A 2000-year Environmental History of Jackson Hole Wyoming Inferred from Lake-sediment Records

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ABSTRACT

Little is known about the disturbance history of low-elevation forest and steppe vegetation in the western U.S., nor about the relative importance of climate and human activity in shaping present-day plant communities. Pollen and high-resolution macroscopic charcoal records spanning the last 2100, 1000, and 550 cal yrs were analyzed from three small lakes in Jackson Hole to reconstruct the vegetation and fire history along a gradient from steppe to dry forest. The pollen data suggest little change in vegetation in the last two millennia, aside from a long-term trend towards more forest at the expense of steppe. One site showed an expansion of mesophytic taxa in the last 350 years, as a result of local changes in hydrology, and another site was dry prior to AD 1000 and showed fluctuations in steppe composition thereafter. The longest record suggests that fire frequency was higher prior to AD 1200 than afterwards. Comparison of the three charcoal records for the last 550 years indicates widespread fire episodes in AD 1980-2000, 1780-1810, ca. 1550, and 1420-1430. Changes in the vegetation and fire history of the last 2000 years show a response to effectively prior to AD 1200 and wetter conditions during the Little Ice Age. Evidence of human influences was muted at best. Native Americans apparently did not alter the vegetation and fire regimes significantly during their occupation of Jackson Hole. Euro-American activities also had minor registration in the paleoecologic record: humans may have been responsible for fires in the mid and late 19th century and indirectly for the recent expansion of forest at the end of the 20th century.

Key words: Grand Teton National Park; fire history; vegetation history; last 2000 years

INTRODUCTION

Evaluating present-day forest health in the western U.S. requires an understanding of the natural variability of ecological processes, including the long-term impact of climate change and natural disturbances on plant communities (Whitlock et al. 2003; McKenzie et al. 2004), as well as the role of past and present human activity. The last 2000 years is often used as a reference period to assess modern ecosystem conditions, because comprehensive tree-ring data provide independent climate information during this time (Cook et al. 2004), and it is possible to examine ecological response to well-documented climate events, such as the Medieval Climate Anomaly (ca. AD 900-1300; Hughes and Diaz 1994; Pierce et al. 2004) and the Little Ice Age (ca. AD 1350-1850; Carrara 1989; Luckman 2000). In addition, this period provides an opportunity to consider the impact of Native American and Euro-American activities on vegetation and fire regimes.

Grand Teton National Park (GTNP) in northwestern Wyoming protects a region of rugged mountains, pristine lakes, and a rich native fauna and flora (Fig. 1). The vegetation is arrayed by elevation with sagebrush (*Artemisia tridentata*) steppe growing below approximately 2000 m elevation on the valley floor of Jackson Hole (botanical nomenclature follows Shaw (2000) and references therein). At higher elevations in the Teton and Gros Ventre ranges (2000-2400 m elevation), steppe is replaced by forests of lodgepole pine (*Pinus contorta*) and Douglas-fir (*Pseudotsuga menziesii*). Engelmann spruce (*Picea engelmannii*), subalpine fir (*Abies lasiocarpa*) and whitebark pine (*P. albicaulis*) grow at higher, more-mesic elevations (2400-2900 m elevation) and form the upper treeline. Alpine meadows and tundra lie above approximately 2900 m elevation on the highest peaks of the Teton Range (Clark 1981).

Historical and archeological data show a long history of human occupation of the valley. Early native encampments are recorded throughout the Holocene and shifts have been noted in their use of the valley during the late Holocene (Connor 1998). Euro-Americans have been in the region for the last 200 years (Daugherty 1999), first as trappers and miners, then as ranchers, and more recently as tourists and recreationalists. Grand Teton National Park was first created in 1929 and included only the Teton Range and the large glacially dammed lakes at the mountain front. Later, Jackson Hole National Monument and other land parcels were included, and the present national park was established in 1950 (Daugherty 1999).

The postglacial vegetation and climate history of the Grand Teton and Yellowstone region has been described in Baker (1976) and Whitlock (1993), but the history of the low-elevation dry forest and steppe in Jackson Hole has been poorly studied. To fill this gap in our understanding, an environmental history of the last 2100 years was developed based on paleoecologic data obtained from the sediments of three small lakes. Pollen, charcoal, and lithologic records from each site permitted a reconstruction of local changes in vegetation, fire regimes, and hydrology that could be compared with climate and human impact data from other sources. The lakes were selected along a north-south transect within Jackson Hole to capture a range of habitats (Fig. 1):

Swan Lake (lat. 43.89°N, long. 110.63°W, elevation 2072 m) is located on late-Pinedale ground moraine, and is the wettest site with the most extensive forest cover. The site is surrounded by closed lodgepole pine forest, but sagebrush steppe and meadow communities grow in forest openings and on the Pilgrim Creek alluvial fan to the south and east of the site. The fan dams the lake and creates a large riparian community of Engelmann spruce, blue spruce (*Picea pungens*), subalpine fir, willow (*Salix* spp), and thinleaf alder (*Alnus incana*) to the east.

Pothole Lake (lat. 43.78°N, long. 110.62°W, elevation 2033 m) is located in the center of the Jackson Hole and represents the driest site. Sagebrush steppe communities surround the site and are the dominant plant community of Jackson Hole as a result of well-drained gravelly glacial outwash of late-Pinedale age (Good and Pierce 1996). Scattered exposures of glacial till near Pothole Lake support stands of Douglas-fir and lodgepole pine, and springs support local wetland and aspen (*Populus tremuloides*) communities.

Hedrick Pond (lat. 43.73°N, long. 110.59°W, elevation 2048 m) lies near the boundary between forest in the Gros Ventre Range to the east and sagebrush steppe in Jackson Hole to the west. It is considered a transitional site in the moisture gradient between Swan and Pothole lakes. The steep slopes and morainal soils favor forests of lodgepole pine, and lesser amounts of Douglas-fir, subalpine fir, and common juniper (*Juniperus communis*). The well-drained glacial outwash to the south of Hedrick Pond and forest openings support steppe vegetation and meadow communities. *Populus tremuloides* (quaking aspen) stands grow near wet seepages.

METHODS

Field

Sediment cores were collected in 2005 with a 5-cm-diameter modified Livingstone square-rod piston sampler (Wright et al. 1983) in the deepest portion of each lake from the ice surface in winter and from an anchored floating platform in summer. Cores were extruded in the field, wrapped in plastic wrap and aluminum foil, and taken to the Montana State University Paleoecology Lab where they were refrigerated. In addition, short sediment cores were taken from each site with a 7-cm-diameter Klein piston corer to recover the mud-water interface and the upper half-meter of sediment. Each short core was sub-sampled in the field at 1-cm intervals, and samples were stored in Whirlpak bags and refrigerated.

Laboratory

Loss-on-ignition (LOI) analysis was undertaken to measure the organic and carbonate content of the sediment and provide information on lake productivity (Dean 1974). LOI samples of 1-cm^3 volume were taken at contiguous 1-cm intervals to a depth of 20 cm in the Hedrick Pond short core and for every other cm to 60 cm depth. In the long core, samples were taken every 5 cm. In the Pothole Lake short core, contiguous 1-cm intervals were sampled to a depth of 14 cm, and at 2-cm intervals to 66 cm depth. At Swan Lake, contiguous 1-cm intervals were sampled to a depth of 8 cm in the short core and at 5-cm intervals in the long core. Samples were dried at 90°C for 24 hours and ashed for two hours at 550°C and then two hours at 900°C. Weight-loss after each treatment was used to calculate percentage of dry weight, organic content, and carbonate content, respectively (Dean 1974).

