateau (≈250 km north of the AqP) note moisture conditions were intermittently wet/dry at around 2,000 cal yr BP to modern, suggestive of ENSO. It is likely that the subalpine forests on the AqP, due to its relatively high elevation, accumulated greater amounts of and more persistent snow pack, and experienced only relatively brief periods of moisture deficits conducive to fire during the late Holocene.

As noted by Veblen (2000) and Baker (2003), even though fuel may be abundant in subalpine spruce-fir forests, fire occurrence is limited to circumstances of extremely dry conditions. Weather and climate are especially important in fire occurrence and severity in mesic coniferous forest (Brotak and Reifsnyder, 1977; Bessie and Johnson, 1995; Skinner et al., 2002). Limber pine competes poorly in closed-canopy forests, and when fire is infrequent, it is generally restricted to rocky, exposed settings in subalpine forests (Peet, 1981; Youngblood and Mauk, 1985). Declining pine percentages during the late Holocene suggest that fire played a greater role in driving forest structure during the early Holocene than the late Holocene. As fire became infrequent because of prevailing climate conditions, limber pine becomes increasingly excluded from these forests.

Chironomid-inferred summer temperatures were cool (Reinemann et al., 2009) and regional pollen data indicate moist conditions (Petersen and Mehringer, 1976; Fall, 1997; Anderson et al., 1999; Weng and Jackson et al., 1999); therefore, it is likely that late summer conditions on the AqP were unfavorable for burning during the late Holocene. The Purple Lake record indicates a prolonged period of limited fire activity lasting from 3,000 cal yr BP until the arrival of Euro-American settlers to the region around AD 1850. Brown et al. (2008) note occurrence of fire on Boulder Mountain (northeast AqP) over the last several centuries, though the relative absence of charcoal accumulation in Purple Lake suggests inherent differences in sensitivity among tree-rings and lake sediments. Brown et al. (2008) define a fire event as ≥2 fire scarred trees, and such spatially small fire episodes may or may not be a fire event producing enough charcoal to provide sedimentary evidence (Gardner and Whitlock, 2001).

Spruce:fir ratio during the late Holocene suggest spruce was dominant at Purple Lake, with no indication of SB outbreak (Fig. 15). However, Purple Lake is currently surrounded by palynologically indistinguishable species of spruce with only a minor fir component and ratios of spruce to nonarboreal taxa may not reflect SB events as sediment compression includes several decades in 1 cm.

At Posy Lake, the long-term increase in snow over this period is probably favorable for fir (Fall 1997) (Fig. 15) and does not appear to be punctuated by an ‘instantaneous decline’ similar to the mid-Holocene. Long-term changes in moisture seasonality at Posy Lake are indicated by changes in ArtAm and AC ratios. AC ratio at Posy Lake increases at around 2,000 cal yrs BP which is synchronous with increasing fir pollen, which supports an interpretation of increasing snowpack during the late Holocene. Similarly, $CaCO_3$ content begins an abrupt increase at ca. 2,000 ka despite general complacency over the prior 7,000 years, suggesting greater groundwater flow into Purple Lake, which is also consistent with increasing snowpack during this period.

<u>Settlement Era (AD 1850 – 2007)</u>

The settlement-era pollen sequences from Purple Lake and Banana Lake (Figs. 18a and 18b) are similar to the last 8,600 years, though the higher temporal resolution of these records allows an of examination of historical disturbances. A small fire in the southeastern region of the Purple Lake watershed in AD 1993 was subsequently colonization by aspen (USFS unpublished data; Fig. 18a). The spruce:fir ratios at both sites suggest that pollen accumulation during a known SB outbreak generally mirrors stand conditions (Chapter 2). The greater amount of spruce relative to fir at Purple Lake is evident in the pollen stratigraphy, though the spruce:fir ratio is not as visually compelling at Purple Lake as it is at Banana Lake, which has a greater abundance of fir surrounding the basin.

An examination of historical photos from Purple Lake suggests heavy impacts from ungulate grazing, perhaps similar to those documented on other High Plateaus (Figure 10) (Madany and West, 1983; Hall, 2001; Gill, 2007) where livestock grazing diminishes the herbaceous understory in favor of nonforage vegetation, particularly conifers. Observed ecological changes from grazing suggest that conifer stand density may be unnaturally elevated in summer rangelands due to ungulate herbivory (Mandany and West, 1983). Stand density is an important consideration in assessing forest health and resilience because greater stand density increases susceptibility to drought, provides fuel connectivity (fire), and continuous susceptible host (insects). Unlike areas of the Wasatch Plateau (175 km northwest; Hall, 2001), the AqP was not significantly logged following settlement, nor was it during the 20th century. Charcoal returns to the Purple

Lake record after Euro-American settlement in the region occur around AD 1850, following a general absence of charcoal accumulation in the preceding three millennia.

Conclusions

The Purple Lake record provides evidence that fire regimes on the AqP exhibit considerable variability from 8,600 cal yr BP to present. The geographic isolation of this landform from other subalpine ecosystems and the remarkably stable coniferous forest community assessed from sedimentary pollen discounts the possibility that the fire regime of the AqP has been modified by invasion or colonization by fire-prone trees. Our record suggests that insolation-driven changes in climate, precipitation seasonality, and strength and intensity of ENSO are responsible for fire regime variability. Our record also indicates that these subalpine forests are resilient to a range of fire regimes, climate conditions, and eruptive populations of bark beetles. Despite heterogeneity in seasonal precipitation maxima in the eastern Great Basin and Colorado Plateau (Mock, 1996), the vegetation and charcoal record from Purple Lake appears to be responding similarly to long-term climate variability with other sites along a latitudinal gradient ($\approx 38^\circ$ N) in the eastern Great Basin, Colorado Plateau, and into the Central Rocky Mountains. However, more high-resolution charcoal records from this region are required to improve upon these interpretations of climate-fire relationships in the subalpine zone of the SW ENSO realm.

Bark beetle outbreaks equal (Baker and Veblen, 1990) or exceed (Logan and Powell, 2001) the ecological and economic impacts of wildfire, but are not accounted for in many Holocene paleoecological reconstructions. Despite evidence that host/nonhost pollen accumulation mirrors stand-level conditions observed during modern bark beetle disturbances, additional research is required to assess the full range of responding ecological variables. Using spruce:fir ratios is suggestive of SB disturbance on the AqP ca. 8,200 cal yr BP and also during the mid-Holocene, though supporting evidence (beetle macrofossils or geochemical marker) would provide crucial evidence to support this interpretation.

CHAPTER 4

HOLOCENE FIRE DISTURBANCE FROM SOUTH-CENTRAL UTAH

Introduction

Variations in synoptic-scale climate patterns and atmospheric teleconnections are important controls on fire occurrence and severity in western North America (NA hereafter; Brotak and Reifsnyder, 1977; Bartlein et al., 1998; Swetnam and Betancourt, 1998; Schoennagel et al., 2005; Brown et al., 2008; Whitlock et al., 2008). In the southwest (SW), fire season is controlled primarily by autumn-winter-spring precipitation (Wright, 1989; Swetnam and Betancourt, 1990) and moisture variability in this region is modulated by Pacific Ocean sea surface temperatures (SST) and sea-level pressure anomalies (Cayan, 1996; Hidalgo and Dracup, 2003). Subdecadal to decadal indices of these climate features are described by the El Niño-Southern Oscillation (ENSO; Diaz and Markgraf, 2000) and the Pacific Decadal Oscillation (PDO; Mantua et al., 1997). ENSO and PDO are important mechanisms in modifying cold season precipitation in western NA (Cayan et al., 1998; Wise, 2010) and are controls on wildfire disturbance (Swetnam and Beatncourt, 1990, 1998; Scheonnagel et al., 2005; Brown et al., 2008; Heyerdahl et al., 2008).

In western NA, the ≈42˚ parallel delineates the boundary of the ENSO winter precipitation dipole (Ropelewski and Halpert, 1986; Dettinger et al. 1998; Cayan et al., 1999; Brown and Comrie, 2004; McCabe and Dettinger, 2008; Wise, 2010). The dipole boundary is approximate and has probably migrated from its present day orientation in the past (Cayan et al., 2002). ENSO status is described as positive (negative) indicating warm (cool) SST in the eastern Pacific Ocean. During a moderate to strong El Niño episode, the SW generally receives greater winter precipitation, whereas the Pacific Northwest (PNW) experiences decreases in winter precipitation. The opposite occurs during La Niña episodes. ENSO periodicity is generally 2-7 years, which include years of neutrality (Diaz and Markgraf, 2000). The PDO is similar in terms of climate and circulation response, though exhibiting 20-30 year periods (Mantua et al., 1997). The PDO is similarly described as ENSO with positive (negative) phases describing warm (cool) SST conditions though the northern Pacific Ocean. Given the comparatively low temporal frequency of PDO, its status can enhance (constructive) or suppress (destructive) winter precipitation during El Niño and La Niña events in western NA (Gershunov and Barnett, 1998; McCabe and Dettinger, 1999; Biondi, 2001; Gray et al., 2003; Wise, 2010).

Variations in ENSO over the Holocene exhibit a considerable range of frequency and intensity (Clement et al., 2000; Moy et al., 2002; Koutavas et al., 2006; Barron and Anderson, 2011) and proxy evidence suggests that persistent El Niño or La Niña patterns have occurred across a broad range of temporal scales (Tudhope et al., 2001; Koutavas et al., 2002, 2006; Moy et al., 2002; Shin et al., 2006; Marchitto et al., 2010; Asmerom et al., 2011). Sedimentary records and model simulations indicate that the frequency and amplitude of ENSO events have varied considerably during the last 8,000 years (Clement et al., 2000; Moy et al., 2002; Koutavas et al., 2006). An insolation-driven, persistent La Niña-like state existed in the eastern Pacific between 8,000 and 4,000 cal yr BP (Koutavas et al., 2006; Shin et al., 2006; Barron and Anderson, 2011) resulting in winter aridity in the SW (Asmerom et al., 2011). A drought episode in western North America during this period is suggested in records from lake sites in the eastern Great Basin and central Rocky Mountains (Madsen and Currey, 1979; Feiler et al., 1997; Weng and Jackson, 1999; Shuman et al., 2009). However, other records suggest that despite dry winter conditions, summer conditions were wet (Anderson et al., 1999; Mock and Brunelle-Daines, 1999).