Magnetic susceptibility, an indicator of deposition of mineral soil or fire-created detrital magnetite or maghemite (Thompson and Oldfield 1986), was measured with a Bartington MS2 magnetic susceptibility cup sensor and ring sensor. Contiguous 10 cm^3 samples were analyzed in the long and short cores from the Hedrick Pond and Swan Lake with the cup sensor, and 10 cm^3 samples were analyzed at 2-cm intervals with the ring sensor in the Pothole Lake core.

Charcoal

Macroscopic charcoal analysis was performed on contiguous 1-cm interval samples to reconstruct the local fire history for each site, following the modified sieving approach of Whitlock and Larsen (2001). Samples of 3 cm^3 (Hedrick Pond and Swan Lake) and 4 cm^3 (Pothole Lake) were soaked in a solution of 5% sodium metaphosphate and 6% bleach for 24 hours and washed through nested sieves (mesh size 250 and 125 μ). Charcoal particles >125μ in minimum diameter were examined because they have been shown to record local fire activity (Whitlock and Larsen 2001). Residues were placed in a gridded Petri dish and identified under a stereoscope at magnifications of 120 and 250x. Charcoal counts were divided by sample volume to calculate charcoal concentrations (particles cm^{-3}). Concentrations and sedimentation rates were interpolated to pseudo-annual values and then binned in 10-yr-long intervals. Charcoal accumulation rates (CHAR; particles cm^{-2} yr^{-1}) were calculated by dividing charcoal concentration by the deposition time of the sediment (yr cm^{-1}). Interpolation of concentration values to pseudo-annual values followed by binning and calculation of CHAR preserved the total number of particles accumulated over time. CHAPS software (Bartlein, unpub.) was used.

Pollen

Pollen samples were taken at 4- to 6-cm intervals (Hedrick Pond), 4-cm intervals (Pothole Lake), and 3-cm intervals (Swan Lake). Samples were processed following methods of Faegri et al. (1989), but with the use of Schulze's solution in place of acetolysis (e.g., Doher 1980). Pollen preparations were mounted in silicone oil and examined under magnifications of 400 and 1000x. Identifications were based on a comparison of published atlases and keys (e.g., Kapp et al. 2000;

Moore and Webb 1978). Whenever the distal membrane was preserved, pine pollen was separated into diploxylon-type (*Pinus contorta*) and haploxylon-type (*P. flexilis, P. albicaulis*). The addition of unidentifiable *Pinus* grains yielded Total *Pinus*. Grains that could not be identified were designated as Unknown (<1% of total pollen in all samples); grains that were deteriorated, corroded, or severely broken were designated as degraded (not shown on diagram).

Percentages of terrestrial pollen types were tallied based on the sum of all terrestrial taxa. Percentages of aquatic taxa were based on the sum of all terrestrial, aquatic and wetland taxa. Pollen records were zoned using CONISS, a constrained cluster analysis (Grimm 1987) of the dominant taxa in the percentage data. A known amount of *Lycopodium* spores was added as a “spike” to each sample to calculate pollen concentrations (pollen cm^{-3}). Concentration data were divided by the calculated deposition time (yr cm^{-1}) of each sample to calculate pollen accumulation rates (PAR; pollen cm^{-2} yr^{-1}).

RESULTS

Lithology and Chronology

Chronologies for the sites were based on a series of AMS ^{14}C and ^{210}Pb dates taken on terrestrial plant macrofossils (Tables 1 and 2). Radiocarbon ages were converted to calendar years using the CALIB program of Stuiver et al. (2005). This suite of age determinations was fitted with a polynomial to develop a smooth age-depth model. Calibration of ^{14}C dates yielded multiple age possibilities in most cases, and the mean age with the highest probability was used. ^{210}Pb dates have errors of years (for the youngest) to decades (for the oldest) in general. Specific ages were based on the polynomial regression, but it is important to recognize that the error around age assignments ranges from years to decades. Throughout the Results and Discussion, ages <950 cal yr BP are presented first in years AD.

At Hedrick Pond, a 137-cm-long core was recovered from beneath 4.70 m of water. The sediments consisted of homogeneous fine detritus gyttja (Fig. 2). Two AMS ^{14}C dates (Table 1) were obtained on terrestrial plant macrofossils from 69 and 137 cm depth (below mud surface), and.

Fourteen ^{210}Pb dates were obtained from the top 14 cm of the core (Table 2). The AMS ^{14}C and ^{210}Pb dates were fitted with a 3rd-order polynomial age-depth model. The base of the core was dated at 2182 cal yr BP. The organic content of the Hedrick Pond core varied between 40 and 60%, and $CaCO_3$ content was <10% (Fig. 2). Magnetic susceptibility was very low through the core, and variations in values were not associated with those in charcoal concentration, as was found at sites in Yellowstone National Park (e.g., Millspaugh and Whitlock 1995; Millspaugh et al. 2000).

At Pothole Lake, a 66-cm-long short core was recovered from 2.10 m of water. The base of the cores was crumbly silty clay with fine rootlets that appeared to be a buried soil. It was overlain by silty detritus gyttja (17-65 cm depth), which graded upwards into a fine detritus gyttja. An inorganic clay unit was present from 15-25 cm depth. Two AMS ^{14}C dates were obtained at 33 and 48 cm depth (Table 1). Twelve ^{210}Pb dates were obtained from the top 12 cm of the core (Table 2). A 3rd-order polynomial age-depth model was fitted to the AMS ^{14}C and ^{210}Pb dates. The base of the core was extrapolated to 2136 cal yr BP, but the limnic part of the record analyzed in this study began at ca. 990 cal yr BP (48 cm depth).

The organic content of the Pothole Lake core varied between 25 and 40%. The $CaCO_3$ content was generally <10% except for a peak (15%) at 8 cm depth. Low organic content and high magnetic susceptibility were associated with the clay unit. Magnetic susceptibility was high from 66 to 50 cm depth, suggesting high input of allochthonous inorganic material to the lake. The shift to limnic sediments (i.e., gyttja and clay) at 990 cal yr BP marks the time when the basin held water year-round.

At Swan Lake, a 73-cm-long core was recovered from beneath 3.30 m of water. The core consisted of dark brown clay with roots at its base (60-73 cm depth), overlain by gray-brown clay (29-60 cm depth), and fine detritus gyttja (0-29 cm depth). An AMS ^{14}C date from the clay unit had an age of 510 cal yr BP, and 12 ^{210}Pb dates were obtained from the top 12 cm of the core (Tables 1 and 2). The age-depth model based on the ^{210}Pb dates was incongruent with that based on the AMS ^{14}C date. Therefore, a 4th-order polynomial age model based on the ^{210}Pb dates was used for the top

12 samples, and a linear model that included the oldest ^{210}Pb date and the AMS ^{14}C date was used for the remainder of the core. The base of the Swan Lake core was linearly interpolated to 540 cal yr BP.

Organic content in the Swan Lake core varied between 10 and 90%. $CaCO_3$ content was <10%. A significant drop in organic content between 20 and 60 cm depth and a rise in magnetic susceptibility were associated with the gray brown clay unit. The clay is attributed to the creation of the lake, which was dammed by the build up of the Pilgrim Creek alluvial fan (K. Pierce, unpublished data, 2007). Occasional overbank flood events during this build-up period spilled into Swan Lake from the Pilgrim Creek drainage and deposited the clay.

Charcoal Records

The CHAR time series were divided into two components (Long et al. 1998). Background CHAR (BCHAR), or the low-frequency slowly varying component, was determined using a locally-weighted (moving) average through the time series, where the width of the weight function (window width) controlled the smoothness of the curve. For all sites, a standard window width of 500 years was used to calculate BCHAR to match other studies in the region, and variations in BCHAR were ascribed to changes in regional fire activity and fuel biomass (Marlon et al. 2006). BCHAR at all sites showed little change through time, consistent with the pollen data (see below). The values, however, were highest overall in the most mesic site (Swan Lake) and lowest in the steppe site (Pothole Lake), and this difference probably reflected the higher fuel biomass in the more forested location.

Positive deviations of CHAR (i.e., charcoal peaks) above BCHAR were interpreted as charcoal accumulation during one or more local fires (so-called fire episodes). The peaks were identified as levels that exceeded a prescribed threshold ratio of total CHAR to BCHAR (a threshold ratio of 1.0, for example, would identify all CHAR peaks that exceed the BCHAR level as fire episodes). A threshold ratio of 1.15 was used in this study because it produced charcoal peaks that corresponded in time with known fires in the vicinity of each site (Loope 1974; Grand Teton National Park Fire Management Office, unpublished data, 2006). The ratio also resulted in few spurious charcoal episodes in the uppermost record, i.e. ones that did not match known fires. Unlike other studies that consider the fire episode to represent a single time marked by the beginning of the charcoal peak (e.g., Long et al. 1998; Millspaugh et al. 2000), we conservatively identified fire episodes as the entire time span of the peak (i.e., the time when the threshold ratio was first exceeded to the time when CHAR values dropped below the ratio). With our approach, fire episodes were decades long and considered to be periods of high fire activity, rather than single fire events.

The average resolution of the Hedrick Pond charcoal record was approximately 17.5 years cm^{-1}. BCHAR ranged between 0.22 and 0.13 particles cm^{-2} yr^{-1} (Fig. 3). In the last 500 cal yr, background CHAR decreased from about 0.20 to ~0.1 particles cm^{-2} yr^{-1}. In the last 900 cal yrs, fire episodes, i.e. charcoal peaks above the threshold, were relatively infrequent and several spanned long intervals. Episodes occurred between AD 1980-2000 (-30 - -50 cal yr BP), AD 1780-1850 (170-100 cal yr BP), AD 1740-1750 (210-200 cal yr BP), AD 1540-1550 (410-400 cal yr BP), AD 1400-1500 (550-450 cal yr BP), and AD 1060-1150 (890-800 cal yr BP). Prior to that, fire episodes were more frequent and spanned shorter intervals. Older episodes were recorded at 1020-1040, 1160-1180, 1210-1230, 1250-1280, 1380-1420, 1570-1610, 1640-1730, 1910-2000, 2070, and 2110-2120 cal yr BP.

At Pothole Lake, the deposition time for each sample was approximately 27.2 years cm^{-1}. BCHAR was low, ranging from 0.02 to 0.09 particles cm^{-2} yr^{-1}. A large peak in CHAR (0.29 particles cm^{-2} yr^{-1}) occurred at ca. AD 1800 (ca. 150 cal yr BP) (Fig. 4). Fire-episodes in the last 400 cal yr were dated from AD 1980-2000 (-30 - -50 cal yr BP), AD 1760-1810 (190-140 cal yr BP), AD 1650-1670 (300-280 cal yr BP), and AD 1550-1570 (400-380 cal yr BP). Earlier episodes occurred at AD 1390-1450 (560-500 cal yr BP), AD 1260-1300 (690-650 cal yr BP) and AD 1010-1110 (940-840 cal yr BP).

The Swan Lake charcoal record had a sampling resolution of approximately 9.6 years cm^{-1}. BCHAR levels were highest at AD 1400 (550 cal yr BP) (1.09 particle cm^{-2} yr^{-1}) and declined from AD 1400 to 1750 (550 to 200 cal yr BP) to ~1 particle cm^{-2} yr^{-1}and decreased to ~0.3 particles cm^{-2}

year^{-1} at present (Fig.4). Fire episodes occurred at AD 1980-2000 (-30 - -50 cal yr BP), AD 1920 (30 cal yr BP), AD 1860-1870 (90-80 cal yr BP), AD 1770-1830 (180-120 cal yr BP), AD 1550-1560 (400-390 cal yr BP), AD 1460-1520 (490-430 cal yr BP), and AD 1420-1430 (530-520 cal yr BP).

Pollen Records

Hedrick Pond (Fig. 3)

Average spacing between pollen samples in the Hedrick Pond core was 60 years. Zone HED-1 (86-137 cm depth; ca. 960-2130 cal yr BP) featured high percentages of *Pinus* (mostly *P. contorta*-type) (47-52%), *Artemisia* (20-30%) and Poaceae (grass family) (5-10%). *Picea*, *Abies*, Juniperus, Salix Chenopodiineae (goosefoot and amaranth families), and *Ambrosia*-type (ragweed) were present in low amounts (<5%). Total PAR averaged 1350 grains cm^{-2} yr^{-1}, and these values and the percentage data suggest that vegetation was more open than at present (Fall 1992; Whitlock 1993).

Zone HED-2 (20-82 cm depth; 90-960 cal yr BP; AD 1860-990) was characterized by increasing *Pinus* percentages (55 to 84%) and decreasing *Artemisia* values (24 to 10%). *P. flexilis*-type decreased towards the top of this zone while *P. contorta*-type increased. *Picea* occurred at its highest percentages but still in low values (<4%). *Abies*, *Salix*, and *Ambrosia*-type pollen were present in small amounts (<2%). Poaceae percentages were lower than in the previous zone (<6%). *Juniperus*-type pollen was present in low percentages at the beginning of this zone (up to 1%) and disappeared at ca. AD 1770. Total PAR increased from previous values, and the combination of high *Pinus* percentages, moderately high *Artemisia* percentages, and low *Picea* percentages is consistent with the modern pollen assemblages from lodgepole pine forest in GTNP (Whitlock 1993). It suggests an increase in forest cover near the site.

Zone HED-3 (0-20 cm depth; present-90 cal yr BP; AD 2005-1860) featured a peak in *Pinus* percentages (85%) and PAR (5700 grains cm^{-2} yr^{-1}) at ca. AD 1900. The uppermost samples returned to high percentages of *Artemisia* (~30%), *Ambrosia*-type (1-2%), and moderate percentages of *Pinus* (~60%). The percentages in this zone fall within the range of those from dry low-elevation forests in the GTNP region (Whitlock 1993), and the assemblage is consistent with the modern presence of forested and open communities at the site.