Paleoecological records are essential in understanding how long-term variations in atmospheric teleconnections influence vegetation communities and disturbance. Tree-ring reconstructions provide invaluable information on how ENSO and PDO influenced moisture seasonality over centennial timescales and are particularly useful in the SW (Swetnam and Betancourt, 1998) because tree ring growth in this region is especially sensitive to winter precipitation (St. George et al., 2010). Tree rings records are annually resolved and sensitive to both climate and disturbance, though dendroecological reconstructions are generally limited to ≤500 years. Sedimentary records, while coarser in temporal resolution, commonly extend over millennia and can provide information about long-term variability of climate, vegetation, and disturbance (Brunelle et al., 2005; Whitlock et al., 2008).

Climate projections for the 21st century indicate warming temperatures by as much as 4˚C from anthropogenic greenhouse gas emissions and increased drought from restructuring of mesoscale atmospheric circulation patterns (IPCC AR 4, 2007; Sokolov et al., 2009; Cayan et al., 2010; Seager and Vecchi, 2010). Recent droughts during the late 20th and early 21st century (Piechota et al., 2006) resulted from temperature increases of 0.5˚ to 1˚ C warming which were accompanied by snowpack reductions, earlier spring melt of snowpack, and low late season soil moisture (Cayan et al., 2010). These recent droughts contributed to regional eruptions of phytophagus insects due to decreased host tree vigor and warming temperatures which facilitated faster and synchronous reproduction rates of these insects (Logan and Powell, 2001; Fettig et al., 2007).

Numerous studies link La Niña ENSO phase and negative PDO to severe drought conditions in the SW (McCabe et al., 2004) that increase both predicted (Schoennagel et al., 2005) and reconstructed (Brown et al., 2008) fire in this region. Climate forecast models for the 21st century acknowledge uncertainties as to how ENSO conditions will respond, where some authors suggest dominance of El Niño conditions (Wara et al., 2005) similar to the warmer-than-modern Pliocene (~4.5-3.0 million years ago), while other models suggest persistent La Niña conditions like those that occurred during the mid-Holocene (Seager et al., 2007). With uncertainty in the models for future ENSO status, it is difficult to predict how fire regimes will likewise change.

Subalpine forests above elevations of 2,700 m in the SW are composed mostly of Engelmann spruce and subalpine fir. Fires in spruce-fir forests are generally infrequent and recur at mean fire return (MFRI) intervals of 200-400 years (Veblen et al., 1994; Kipfmueller and Baker, 2000). Estimates of FRI are based on tree ring records and stand age reconstructions, which are relatively short records (≤500 years) compared to the relatively long fire return intervals (200 – 400 years). Fire occurrence and severity in these systems are generally not limited by available fuel, but by extremely dry climate conditions that are required for burning (Bessie and Johnson, 1995; Veblen, 2000; Baker, 2003). Subalpine spruce-fir forest compositions in south-central Utah are unique when compared to those of neighboring states (e.g., Colorado, Wyoming) or northern Utah because fire-prone lodgepole pine are absent. Occurrence of fire-prone species is important when disentangling the relative influence of climate versus forest composition on fire regimes (Lynch et al., 2004; Seppä et al., 2008; Higuera et al., 2009; Ohlfield et al., 2011). Holocene records of fire disturbance from central and southern Utah are emerging (Morris et al., 2010) and these records are significant because this region lacks sufficient long-term fire reconstructions beyond the most recent centuries (Brown et al., 2008; Morris et al., 2010). The objective of this study is to understand how long-term changes in climate from insolation and ENSO have modified the frequency and magnitude of fire occurrence in south-central Utah. Because ENSO is a dominant driver of moisture in the SW realm and has known relationship with fire occurrence during the historic period and recent centuries, sedimentary records of fire occurrence from sites south of ~42˚ presented here offer supporting lines of evidence for ENSO-forced drought and wildfire over millennial timescales.

Study Area

Sites selected for this study traverse the margin of the eastern Great Basin and into the Colorado Plateau in southwestern and south-central Utah (Fig. 18) and are south of the ~42˚ ENSO dipole boundary (SW). The lowland landscapes of this region are covered by a vast expanse of sagebrush steppe (*Artemisia tridentata*) and pinyon-juniper woodlands (*Pinus edulis-Juniperus* spp.). The upland areas consist of north-south

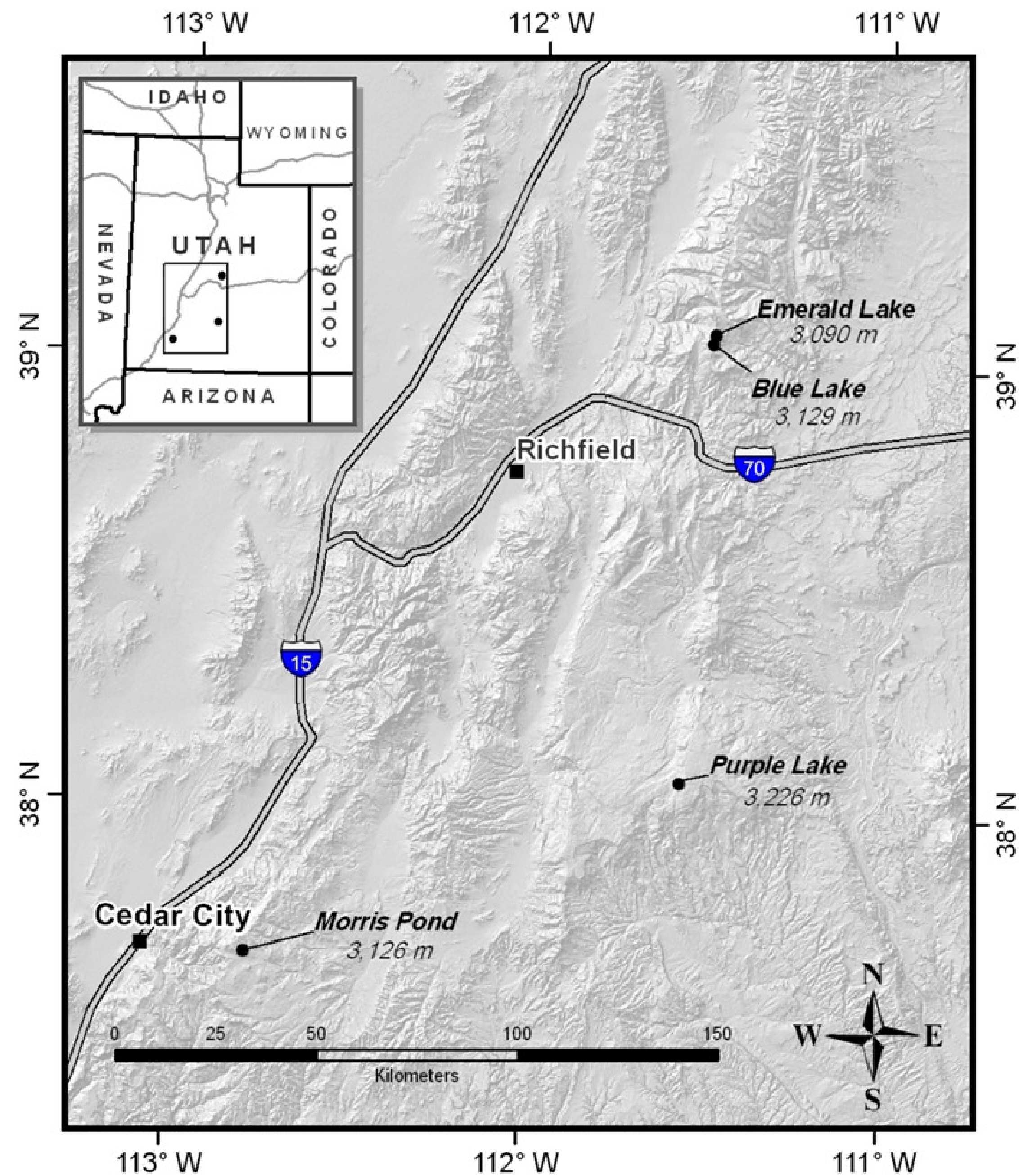

Figure 18. Map of the study area and lake sites discussed in this study.

oriented subalpine plateaus and mountain ranges, with many landforms reaching elevations above 3,000 m (Wannamaker et al., 2001). The study area lies on the transition zone of summer-dominant (monsoon) and winter-dominant (Pacific) moisture regimes (Mitchell, 1976; Petersen, 1994; Mock, 1996), resulting in heterogeneous seasonal and annual precipitation maxima (Houghton, 1976; Cayan, 1996; Mock, 1996; Shinker, 2010). Moisture-receipt in general is controlled by altitude, where greater amounts of precipitation occur at higher elevations. In the subalpine zone (elevations between 2,700 m to 3,300 m), most moisture is received as snowfall during the winter and spring months, with a second precipitation peak occurring during late summer (Fig. 19a-c). Because these plateaus rise steeply above surrounding valleys, the development of convectional and orographically induced storms is common during late summer months. This late summer moisture peak has been described by several authors (Shafer, 1989; Fall, 1997; Anderson et al., 1999; Weng and Jackson,1999) as 'monsoonal' or 'monsoonally-derived' (*sensu* Tang and Reiter, 1984).

Subalpine ecosystems examined in this study are generally composed of dense stands of Engelmann spruce and subalpine fir, with patches of aspen in areas of windthrow or fire disturbance, blue spruce in mesic settings, and limber pine in rocky, exposed locales. During the 20th century, many of the spruce-fir forests in Utah experienced stand-replacing spruce beetle outbreaks with >80% mortality of overstory Engelmann spruce (Matthews et al., 2005). Current forest structure, particularly on the Wasatch Plateau (WP) and Markagunt Plateau (MP), generally reflect seral stand conditions (Dymerski et al., 2001; DeRose and Long, 2007).

a)

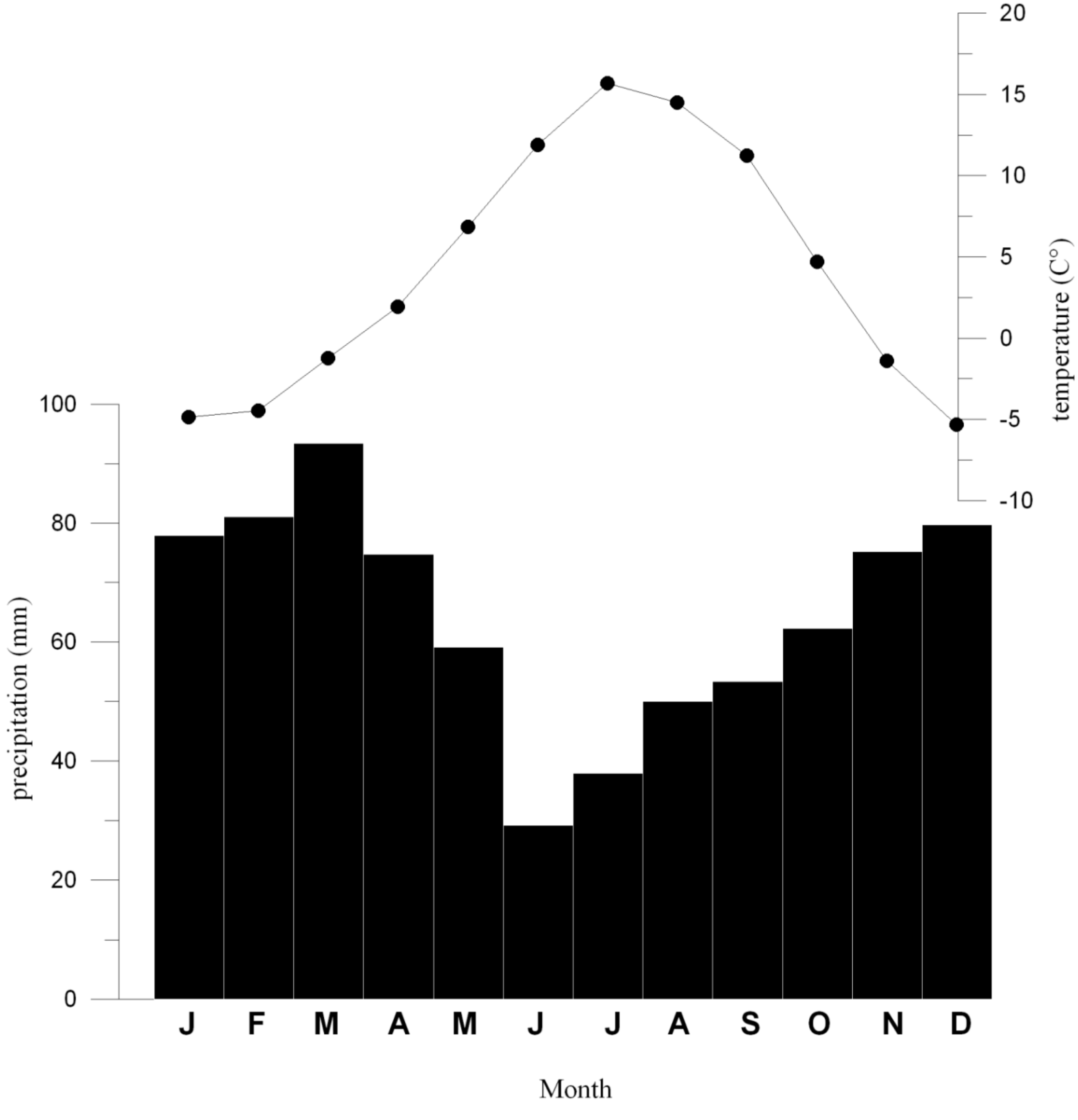

Figure 19 Climagraph describing precipitation (bars) and temperature (line plot) for the Wasatch (a), Aquarius (b), and Markagunt (c) Plateaus. Data are aggregated SNOTEL stations above 3,000 m elevation.

b)

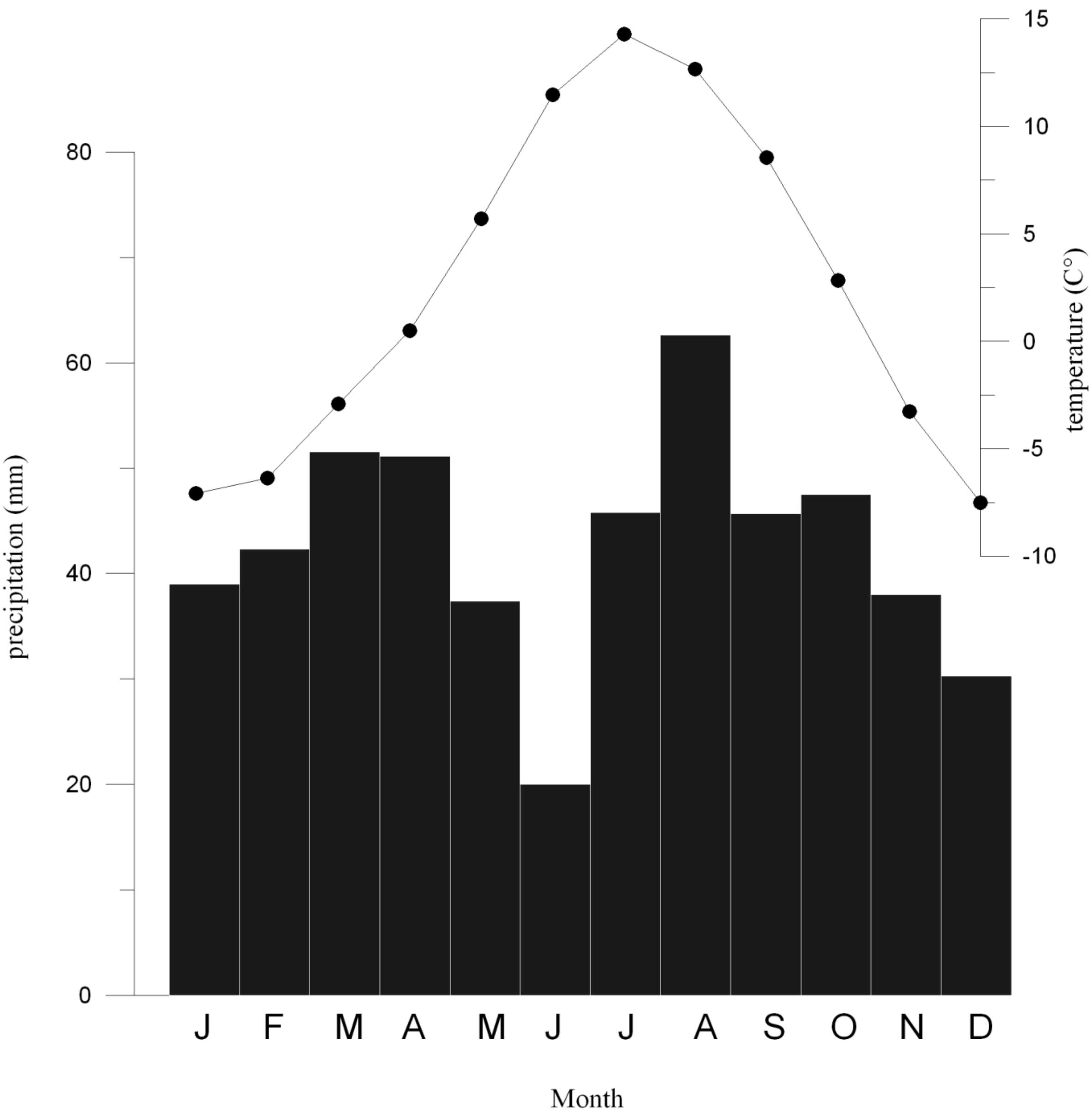

Figure 19. Continued

c)

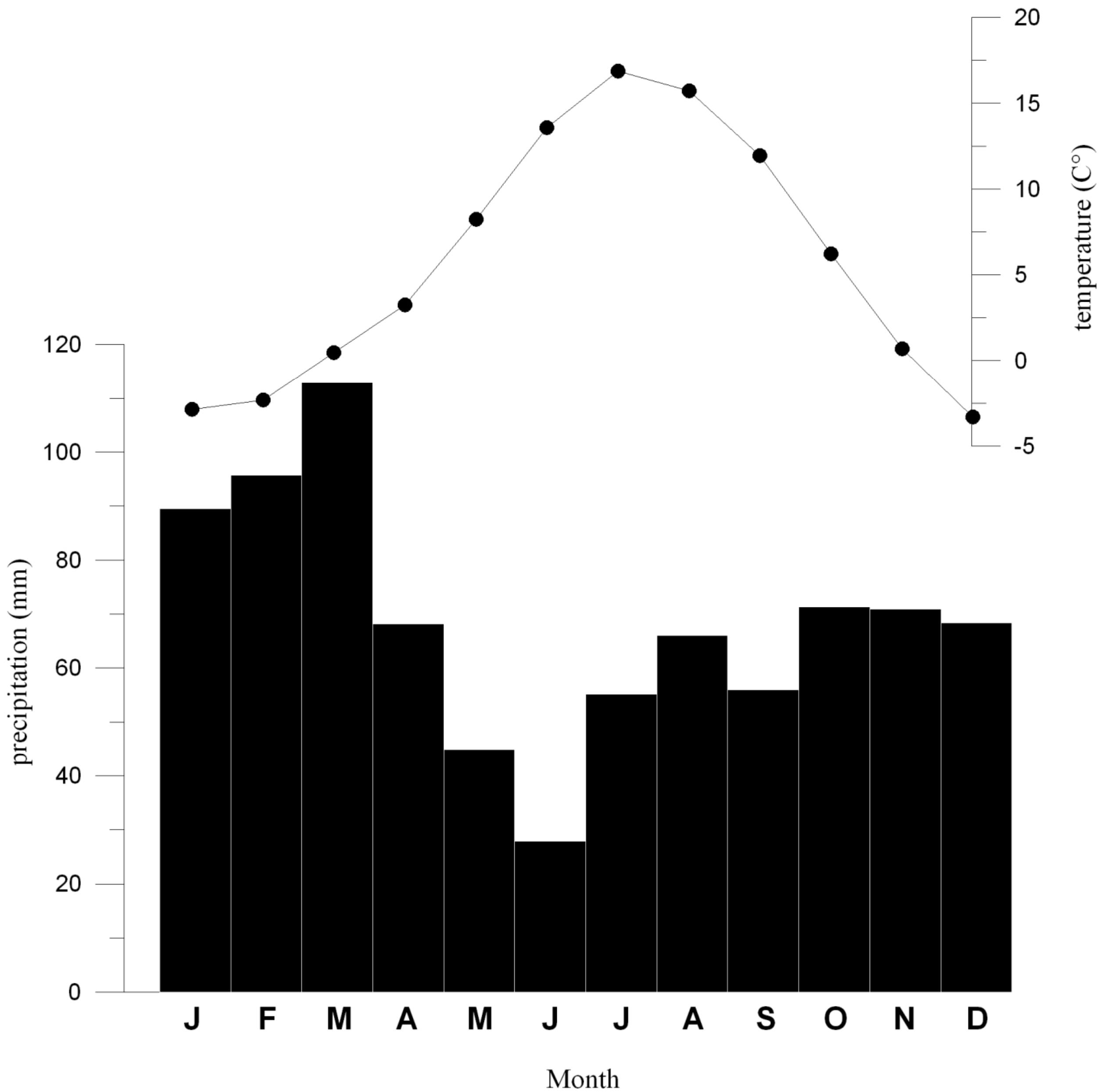

Figure 19. Continued

Subalpine forest communities are interspersed with meadows dominated by herbaceous taxa including grasses (Poaceae) and flowering plants that include members of the sunflower (Asteraceae), bean (Fabaceae), mustard (Brassicaceae), and bell flower families (Campanulaceae). Lake margins are generally fringed by sedges (Cyperaceae) and infrequently by cattails (Typhaceae). Shrub communities are composed mostly of alpine sagebrush (*Artemisia borealis*) and infrequently buckbrush (Rhamnaceae) and common juniper (*Juniperus communis*). Many subalpine meadows have been heavily grazed during in the late 19th and early 20th century which has had a profound effect on the ecology and soils of these plateaus (Ellison, 1954; Mandany and West, 1983; Klemmedson and Tiedemann, 1998; Hall, 2001; Gill, 2007). Additionally, settlement-era logging events (Morris et al., 2010) and fire exclusion policies (Romme and Despain, 1989) have had profound influence on the modern stand structure in western North America in general.