Pothole Lake (Fig. 4)

Average spacing between pollen samples in the Pothole Lake core was 125 years. Zone POT-1 (40-48 cm depth; 550-990 cal yr BP; AD 1400-960) had decreasing percentages of *Pinus* (80% at the base to 40% at the top of the zone) and increasing values of *Artemisia* (from 12% at the base to 44% at the top). *Abies* values declined to zero in the middle of this zone and Poaceae values peaked near the end of this zone at 20%. Pollen of *Betula* and *Populus* were high (20 and 29%, respectively) near the end of the zone at 40 cm depth. Other pollen taxa, including *Juniperus*-type (<2%), *Ambrosia*-type, other Asteraceae Tubuliflorae, Asteraceae Liguliflorae, Caryophyllaceae and Chenopodiineae, were poorly represented (<8%). Total PAR was low at an average of 1130 grains cm^{-2} yr^{-1} and similar to modern values from sagebrush steppe (Fall 1992).

Zone POT-2 (16-40 cm depth; 60-550 cal yr BP; AD 1890-1400) was characterized by a dominance of *Artemisia* with values up to 80%. *Pinus* percentages were very low with values consistently <20%. *Abies* pollen was not present in this zone, and *Juniperus*, *Alnus*, *Betula*, and *Salix* were occurred in small amounts (<5%). *Ambrosia*-type, Asteraceae Tubuliflorae and Liguliflorae, and Chenopodiineae pollen were present in slightly higher amounts (<10%) than before. Total PAR was low, at an average of 800 grains cm^{-2} yr^{-1}, which is consistent with values for sagebrush steppe in the region (Fall 1992).

Zone POT-3 (0-16 cm depth; present-60 cal yr BP; AD 2005-1890) featured a sharp increase in *Pinus* (70%) and the reappearance of *Abies* pollen (also present in the lowest sample of Zone POT-1) in the uppermost sample. At other levels, *Artemisia* (18-60%), *Ambrosia*-type (1-3%), other Asteraceae (2-8%), and Chenopodiineae (2-13%) were high, and Caryophyllaceae percentages were highest (~12%) in this zone. PAR reached highest values, ranging from 6000 to 13,000 grains cm^{-2} yr^{-1} at the top. The dominance of *Artemisia* and other herbs, as in Zone POT-2, is similar to the modern pollen rain from steppe communities in the region (Whitlock 1993).

Swan Lake (Fig. 5)

The average spacing of pollen samples in the Swan Lake core was 27 years. Zone SW-1 (53-73 cm depth; 375-520 cal yr BP; AD 1575-1430) was dominated by *Artemisia* (15-70%) and had moderate percentages of *Alnus* (1-3%), Salix (1-12%), and Chenopodiineae (3-16%). Percentages of *Pinus*, largely from *P. contorta*-type, were low (<25%), except for one high interval (85%) at 59 cm depth. *Picea* and *Abies* were present in low amounts (<2%). *Ambrosia*-type reached its highest amounts (up to 4%) in this zone, and Asteraceae Liguliflorae was present in trace amounts (<1%). Total PAR ranged from 4000 to 12,000 grains cm^{-2} yr^{-1}, which is consistent with other steppe areas (Fall 1992); *Artemisia* percentages were somewhat higher than those from modern steppe in GTNP (ca. 12-25%) (Whitlock 1993).

Zone SW-2 (35-53 cm depth; 220-375 cal yr BP; AD 1730-1575) featured the highest *Pinus* percentages (52-90%) of the record. *Artemisia* and Chenopodiineae percentages dropped from the previous zone (to <14 and <4%, respectively). Total PAR did not change appreciably from the previous zone. *Pinus contorta*-type percentages (42-78%) were equal or higher than modern values from pine forests in GTNP (Whitlock 1993).

Zone SW-3 (0-35 cm depth; present-220 cal yr BP; AD 2005-1730) was characterized by alternating peaks of *Pinus* and *Picea* percentages. Total *Pinus* percentages ranged between 40 and 80%, and *Picea* percentages ranged between 0 and 50%. *Abies* pollen was present through this zone in low amounts (<2%). *Artemisia* percentages declined from 12% at the base of the zone to 3% at the top. The top two samples (AD 1993-present) showed a slight decrease in total *Pinus* (59-55%) and a peak in *Picea* (to 32%), *Abies* (to 3%), *Salix* (to 3%), and Poaceae (to 3%). Total PAR changed little in this zone, except for a peak near AD 1980 of 41,000 grains cm^{-2} $year^{-1}$, which is largely a result of an increase in *Pinus* PAR at 28,000 grains cm^{-2} yr^{-1}.

DISCUSSION

Environmental History in Jackson Hole

The local vegetation and fire histories were compared (Figs. 3, 4, and 5) to develop a better understanding of the environmental history of Jackson Hole. In addition to the stratigraphic trends of individual pollen types, trends in the arboreal pollen percentages (AP) and PAR help disclose the relative importance of forest over steppe taxa through time (Whitlock and Bartlein 1997). Hedrick Pond provides information on the entire 2100-year period, Pothole Lake spans the last ca. 1000 cal yrs, and Swan Lake data cover the last 550 cal yrs.

Persistent high values of *Pinus* and *Artemisia* pollen at Hedrick Pond show little change (with the exception of a single sample), and it seems likely that the mix of the forest and steppe communities at this site has not changed substantially in the last 2100 years. The slightly lower AP before AD 970 implies that somewhat more open vegetation than at present and in the last 1000 years forest cover has apparently increased. This trend toward more forest cover has been noted at other sites in the region and may be part of shift towards cooler wetter conditions during the late Holocene (Whitlock 1993). The sharp increase of *Pinus* at ca AD 1900 is based on a single sample and not easily interpreted, but it comes after several fires in the 19th century and may be related to forest regeneration.

The pollen records from Pothole and Swan lakes, in contrast, indicate significant changes in local vegetation that are probably a response to shifts in hydrology. Pothole Lake apparently has had a history of fluctuating water levels, and it was dry or only seasonally wet prior to ca. AD 960, the beginning of our record. AP values, mostly from *Pinus*, were initially high, although *Pinus* PAR was low, and some grains were degraded, which is consistent with an initially dry basin. As the site became wetter, the sediments became more organic and limnic, and percentages of *Artemisia* pollen increased between ca. AD 1100 and 1890. It seems likely that this increase marks a shift to a local steppe pollen source area as the lake developed, rather than a vegetation change. Notable increases in *Betula*, *Populus*, and Poaceae pollen occurred at ca. AD 1300 and at AD 1820, suggesting brief wet periods that increased the representation of mesophytic taxa. Both Pothole and Swan lakes show an increase in conifers in the late 20th century.

The Swan Lake area supported sagebrush steppe with Chenopodiineae between AD 1430 and 1575, as evidenced by low AP percentages, high values of *Artemisia* (Fig. 5), and evidence of riparian communities of *Alnus* and *Salix*. By ca. AD 1575, *Artemisia* decreased and *Pinus* increased, marking a shift from steppe to more closed lodgepole pine forest. *Picea*, *Alnus*, and *Salix* percentages increased after ca. AD 1670, and their abundance has fluctuated in recent centuries. These taxa grow in riparian forest along Pilgrim Creek, and fluctuations in their pollen abundance may signify short-term changes in hydrology related to climate.