Wasatch Plateau

Emerald Lake (39° 4'26.72"N, 111°29'50.964"W) (Fig. 18, Table 4) occupies a north-facing cirque basin at 3,090 m elevation. Sediment cores were collected from Emerald Lake during the summers of AD 2006 and 2007. A 2.87 m sediment core spanning the last 13,000 years was obtained from Emerald Lake. Pollen and charcoal data are presented and discussed by Brunelle et al. (in review). The WP exhibits the most classic winter wet/summer dry response in the study area but still receives significant summer precipitation (Fig. 19). Due to its more northerly location (39˚ N) the WP is well-positioned to receive winter storms from the northwest and west.

Table 4. Age/depth summary for Emerald Lake.

Wasatch Plateau - Emerald Lake							
Depth (m)	Assigned Age		Age BP (two sigma, Calib 6.0)	14C age (14C yr BP)	+/-	Material dated	Analysis
	(year AD)	(cal yr BP)					
0.00	2007				0	sediment	$^{210}Pb/^{137}Cs$
0.02	2004				2	sediment	$^{210}Pb/^{137}Cs$
0.04	1997				2	sediment	$^{210}Pb/^{137}Cs$
0.06	1987				2	sediment	$^{210}Pb/^{137}Cs$
0.08	1977				3	sediment	$^{210}Pb/^{137}Cs$
0.10	1965				4	sediment	$^{210}Pb/^{137}Cs$
0.12	1950				5	sediment	$^{210}Pb/^{137}Cs$
0.14	1933				7	sediment	$^{210}Pb/^{137}Cs$
0.16	1919				9	sediment	$^{210}Pb/^{137}Cs$
0.18	1908				9	sediment	$^{210}Pb/^{137}Cs$
0.20	1900				9	sediment	$^{210}Pb/^{137}Cs$
0.22	1888				8	sediment	$^{210}Pb/^{137}Cs$
0.24	1857				7	sediment	$^{210}Pb/^{137}Cs$
50.50		2092	2035-2149	2116	22	pollen	^{14}C AMS
89.50		3418	3377-3459	3201	22	pollen	^{14}C AMS
123.50		4039	3981-4096	3713	23	pollen	^{14}C AMS
169.00		5172	5048-5896	4504	25	pollen	^{14}C AMS
213.50		6620	6560-6679	5829	23	pollen	^{14}C AMS
253.50		11296	11234-11358	9900	28	pollen	^{14}C AMS

[a] Depth below mud-water interface, uppermost sample assigned to year core was collected.

[b] Bulk sediment samples were submitted for all ^{210}Pb dates to US Geologic Survey in Denver, Colorado by James Budahn.

Aquarius Plateau

Purple Lake (38°4'28.33"N, 111°34'16.47"W) (Fig. 18, Table 5) is a kettle lake that occurs at an altitude of 3,226 m. Purple Lake has the highest percentage of Engelmann spruce of all basins discussed in this study (Chapter 3). The Aquarius Plateau (AqP) is the 'top stair' of the Grand Staircase and receives moisture relatively unimpeded from the south, but is blocked topographically from air masses arriving from the southwest, west, and northwest. Despite its relatively high elevation, it receives surprisingly less winter precipitation compared to the WP and MP, because the AqP is located in a topographic winter rainshadow (Fig. 19).

Historic fire disturbance (1960-2010) from the AqP collected by the United States Forest Service (Figs. 20a and 20b) reveals that spatially large, lightning-ignited fires typically occur during July. Large fires in July are probably due to two factors: 1) June receives the least amount of precipitation of any month, increasing likelihood for dry fuel conditions and 2) July marks the onset of convective thunderstorm activity providing an ignition source (lightning). The greatest number of lightning-ignited fires occurs in September. Though these data are presumably influenced to some degree by fire suppression policies, these data are important because they suggest timing of annual weather conditions favorable for ignition and wildfire.

Markagunt Plateau

Morris Pond (37°40'25.48"N, 112°46'49.75"W) (Fig. 18, Table 6) is dammed by a recessional moraine and occurs at an elevation of 3,126 m above sea level. Basalt lava flows dating to ca. 1,200 cal yr BP are present on the MP, including areas adjacent to

Table 5. Age/depth summary for Purple Lake.

Aquarius Plateau - Purple Lake							
Depth (m)	Assigned Age (year AD)	(cal yr BP)	Age BP (two sigma, Calib 6.0)	14C age (14C yr BP)	+/-	Material dated	Analysis
0.00	2007				0	sediment	$^{210}Pb/^{137}Cs$
0.02	2003				4	sediment	$^{210}Pb/^{137}Cs$
0.04	1994				5	sediment	$^{210}Pb/^{137}Cs$
0.06	1983				6	sediment	$^{210}Pb/^{137}Cs$
0.08	1971				7	sediment	$^{210}Pb/^{137}Cs$
0.10	1963				9	sediment	$^{210}Pb/^{137}Cs$
0.12	1958				9	sediment	$^{210}Pb/^{137}Cs$
0.14	1953				9	sediment	$^{210}Pb/^{137}Cs$
0.16	1944				10	sediment	$^{210}Pb/^{137}Cs$
0.18	1927				12	sediment	$^{210}Pb/^{137}Cs$
0.20	1911				14	sediment	$^{210}Pb/^{137}Cs$
0.22	1896				14	sediment	$^{210}Pb/^{137}Cs$
0.24	1851				18	sediment	$^{210}Pb/^{137}Cs$
0.68		2141	2096-2186	2160	25	pollen	^{14}C AMS
1.19		4355	4285-4424	3920	25	pollen	^{14}C AMS
1.97		7740	7680-7799	6920	30	pollen	^{14}C AMS
2.76		8650	8579-8721	7852	27	pollen	^{14}C AMS

[a] Depth below mud-water interface, uppermost sample assigned to year core was collected.

[b] Bulk sediment samples were submitted for all ^{210}Pb dates to US Geologic Survey in Denver,
Colorado by James
Budahn.

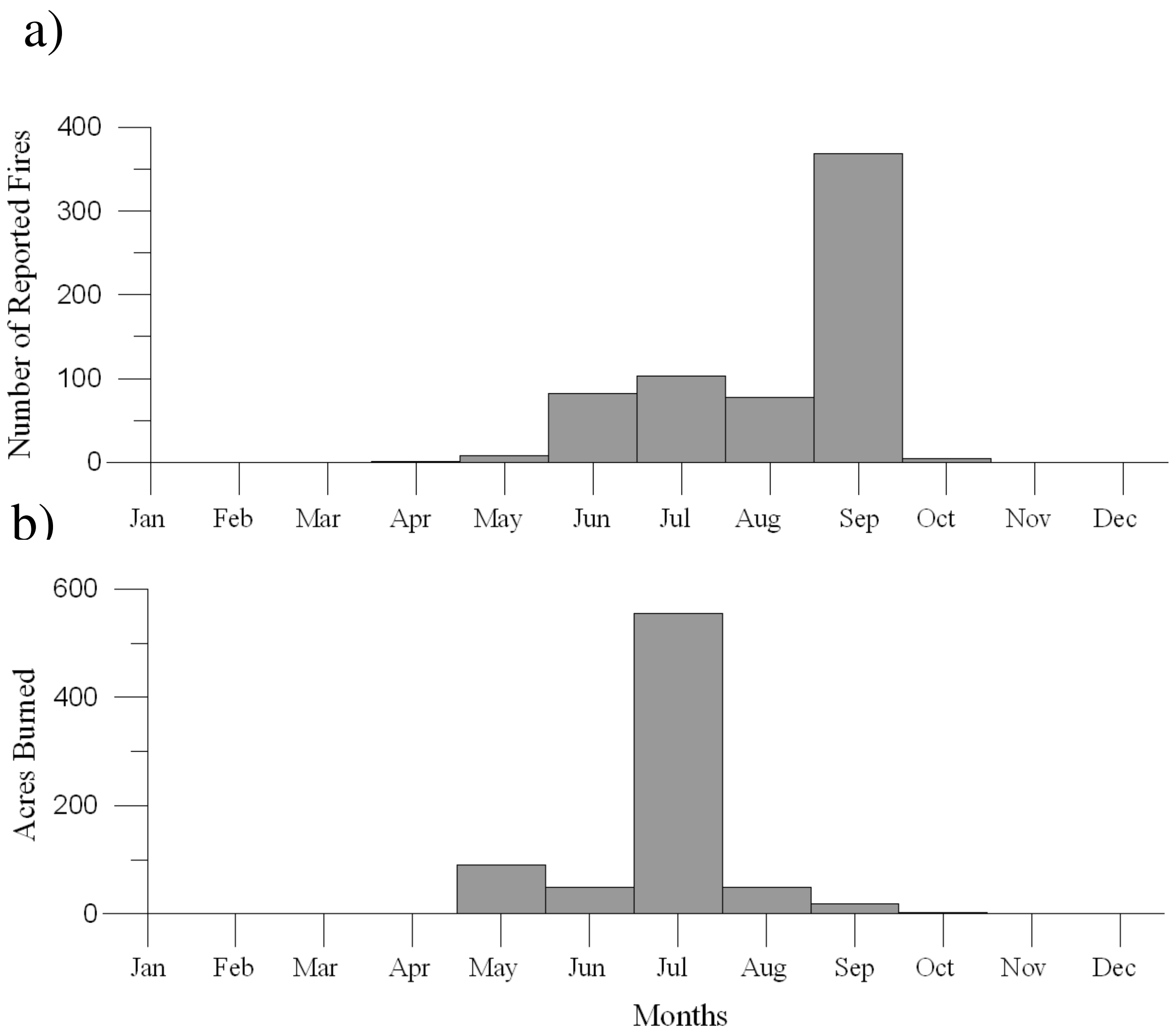

Figure 20. Historical fire data summaries for number of reported lightning-ignited fires (a) in a 10 km diameter plot around Purple Lake on the Aquarius Plateau and (b) compiled acres burned between AD 1960-2010.

Table 6. Age/depth summary for Morris Pond.

Markagunt Plateau - Morris Pond							
Depth (m)	Assigned Age (year AD)	Assigned Age (cal yr BP)	Age BP (two sigma, Calib 6.0)	14C age (14C yr BP)	+/-	Material dated	Analysis
0.02	2003				2	sediment	$^{210}Pb/^{137}Cs$
0.04	1993				2	sediment	$^{210}Pb/^{137}Cs$
0.06	1983				3	sediment	$^{210}Pb/^{137}Cs$
0.08	1973				3	sediment	$^{210}Pb/^{137}Cs$
0.10	1967				4	sediment	$^{210}Pb/^{137}Cs$
0.12	1964				5	sediment	$^{210}Pb/^{137}Cs$
0.14	1960				6	sediment	$^{210}Pb/^{137}Cs$
0.16	1956				9	sediment	$^{210}Pb/^{137}Cs$
0.18	1953				10	sediment	$^{210}Pb/^{137}Cs$
0.20	1950				11	sediment	$^{210}Pb/^{137}Cs$
0.22	1948				12	sediment	$^{210}Pb/^{137}Cs$
0.24	1884				15	sediment	$^{210}Pb/^{137}Cs$
0.36		680	660-699	738	20	pollen	^{14}C AMS
0.88		1288	1270-1306	1360	20	pollen	^{14}C AMS
1.83		2909	2846-2971	2804	25	pollen	^{14}C AMS
2.58		5122	5051-5192	4516	26	pollen	^{14}C AMS
3.33		6708	6661-6755	5893	25	pollen	^{14}C AMS
4.05		8320	8275-8364	7467	29	pollen	^{14}C AMS
4.81		8693	8597-8788	7901	32	pollen	^{14}C AMS

[a] Depth below mud-water interface, uppermost sample assigned to year core was collected.
[b] Bulk sediment samples were submitted for all ^{210}Pb dates to US Geologic Survey in Denver,
Colorado by James Budahn.

Morris Pond. A 4.82 m sediment core spanning the last 8,700 cal yr BP was retrieved from this basin in 2009. The MP is exposed to direct moisture via an unimpeded topographical pathway from the southwest, west, and south (Fig. 18). The MP is located in an area that currently receives substantial moisture input during the spring and winterand is the farthest south (~37˚ N) among sites in the study area (Fig. 19).

Methods

Data from the last 9,000 cal yrs BP are presented and discussed here. The Emerald Lake record extends to 13,000 cal yr BP. However, because fires are essentially absent between 9,000 and 13,000 (Brunelle et al., in review) and because it is the only record to represent this time period, the focus is on the last 9,000 cal yr BP. Furthermore, the basal dates for Purple Lake and Morris Pond both occur near 9,000, and to maintain continuity among these records, only data from 9,000 to present are discussed and presented.

Charcoal Analysis

Samples for charcoal and macrofossil analysis (5-10 cc) were collected and analyzed for the upper 24 cm of each core and were prepared following Whitlock and Millspaugh (1996). Sediments samples were screened using 125 µm and 250 µm nested sieves. Retrieved materials were placed on gridded petri dishes and then examined and counted using light microscopy at 40x.These size fractions were selected because modern studies have shown that large particles do not travel far from their source and therefore most likely represent local, watershed-scale fire history (Clark, 1988; Gardner and Whitlock, 2001).

Charcoal counts for each sample were converted to concentration (particles cm-1) and then calculated as influx. To minimize variations in the record that might arise due to changes in sediment deposition rates, the concentrations were binned using the median sediment deposition time (25, 27, and 25 years for Emerald Lake, Purple Land, and Morris Pond, respectively). Newly binned concentrations were then converted to charcoal accumulation rates (CHAR, particles cm-1 yr-1) and decomposed into background and peak components (Higuera et al., 2009; http://CharAnalysis.googlepages.com). Background is defined as the slowly varying trend in CHAR as a primary result of changes in fuel abundance and vegetation composition (Marlon et al., 2006). Peaks, which are positive deviations from the background CHAR, are interpreted as input of charcoal originating from a fire episode. Peaks were determined using a Lowess smoother which is robust to outliers within a 500-year window width (Higuera et al., 2010). The background values for each time interval were then subtracted from the total CHAR accumulation for each interval. The peaks in the charcoal record (i.e., intervals with CHAR values above background) were tested for significance using a Gaussian distribution, where peak CHAR values that exceeded the 95th percentile were considered significant. This procedure was applied for every 500-year overlapping portion of the CHAR record, producing a unique threshold for each sample. Once identified, all peaks were screened to eliminate those that resulted from statistically insignificant variations in CHAR (Gavin et al., 2006). If the maximum count in a CHAR peak had a >5% chance of coming from the same Poisson distribution population as the minimum charcoal count with the proceeding 75 years, then the peak was rejected (Higuera et al., 2010).

Pollen Analysis

Pollen samples (1 cc) were analyzed at 4, 8, and 4 cm intervals for Emerald Lake, Purple Lake, and Morris Pond, respectively, following methods described by Faegri et al. (1989). *Lycopodium*, an exotic spore, was introduced to each sample during processing as a tracer. Slide-mounted pollen samples were examined using light microscopy at 500x and counted to a minimum of 300 terrestrial grains. Grain identification was aided by laboratory reference collections and relevant dichotomous keys and literature (Erdtman 1952; Bassett et al. 1978; Kapp et al. 2000).

Chronology

Chronologies for the historic sediments were established by analyzing the upper 24 cm of the short core profiles for ^{210}Pb /^{137}Cs. Samples were weighed and then dried in a muffle furnace at 100° C to remove water. Dehydrated samples were submitted for analysis to Dr. James Budahn at the USGS Laboratory in Denver, CO. The ^{210}Pb record was interpreted using 1963 as the peak in ^{137}Cs associated with climax of atmospheric detonation of nuclear test weapons. The upper cm was assigned to the year of core retrieval. Short core sediments were linked to long core segments by matching discrete peaks in charcoal accumulation.

Accelerator mass spectrometry (AMS) ^{14}C dates were obtained from shultzed pollen samples to establish chronologic control for long cores. Dates were submitted to the Center for Applied Isotope Studies at the University of Georgia for analysis. AMS results (Table 3, 5) were converted from ^{14}C years to calendar years before present (Cal yr BP) using the Calib 6.0 software package (Reimer et al., 2009). Depth-age relationships were developed using smoothing spline, calculated in "R" using a script developed by Dr. Patrick Bartlein at the University of Oregon.

Historical Data

Historical climate data used to construct climagraphs (Fig. 19) were retrieved from SNOTEL stations. Precipitation and temperature data were aggregated from all stations located on the plateaus discussed in this study. Historical fire data were provided by the USDA Forest Service for the period of AD 1960 to 2010 (Figs. 20b and 20b). Only lightening ignited fires were used and only fires reported within 10 km of Purple Lake were selected to minimize variations in the influence of fires occurring at lower elevations in dissimilar vegetation communities.

Results

Wasatch Plateau

Pollen and charcoal data are discussed in Brunelle et al. (in review) and only select taxa are presented here (Fig. 21). The pollen data indicate that Emerald Lake has been surrounded by spruce-fir forests for the last ~9,000 years, with pine present in slightly greater amount between 7,000 to 8,000 cal yr BP (probably limber pine). In general, the forest community has changed relatively little with regards to arboreal, shrub, and herb pollen for the last 9,000 years.

Charcoal accumulation at Emerald Lake is variable over the last ~9,000 years (Fig. 22). Relatively low charcoal accumulation with infrequent fire (MFRI ~800 yr between episodes) characterizes the early Holocene. Fire episodes are both more frequent (MFRI ~200 years) and of a larger magnitude (25 cm-2/peak-1) during the mid-