Over the last 550 years, all three sites indicate periods of fire at AD 1980-2000, 1780-1810, ca. 1550, and 1420-1430. Hedrick Pond and Pothole Lake were also compared for the previous 450 cal years of overlap and shared a broad period of high fire activity from AD 1060 to 1110 (Fig. 6). Recent fire episodes at these sites match known fire events registered in tree-ring and historical records. For example, fires were widespread in and around Jackson Hole in the 1980s, including large fires in 1986 and 1988 (Grand Teton National Park Fire Management Office, unpublished report 2006). Tree-ring records identify several fire years in Jackson Hole in the early to mid 19th century (Loope 1974), including those in the 1880s, 1870s, 1850s, and late 1700s south of Jackson Lake. Some of these dates match fires registered at Pothole Lake and Hedrick Pond (Figs. 2 and 3). Tree-ring records also indicate fires in the Colter Bay area near Swan Lake in the 1850s, and these are a likely source for charcoal peaks at about that time. A tree-ring fire date at ca. AD 1910 (Loope 1974) was not found in the charcoal record, and other fire episodes at Swan Lake in AD 1770-1830 and ca. AD 1920 are not evident in the tree-ring record (Fig. 4).

Climate and Human Influences

The pollen and charcoal records were compared with widely recognized climate events in the Rocky Mountain region (Fig. 6). The Medieval Climate Anomaly (MCA) between ca. AD 800 and 1300 was a period of low average precipitation and widespread drought in the western U.S. (Cook et al. 2004). The Little Ice Age (LIA) in the northern Rocky Mountains was a time of cooler conditions and renewed glacial activity between AD 1300 and 1900 that culminated between AD 1700 and 1900

(Carrara 1989; Luckman 2000). The Gannett Peak cirque glacial advance in the Teton Range dates between ca. AD 1450 and 1800 and is considered a LIA event. A poorly dated Audobon advance, however, occurred before ca. AD 1000 (Mahaney and Spence 1990).

The reconstructed Palmer Drought Severity Index (PDSI) of Cook et al. (2004), based on a compilation of long tree-ring chronologies throughout the United States, offers additional information on variations in effective moisture during the last 2000 years. Gridpoint 100 in the PDSI reconstruction from the GTNP region was used for comparison (Fig. 6). Although variability on interannual to decadal time scales is considerable, the PDSI data smoothed at 100-year and 500-year times showed trends that are relevant to this study. A prolonged dry period in this region extended from ca. AD 0 to 1200, while the “classic” MCA occurred at the end of this period during a time of high moisture variability. Positive values (wet) extended from ca. AD 1200 to 1900, and the LIA was part of sustained wet period within this period. Thus, both MCA and LIA are somewhat different in duration and signal at this gridpoint than elsewhere in the West.

The Hedrick Pond data suggest shorter and more frequent fire episodes prior to 1200 cal yr BP, when conditions were drier than afterwards. On shorter time scales, several fire episodes occurred during wet century-long periods, for example, centered around ca. AD 550, 790, 1100, 1300, and 1800. This relation between fire and wet periods has been described in sagebrush steppe elsewhere in the western U.S. (e.g., Mensing et al. 2006), and it is possible that wet decades increased the fine-fuel biomass, which then ignited during brief periods of drought (Tirmenstein 1999).

Swan Lake was formed near the beginning of the LIA, when the alluvial fan from Pilgrim Creek blocked its outlet. The period from ca. AD 1430 to 1575 featured three broad fire episodes and more-extensive steppe vegetation than at present. Lodgepole pine forest dominated after AD 1575, and riparian forest developed after AD 1670, accounting for the rise in AP values (Fig. 5). Fire episodes throughout this record were associated with drops in *Pinus* percentages, suggesting that the local forest was the primary fuel.

Concurrent fire activity at all three sites in the past raise the possibility that humans were a source of ignitions (Baker and Ehle 2001; Barrett and Arno 1982; Keely 2002). Native Americans have inhabited Jackson Hole for the last 10,000 years, with the oldest records dated by projectile point type (Connor 1998) (Fig. 6). Archaeological sites with roasting pits and concentrations of lithic artifacts of Holocene age are found throughout the valley. Season of occupancy, inferred from the type of roasting pits, associated utensils and food remnants (Connor 1998), indicates that the northern valley was heavily occupied in the late summer and fall from AD 0 to 1150, when the number of roasting pits reached a maximum. Between AD 1150 and 1750, more sites were found in southern Jackson Hole than before, although few were roasting pits. These later southern sites are thought to have been used in the spring and summer when food processing and storage were less important activities (Connor 1998). The Hedrick Pond record does not show a corresponding change in fire activity that might be expected with an increase in Native American occupancy of the southern region. In fact, none of the charcoal and pollen records offer evidence that could unequivocally be attributed to temporal or spatial changes in Native American use of the valley.

Trappers and fur-traders entered Jackson Hole in the early 19th century (Daugherty 1999) and may have been the first Europeans to alter the fire regime. John Colter, a member of the Lewis and Clark Expedition, was allegedly the first white man to travel through Jackson Hole in 1807. A group representing John Jacob Astor's fur trading company passed through the valley in 1811, and the Tetons became a major landmark for trappers in the Greater Yellowstone area for the next 30 years. In 1860, a military expedition under the leadership of Captain W.F. Raynolds entered Jackson Hole as the first of three military surveys to pass through the area. Photographs taken William Henry Jackson during the 1872 Hayden survey expedition, show burned forest stands, and burned forest was described in journal entries from the surveys in 1872 and 1877 (Daugherty 1999).

Miners in the 1860s and 1870s panned nearly every stream in the valley with little success. Elaborate placer mines were set up on Pilgrim Creek above Swan Lake (Daugherty 1999). Fire episodes at that site in the mid 1800s fall within this period, although it is not possible to determine their cause. Homesteaders arrived in AD 1884 and inhabited Jackson Hole year-round. According to the 1900 census (Census of the United States 1900, Jackson Precinct; Daugherty 1999), 638 people lived in the valley including the towns of Jackson, Moran and Kelly; the numbers of settlers steadily increased after AD 1900 (Daugherty 1999). Farmers and ranchers settled mainly in the southern valley near the town of Jackson, and oats, barley, wheat and alfalfa were planted on cleared and burned sagebrush steppe (Daugherty 1999). Pollen records show a few grains nonnative taxa at the top (*Rumex, Plantago*) (Whitlock, 1993), but no major changes. The charcoal records also provide no evidence of a change in fire frequency during the settlement period.

The most notable change in the pollen records at Pothole and Swan lakes is the increase in *Pinus* and other conifers in the 20th century. Photographic comparisons between the late 19th century and present, for example, indicate that low-elevation forest in many parts of the Grand Teton and Yellowstone region has become denser within the last ~100 years (Arno and Gruell 1983; Meagher and Houston 1998). These photos document a trend that has been noted throughout the West and attributed to the effects of fire elimination and grazing (Savage 1991; Veblen and Lorenz 1991; Miller and Wigand 1994). It is likely that such changes in GTNP are also the direct or indirect result of fire suppression policies and other land-use changes.

CONCLUSIONS

The pollen and charcoal records from three sites in Jackson Hole provide information on environmental changes at low elevations in Grand Teton National Park that can be compared with paleoclimatic, archeologic and historic data from the region. The vegetation history suggests little change other than that related to local hydrology. The charcoal record indicates a decrease in fire frequency at AD 1200 that is likely related to the long-term increase in effective moisture shown by the PDSI reconstructions. At Hedrick Pond, high fires activity is consistent with drier-than-present conditions prior to AD 1200. Since the, the records show a response to increasingly wet conditions through changes in hydrology, vegetation, and fire regime. The comparison of the charcoal records over the last 550 cal yrs suggest intervals of high fire activity at all sites in AD 1980-2000, 1780-1810, ca. 1550, and 1420-1430. These may have been caused by human activity but the charcoal records do show temporal patterns to match shifts in human occupancy inferred from the archeological record. More recent fires may have been set by Euro-Americas who actively mined and ranched in the region, but our data are inconclusive on this. The increase in forest cover in recent decades, seen at two of our sites, is noted throughout the region and may result from the combined effects of climate change and land-use practices.