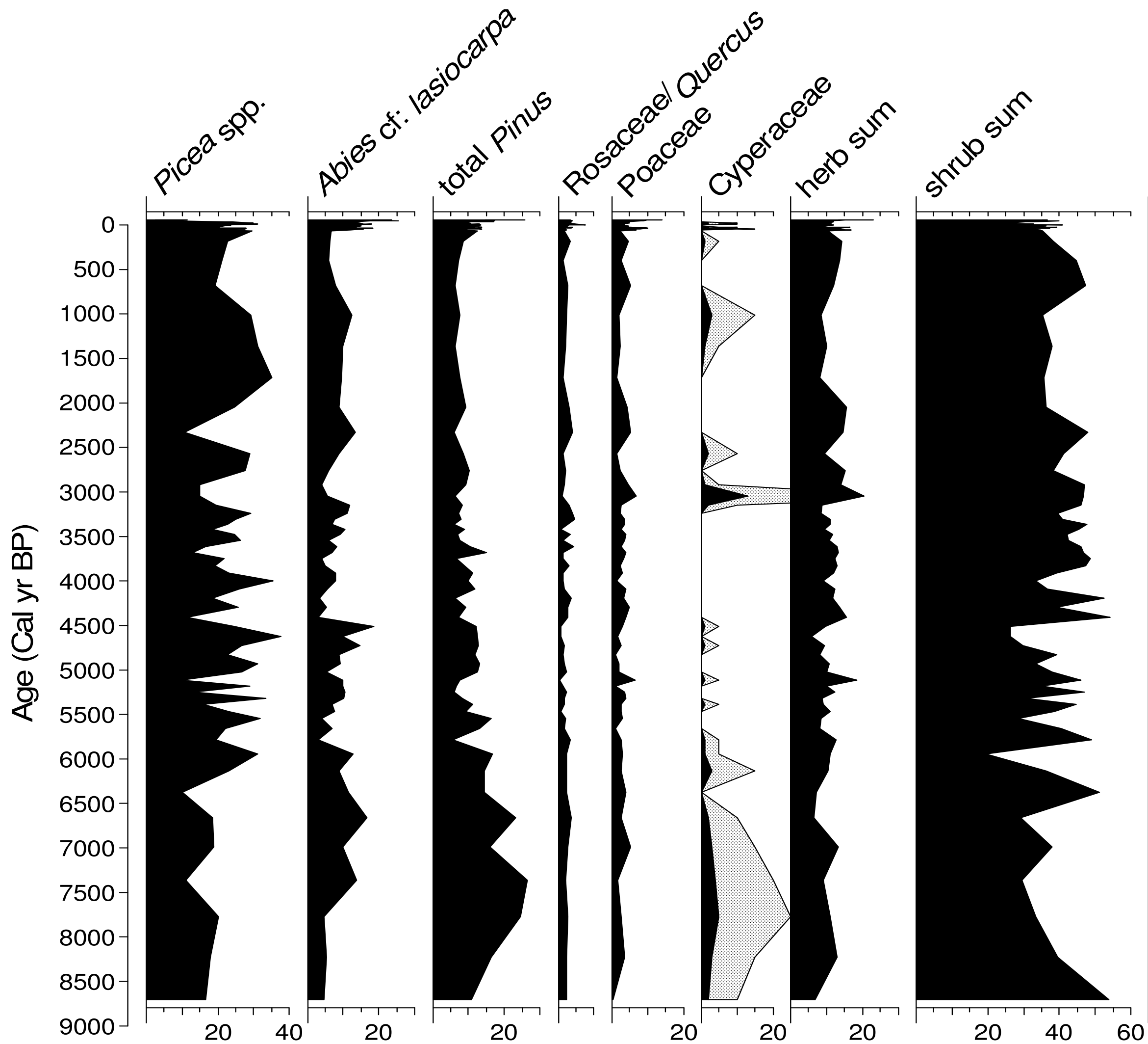

Figure 21. Pollen data for select taxa for Emerald Lake located on the Wasatch Plateau.

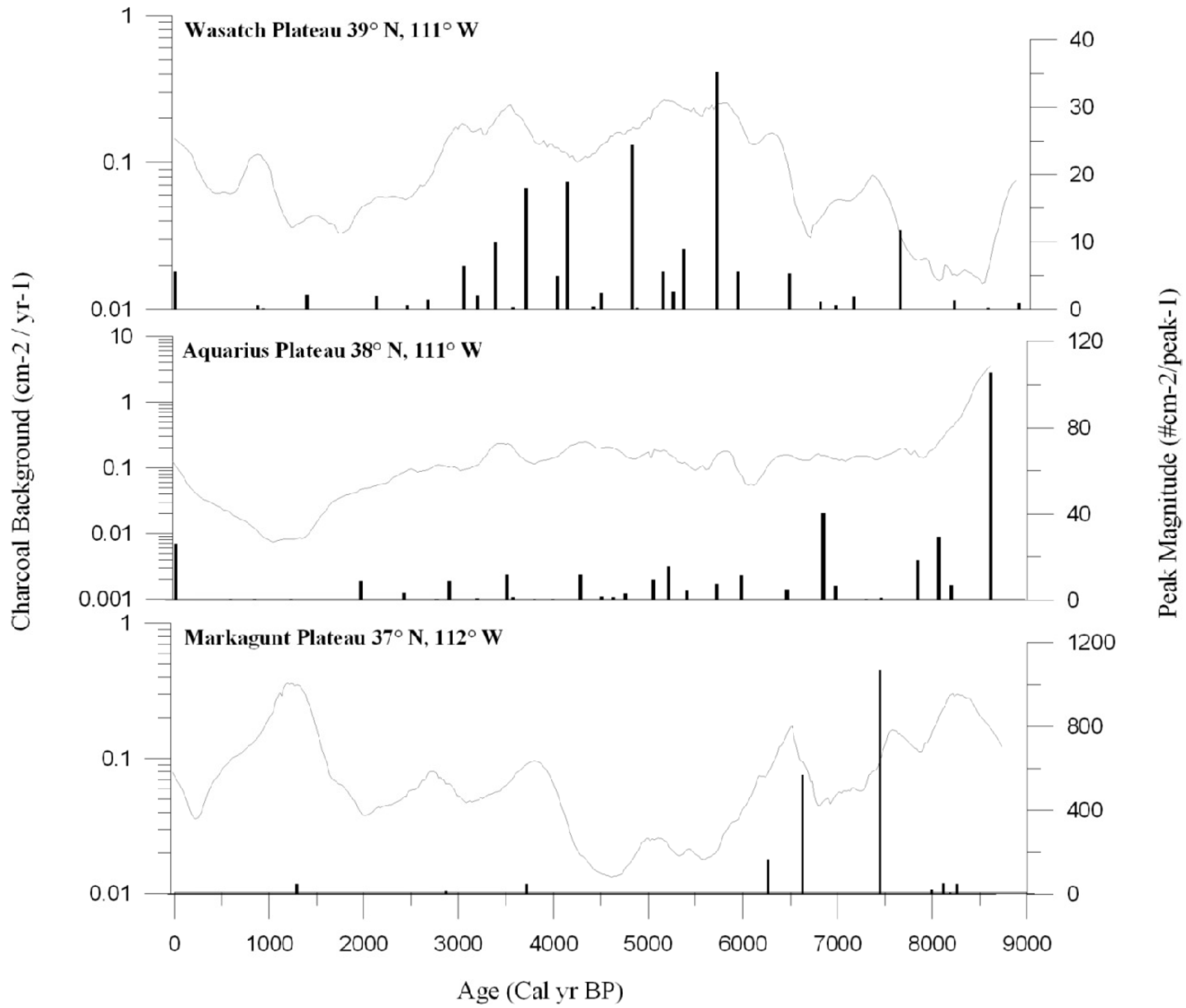

Figure 22. Background charcoal (grey line plot) and peak magnitude (bars) arranged north to south.

Holocene. At around 6,000 cal yr BP, the fire regime shifts towards large magnitude fire events which is roughly coincident with increasing spruce and fir pollen and decreasing shrub pollen. The late Holocene is similar to the early Holocene in that fire becomes infrequent (MFRI of ~800 years) and peak magnitudes are low (<2 cm-2/peak-1) (Fig. 23).

Aquarius Plateau

The pollen stratigraphy from Purple Lake and other AP lakes are discussed in Chapter 3. Select taxa from Purple Lake include the most abundant trees, shrubs, herbs,

and sums (Fig. 24). Pollen data from Purple Lake indicate that a spruce-fir forest existed around the basin for the last ~9,000 cal yr BP with a high pine component occurring during the early Holocene. The middle Holocene suggests continued dominance of spruce and fir, while shrubs and grass decrease. Nearing the late Holocene, (~2,000 cal yr BP) aspen and fir becomes more prevalent.

Fire activity at Purple Lake is greater during the early Holocene, with larger amounts of charcoal accumulation and larger peak magnitudes (between 40-90 cm-2/peak-1) recorded during fire episodes within the context of this record. Both charcoal accumulation and peak magnitudes decrease during the middle Holocene and become essentially absent in the record during the late Holocene (Fig. 22). MFRI is consistent through the early and middle Holocene, varying between 200-400 years (Fig. 23). Between 3,000 cal yr BP to modern, little charcoal is deposited at Purple Lake until following the arrival of Euro-American settlers to the region ca. AD 1850. MFRI in the late Holocene is the highest over the entire record (MFRI ~ 900 to 1,000 years).

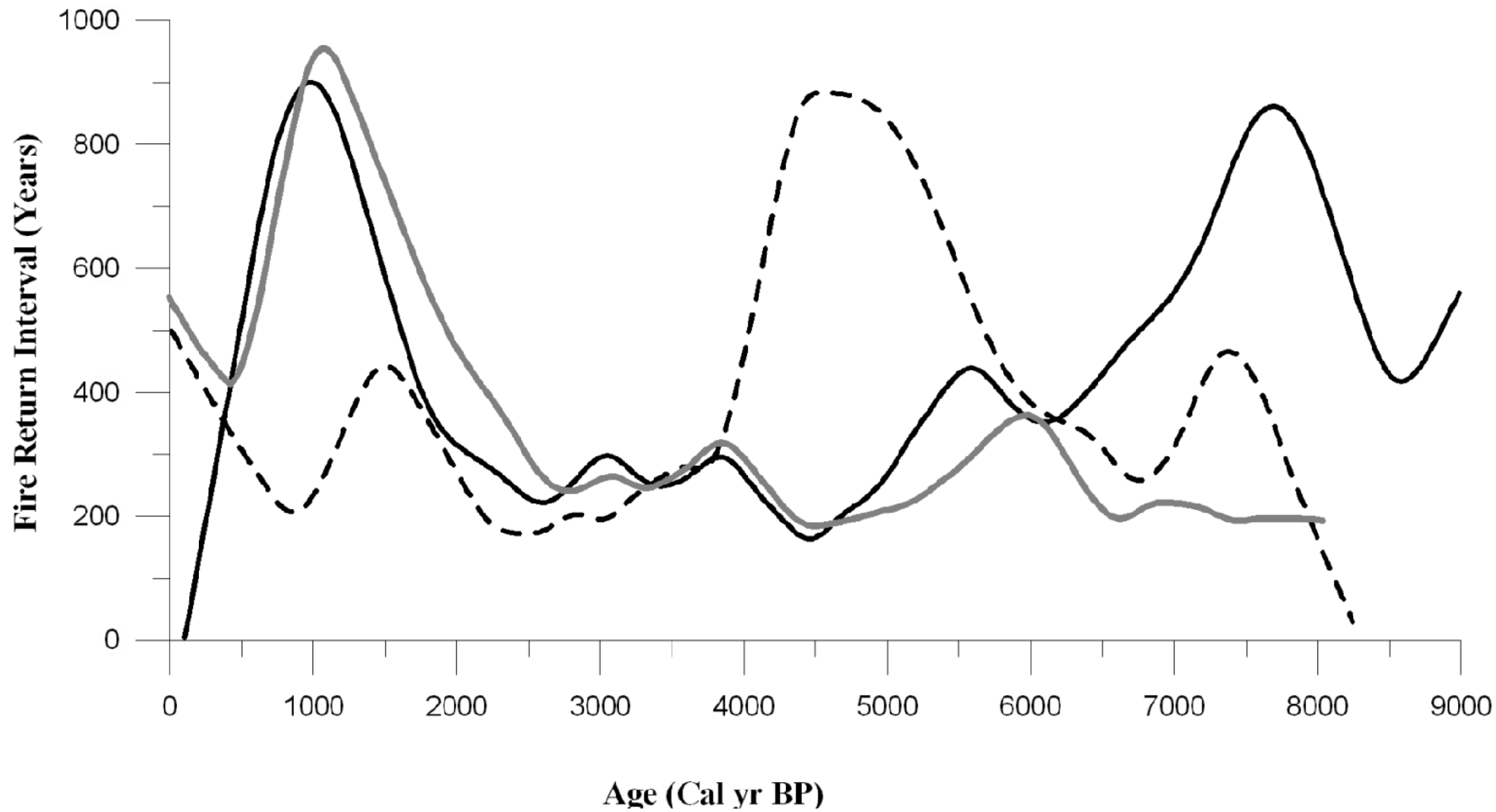

Figure 23. Mean fire return interval (MFRI) for Emerald Lake (solid black line), Purple Lake (solid grey line), and Morris Pond (dashed black like).