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TABLE 1. Uncalibrated radiocarbon dates, calibrated ages, and age models

Depth (m)[a]	Uncalibrated ^{14}C age (^{14}C yr BP)	Calibrated age (cal yr BP) with 2 sigma range[b]	Material dated	Lab number[c]
Hedrick Pond				
0.69	700 ± 40	575, **666**, 580, 664, 706, 720 (559-721)	Conifer needle	LL119626
1.37	2209 ± 39	**2182**, 2247, 2301, 2236 (2140-2333)	Unidentified leaf	AA63992
Pothole Lake				
0.33	290 ± 40	314, 364, **400.5**, 160.5, 376 (155-467)	Unidentified leaf	LL119627
0.48	1090 ± 50	**986.5**, 1039, 1008.5, 1121.5, 1164.5 (924-1167)	Unidentified leaf	LL119625
Swan Lake				
0.70	455 ± 35	**511.5**, 344.5, 501.5 (343-541)	Wood bark	LL119624

Age Models (including ^{210}Pb dates)[d]:

Hedrick Pond:

Age (cal yr BP) = $-0.0002 \cdot \text{depth}^3 + 0.1212 \cdot \text{depth}^2 + 2.9296 \cdot \text{depth} - 56.605$ ($r^2 = 0.999$)

Pothole Lake:

Age (cal yr BP) = $0.0038 \cdot \text{depth}^3 + 0.2122 \cdot \text{depth}^2 + 2.6524 \cdot \text{depth} - 55.009$ ($r^2 = 0.999$)

Swan Lake (0 – 59 cal yr BP):

$\text{Age}^e = 0.0263 \cdot \text{depth}^4 - 0.3565 \cdot \text{depth}^3 + 1.2818 \cdot \text{depth}^2 + 1.7373 \cdot \text{depth} - 52.824$ ($r^2 = 0.9987$)

Swan Lake (59 – 550 cal yr BP):

$\text{Age}^f = 8.1441 \cdot \text{depth} - 58.585$

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[a] Depth below mud surface.

[b] ^{14}C ages derived from CALIB 5.0.2 calibration curves (Stuiver et al., 2005). In some cases, multiple ages were possible if the sample crossed multiple points along the calibration curve. In these cases, the mean age with the greatest area under the probability curve was used in the age model (bolded age). The 2 sigma age range is given in parentheses.

[c] AA – University of Arizona AMS Facility; LL – Lawrence Livermore National Laboratory

[d] ^{210}Pb dates were adjusted for the 55 years (the cores were taken in 2005) since 1950 AD in order to compare them with the calibrated radiocarbon dates.

[e] The Swan Lake age model between 0 and 59 cal yr BP was based on ^{210}Pb dates only (Table 2).

[f] The Swan Lake age model prior to 59 cal yr BP was based on calibrated ^{14}C ages and only the oldest ^{210}Pb date.

TABLE 2. Short core ^{210}Pb concentrations and age determinations[a]

Depth (cm)[b]	^{210}Pb dpm g^{-1}	Age (yr AD)
Hedrick Pond		
0-1	67.57	2003
1-2	43.10	2001
2-3	38.64	1999
3-4	28.38	1997
4-5	33.79	1994
5-6	34.70	1991
6-7	30.98	1987
7-8	29.74	1984
8-9	14.88	1980
9-10	19.45	1977
10-11	12.90	1973
11-12	21.74	1968
12-13	17.16	1954
14-15	7.44	1919
Pothole Lake		
0-1	47.67	2003
1-2	28.13	2001
2-3	31.81	1999
3-4	31.01	1996
4-5	36.03	1992
5-6	32.68	1986
6-7	21.73	1981
7-8	18.83	1976
8-9	15.31	1970
9-10	12.62	1965
10-11	12.27	1955
12-13	8.93	1927
Swan Lake		
0-1	72.02	2003
1-2	60.61	2000
2-3	36.02	1996
3-4	22.04	1994
4-5	22.18	1992
5-6	16.83	1991
6-7	14.81	1988
7-8	10.18	1986
8-9	28.09	1983
9-10	26.27	1972
10-11	16.16	1950
11-12	20.62	1919

[a] Concentration age determinations provided by Dr. James Budahn at the U.S. Geological Survey, Denver, CO.

[b] Depth below mud surface.

FIGURE CAPTIONS

Figure 1: Location map of Grand Teton National Park, showing study sites.

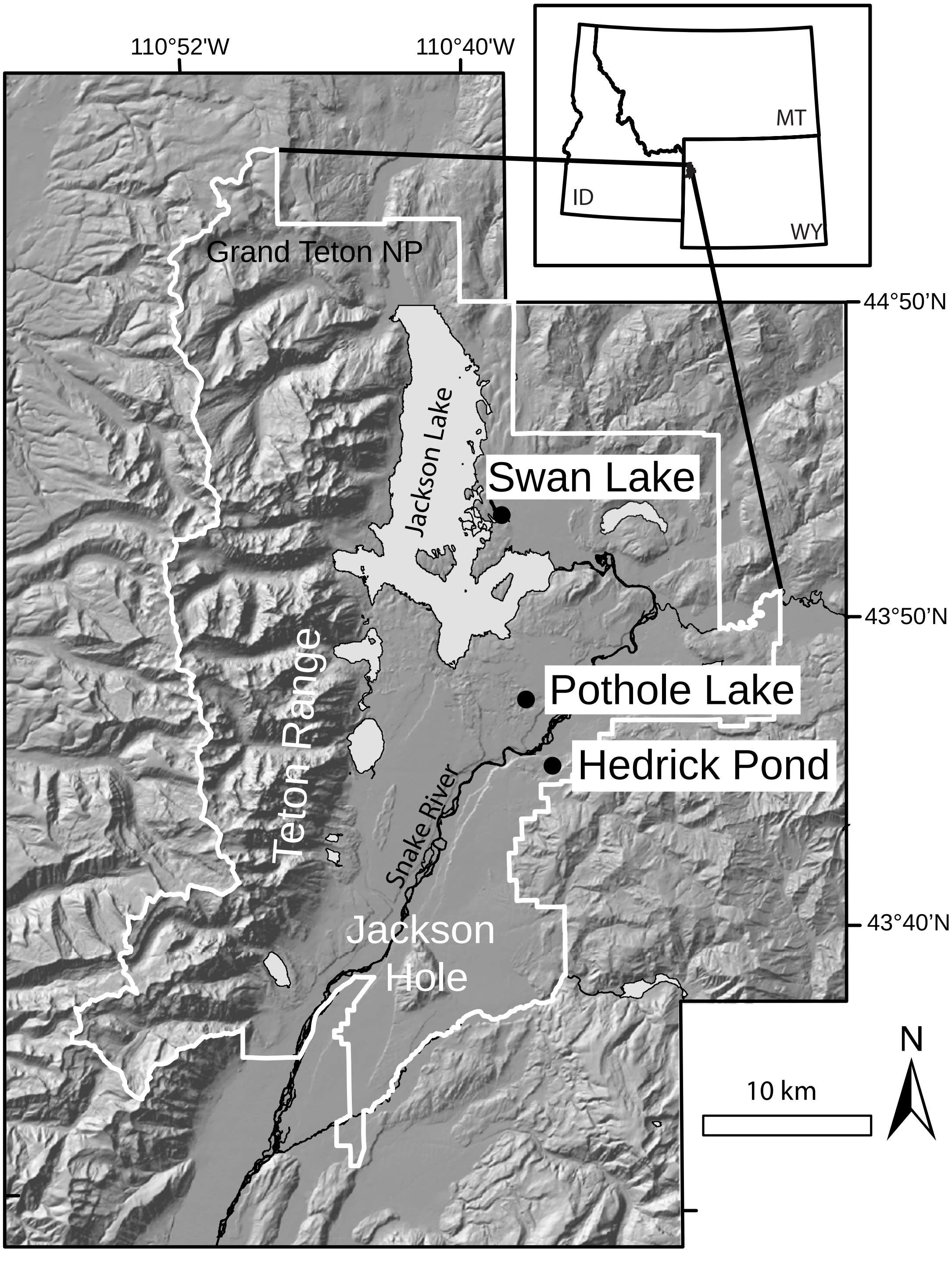
Figure 2: Core lithology, radiocarbon ages, carbonate and organic content, magnetic susceptibility and charcoal concentration for the study sites. MS units were expressed as cgs x 10^{-6}.

Figure 3: Charcoal and pollen records of the last 2100 years at Hedrick Pond. Charcoal accumulation rates (CHAR) were decomposed into background (the slowly varying black line overlying the accumulation rate curve in gray. Fire episodes (black rectangles) at left are decades with higher-than-average fire (charcoal accumulation peaks above the threshold value). Pollen percentages of selected taxa and the pollen accumulation rates of *Artemisia*, total *Pinus* and total terrestrial pollen are shown. Outlined area on pollen curves is 10x exaggeration of percentage data. CONISS dendrogram (at right) was used to define pollen zones.

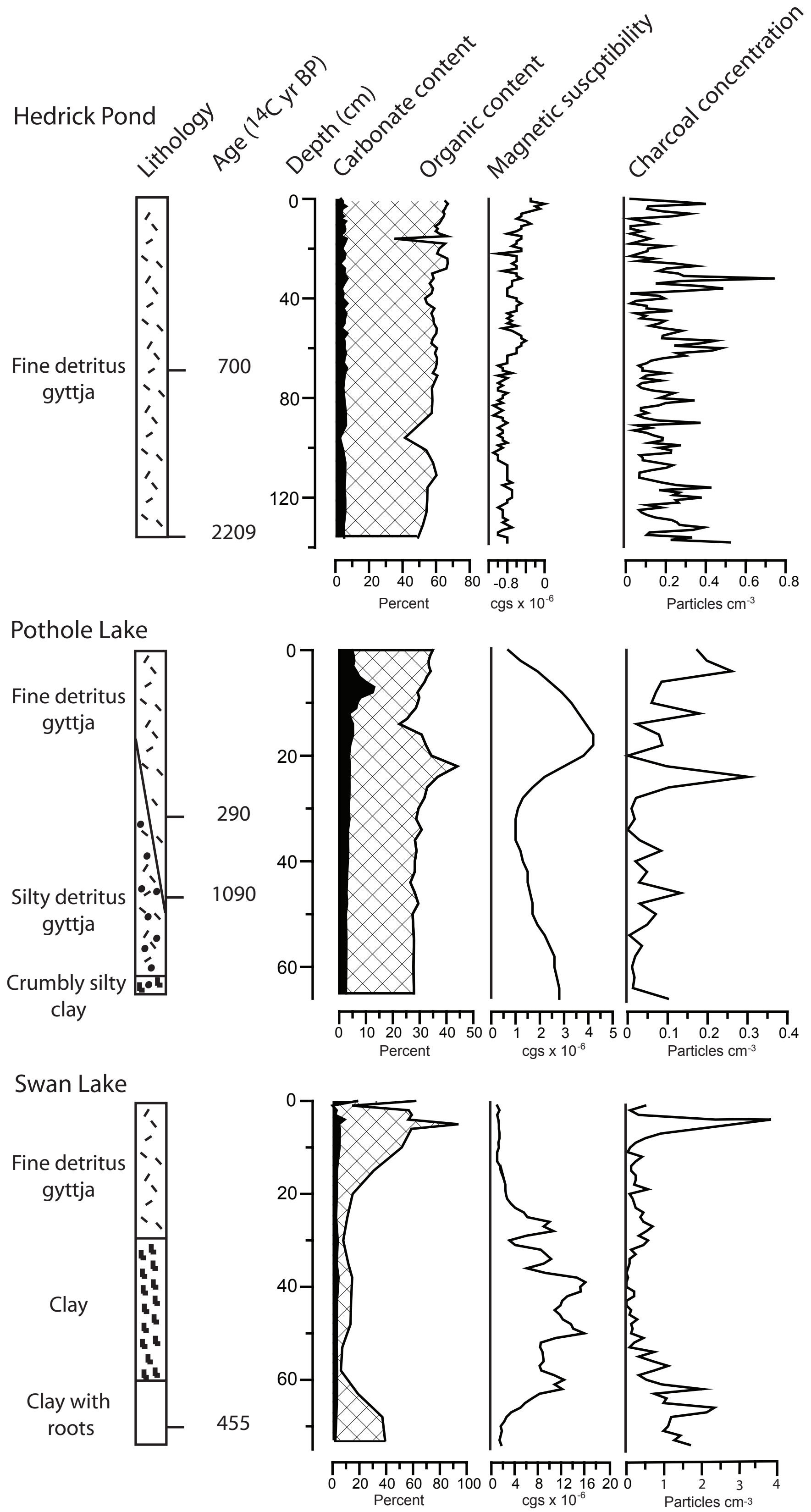
Figure 4: Charcoal and pollen records of the last 990 cal yr BP years at Pothole Lake (see Fig. 3 for explanation).

Figure 5: Charcoal and pollen records of the last 550 years at Swan Lake (see Fig. 3 for explanation).