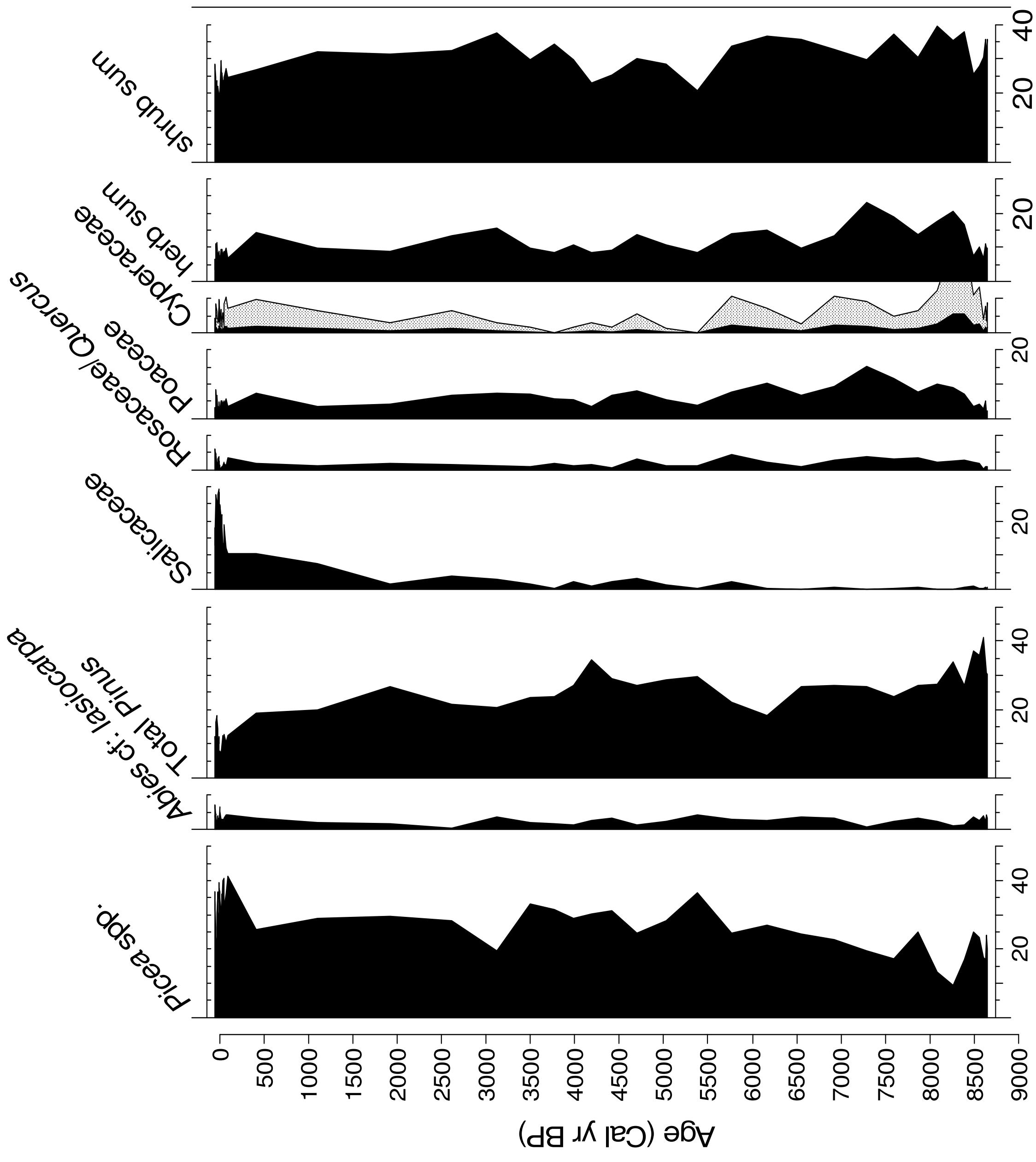

Figure 24. Pollen data for select taxa for Purple Lake located on the Aquarius Plateau.

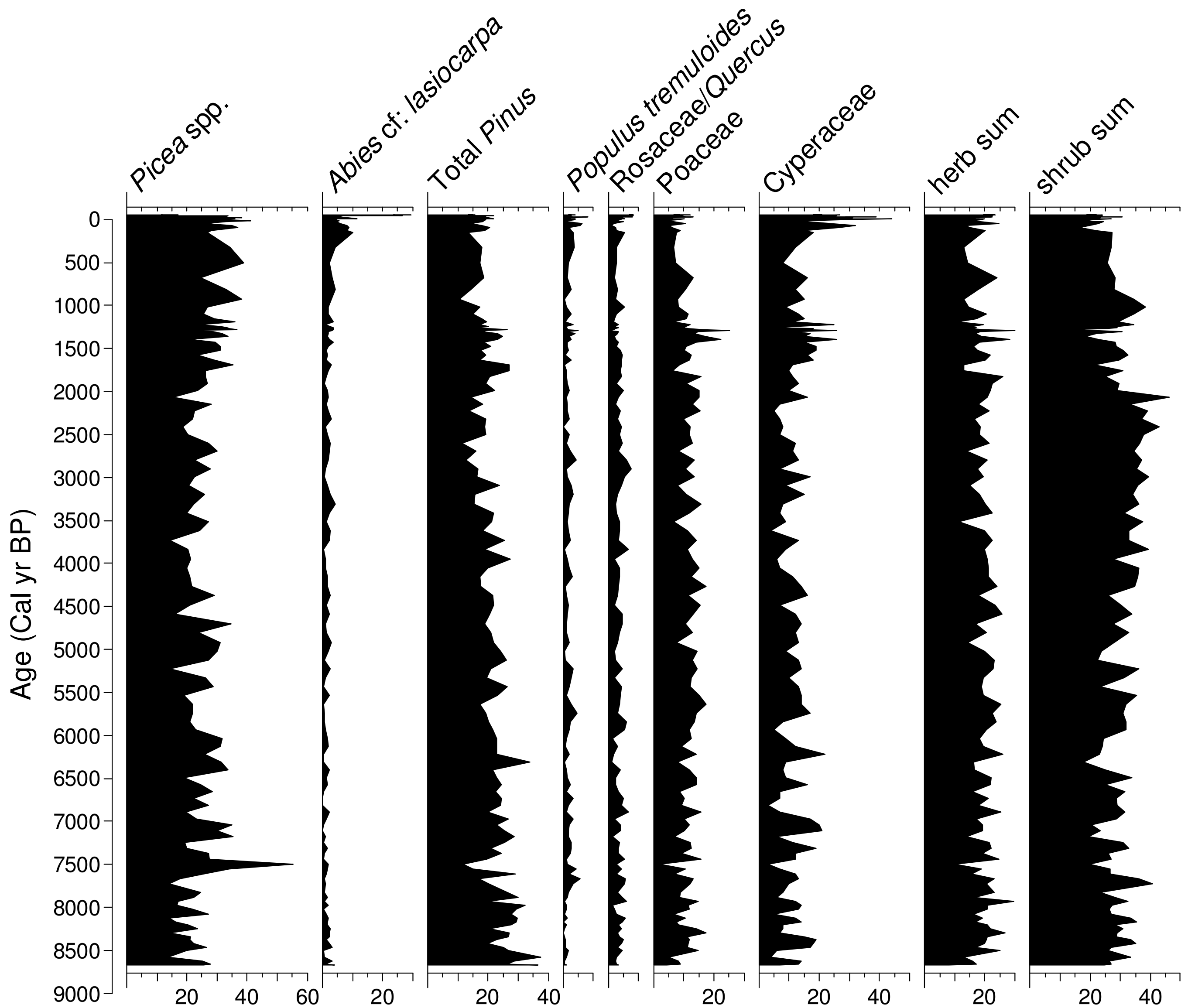

Figure 25. Pollen data for select taxa for Morris Pond located on the Markagunt Plateau.

Markagunt Plateau

Records of vegetation change from the MP are presented as selected taxa from Morris Pond (Morris, J.L., unpublished data) (Fig. 21c). Pollen data indicate that forest conditions have been principally spruce-fir with pine over the last ~9 000 years. Like Emerald and Purple lakes, Morris Pond pollen exhibits little variation, though pine is slightly more abundant during the early Holocene relative to the remainder of the record. Fir percentage gradually increases beginning at ca. 3,000 cal yr BP. The Morris Pond fire record suggests that large peak magnitude fire events are rare. Two large peak magnitude events occurred between 7,400 and 6,400 and exceed 400 cm-2/peak-1. Following these comparatively large magnitude fire events, background charcoal is variable while peak magnitudes are comparatively small (≤ 2 particle cm-2/peak-1). Following these relatively large fire events during the mid-Holocene, MFRI becomes higher than elsewhere in the record (~800 years between episodes).

Discussion

The longitudinal profile of sites presented in this study allows for an interpretation of how fire recurrence has responded to variations in insolation and Pacific Ocean teleconnections over the last 9,000 cal yr BP. The objective of this study was to explore how changes in the major climate forcing mechanisms have influenced fire occurrence in the subalpine zone of the SW realm of North America.

Early Holocene (9,000 to 6,000 cal yr BP)

Early Holocene climate in western North America was strongly seasonal where insolation anomalies lead to warmer-than-present summers and cooler-than-present winters (Berger and Loutre, 1991; Kutzbach et al., 1998). Higher-than-present summer insolation invigorated the North America Monsoon (NAM) and growing season conditions in much of the SW, including southern Utah, were wetter-than-present (Mock and Brunelle-Daines, 1999). Moy et al. (2002) suggest that El Niño events were essentially absent during this period and therefore, climate and seasonal precipitation and temperature regimes were predominantly influenced by insolation (Kutzbach et al., 1998; Berger and Loutre, 2001).

The early Holocene fire histories between 38˚ and 37˚ N (Purple Lake and Morris Pond) are consistent with strong seasonal contrasts. The largest magnitude fire episodes observed in both Morris Pond and Purple Lake records occur during this period. We interpret these fire events as the result of high summer insolation causing more rapid melting of snowpack, therefore creating a longer fire season. The period between 7,400 to 6,400 cal yr BP was interpreted to be the driest period observed during the Holocene in the Lowder Creek Bog record on the MP (Anderson et al. 1999). Fire in the western US generally occurs between May and October (Westerling et al., 2003) but an advance of the annual hydrograph by several weeks (or more) will have nonlinear effects on fire occurrence (Westerling et al., 2006), suggesting that lengthening of fire season occurred across the region during the early Holocene. Pollen-inferred vegetation conditions from Purple Lake and Morris Pond indicate a greater percentage of pine (likely limber pine), which is probably due to a greater recruitment following fire (Peet, 1981).

In contrast, the Emerald Lake (39˚ N) reconstruction exhibits low charcoal accumulation and few, small magnitude charcoal peaks during the early Holocene. Burning at Emerald Lake is generally out of phase with the Purple Lake and Morris Pond charcoal records during this period (Figs. 22 and 23). The winter moisture dominance observed during the historic period (Fig. 19) suggests that summer moisture deficits may have limited the accumulation of fine ground fuels. Stand structure during this period is inferred to be open and park-like based on relatively low pollen accumulation rates (Brunelle et al., in review). At Emerald Lake, the occurrence of large fire was limited until the development of closed canopy forest conditions that were probably facilitated by the long-term increase of snow relative to rainfall over the Holocene (Anderson et al., 2011).

Middle Holocene (6,000 to 3,000 cal yr BP)

During the mid-Holocene, Emerald and Purple lakes both exhibit frequent fire episodes (MFRI ~200 years between episodes) though there are noticeable differences in peak magnitude between the two sites (40 vs. 20 cm-2/peak-1, respectively) (Fig. 23). The virtual absence of charcoal and fire peaks during this time period at Morris Pond is in contrast to the Emerald and Purple Lake records. The MFRI at Morris Pond indicates ~900 years between fire episodes which are nearly 3x the return interval at the other sites. The absence of fire at Morris Pond was probably due to frequent, intense summer precipitation.

Because of the higher elevation AqP, shrub and herb assemblages suggest more mesic warm season conditions during the early and late Holocene and generally arid conditions during the mid-Holocene (Fig. 21b). However, closer examination of the pollen taxa reveals that shrubs and herbs sensitive to water table and/or lake level decline (e.g., cattail, sedge) during this period. Because water table and lake level is controlled by snowpack (Friedman et al., 2002; Dutton et al., 2005), this suggests that these decreasing pollen taxa are likely responding to water table moisture and not summer precipitation.

It is interesting that the pollen spectra from the Markagunt (Morris Pond and Lowder Creek Bog- southernmost sites) does not suggest ecosystem change or indicate drought, whereas both Emerald and Purple Lake records indicate drier conditions through reductions in sedge. Mid-Holocene moisture dynamics in southern Utah are probably reflecting dry winters (La Niña) and wet summer conditions (invigorated NAM), though the NAM probably did not extend north to the WP. Mock and Brunelle-Daines (1999) determined that effective moisture on the Colorado Plateau during this period was essentially unchanged from modern, though sites further north were considerably drier. Considering the evidence for winter drought from persistent La Niña conditions, summer precipitation (i.e., monsoonal) would have to be substantial to meet the needs of most plants communities, which exhibit little change through the mid-Holocene across the study area. Furthermore, chironomid-inferred summer temperature suggests that summer temperatures were very warm during the mid-Holocene (peaking at 5,400 cal yr BP), reiterating that summer precipitation must have been substantial during this period to meet the needs of plant communities (Reinneman et al. 2009).

Late Holocene (3,000 cal yr BP to present)

Fire is generally absent from all three sites during the late Holocene, which is consistent with decreasing summer insolation (Kutzbach et al., 1998) and increasing winter snowpack (Anderson et al., 2011) causing a shortening of fire season. While it is probable that small, isolated fires were occurring (Brown et al., 2008), our records suggest a general absence of frequent, large magnitude wildfire episodes such as those recorded during the early Holocene at Purple Lake and Morris Pond and during the mid-Holocene at Emerald Lake. Increasing amplitude and frequency of ENSO events (Moy et al., 2002) is coincident with regional decreases in burning at subalpine elevations in the SW over the last 3,000 cal yr BP. Infrequent fire during the late Holocene is due, at least in part, to greater amounts of snowpack (Anderson, 2011) from increasing frequency and amplitude of El Niño events (Moy et al., 2002) and cooler summers from declining summer insolation (Berger and Loutre, 1991; Kutzbach et al., 1998).

Conclusions

Because subalpine spruce-fir forests are not generally fuel limited systems, they require extremely dry conditions to be favorable for burning (Bessie and Johnson, 1995; Baker, 2000; Veblen, 2003). Typically, such conditions occur in the SW by either significant reductions in snowpack from variations in ENSO (La Niña conditions) and/or more rapid melting of snowpack by warm spring and summer conditions. Westerling et al. (2006) suggest that lengthening of fire season will provide greater opportunity for more numerous, severe fire episodes in the western US. While this assessment is valid for the vast majority of the west (particularly summer-dry sites), the subalpine plateaus of southern Utah provide exception to this assessment. During the relatively warm conditions during the Holocene, winters were dry from a persistent La Niña state in the Pacific Ocean while warmer temperatures allowed for the development of convective storms that are enhanced by orographic uplift onto the subalpine plateaus of southern Utah, excluding fire.

Despite examples from tree ring records, La Niña conditions alone do not appear to be the driver of increasing fire frequency and larger magnitude events on the sites we examined in south-central Utah. Similarly, modeled PDSI using only winter precipitation indices such as PDO and ENSO do not address key summer moisture inputs that are both significant and important in higher elevations on the Colorado Plateau. Because of the high elevation and incursions of moist 'monsoonally-derived moisture' (*sensu* Tang and Reiter, 1984) during summer months, using winter precipitation is not an adequate predictor for fire in this region.

Summer moisture and temperature conditions are important factors affecting fire occurrence. The strength and northern extent of the North American Monsoon is an important factor in regulating growing season moisture, fuel moisture conditions, and providing potential sources of ignition. Summer temperature influences fire season length and whether spring and fall precipitation arrive as rain or snow. Summer precipitation (promotes or inhibits) the development of biomass in herbaceous and shrubby fuels and increases stand density in arboreal species that require or are adapted to utilize precipitation arriving as rain (e.g., Engelmann spruce).

These fire chronologies are among the first Holocene records to emerge from the SW that are receiving ample precipitation during both summer and winter seasons and providing interpretive power over millennial timescales to variations in ENSO and the NAM. These sites are situated roughly along a longitudinal profile and more records within this region are required to assess how moisture boundaries and fire occurrence have changed through time. Specifically, Holocene-length sedimentary charcoal records from the northern Wasatch Plateau (40˚ N 110˚ W) and further west in the study area such as the Tushar Mountains (39˚ N, 112˚ W) would afford a robust regional perspective of long-term wildfire and climate relationships.

CHAPTER 5

CONCLUSIONS

The objectives of the research presented and discussed here address a need to better understand the relationship between fire and bark beetle disturbances in south-central Utah. Of particular interest was if evidence exists suggesting that bark beetles and wildfire interact during climatic periods different than modern during the Holocene. To accomplish this objective, an analytical methodology for assessing bark beetle outbreaks prior to the historic period was required. In the absence of secondary supporting evidence, pollen mirrors stand-level observations concurrent with spruce beetle outbreaks. Host to nonhost ratios are useful in describing spruce beetle mortality and offer a starting to point to pursue other lines of evidence.

Forest fire disturbances in central and southern Utah are modulated by climate, and fire recurrence and magnitude exhibits a considerable range of variability during the Holocene. ENSO is an important driver of winter precipitation in this region, while the moisture derived from the North American Monsoon also provides a significant warm season precipitation input. Both seasonal precipitation indices are significant drivers (or suppressants) of fire recurrence in this region. Vegetative in the subalpine forest zone, from a palynological perspective, appears to be resilient to a wide range of climatic conditions and fire disturbance regimes over the last 10,000 years.

To disseminate the findings of these data to both land managers and the public, interpretive signs and brochures will be distributed in beetle-affected forests that were examined during this project. Chapters 2-4 will be submitted for peer-reviewed publication in relevant academic journals. Several addition manuscripts will be derived from this project, which will also be submitted for peer review. Manuscripts include a high-resolution Holocene pollen record from the Markagunt Plateau as well as high-resolution pollen and charcoal record spanning the last 6,000 cal yr BP from Thousand Lakes Mountain in central Utah.

Future work related to this project includes analyzing the historic sediment cores (Chapter 2) stable isotopes, specifically carbon ($\delta^{13}C$) and nitrogen ($\delta^{15}N$) (CN hereforward). Stable isotopes potentially offer an affordable and practical means that might provide a secondary line of supporting evidence for reconstructing bark beetle outbreaks. CN from lake sediments reflects whether organic particulates in sediments originate from terrestrial (N-rich) or aquatic (N-depleted) locations, and variations in CN through time provides information about land cover/land use changes from 'naturally' occurring disturbances and from anthropogenic modifications.

The rationale for using CN to address bark beetle disturbances is two-fold. First, bark beetles must kill their host trees in order to successfully reproduce. This is achieved as thousands of synchronously attacking beetles colonizing many individual trees en masse to overcome a host tree's defenses. They enter a host tree by chewing through the bark, creating copious amounts of boring dust (called frass). The beetles feed and nest in the phloem tissue, which disrupts the ability of a tree to transport water and nutrients to its crown where photosynthesis takes place, thus killing the tree. Beetles emerge and seek host trees in early June and in the Rocky Mountains, snowpack is common at this time of year. Observations during peak beetle emergence document tremendous amounts of frass on the snow around attacked trees. When the snow melts, it transports the frass into surface water and ultimately is deposited in lakes. Second, within three years of attack, trees desiccate and lose their needles, generating an additional pulse of mobile terrestrial organic material into lakes. The spike in terrestrial organic material from the boring dust and needles should clearly register in the CN ratio.

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