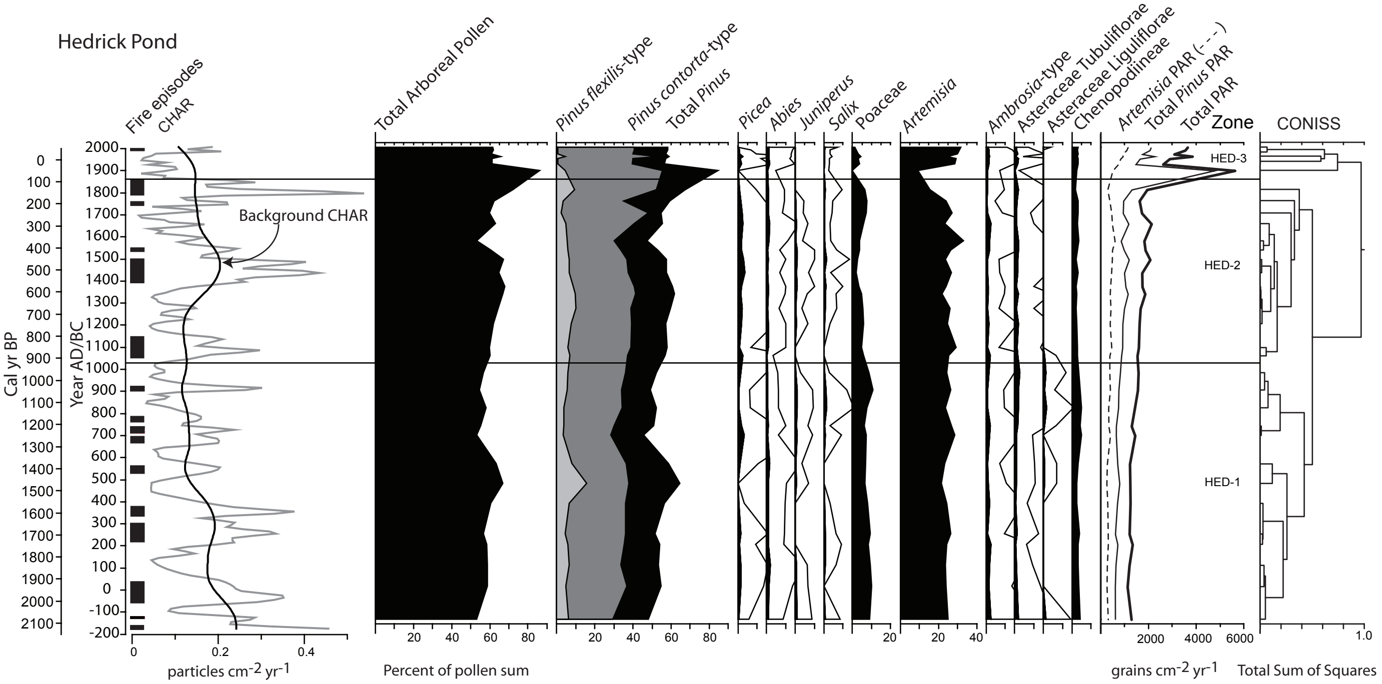
Figure 6: Timeline of climate events, human impacts, and important periods in Jackson Hole (see text for discussion). The PDSI data for gridpoint 100 of Cook et al. (2004) is smoothed with a 100-year and 500-year window to show centennial and longer time variations in effective moisture. Fire episodes at each site (black bars) and the correlation (gray shading) among charcoal records are indicated.



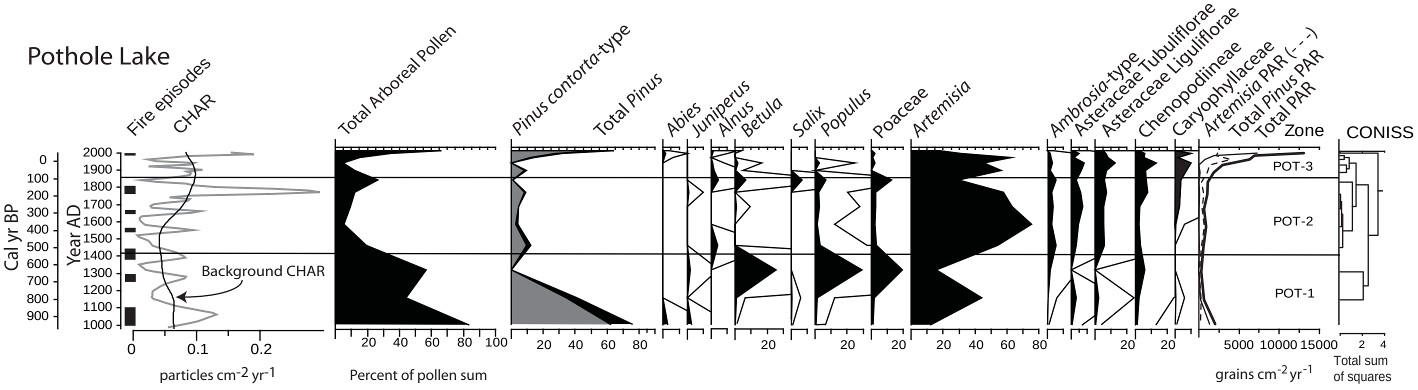
Jacobs & Whitlock, Figure 1



Jacobs & Whitlock, Figure 2



& Whitlock Figure



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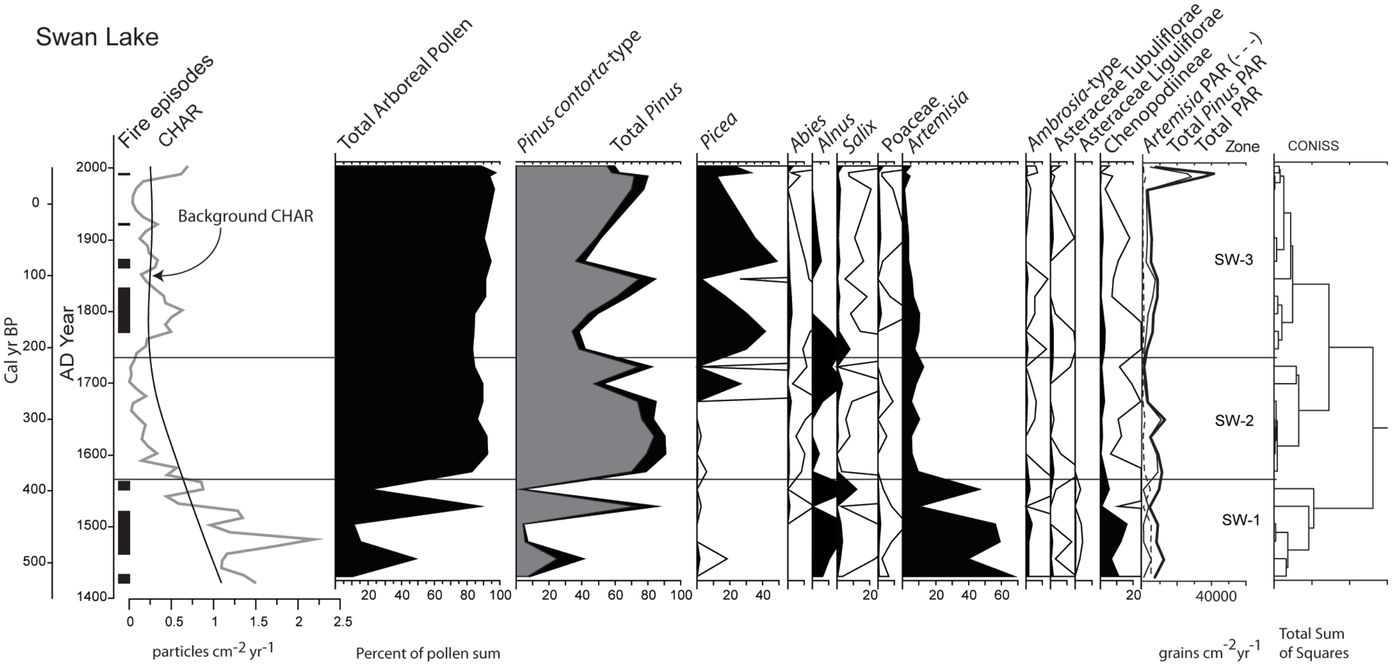
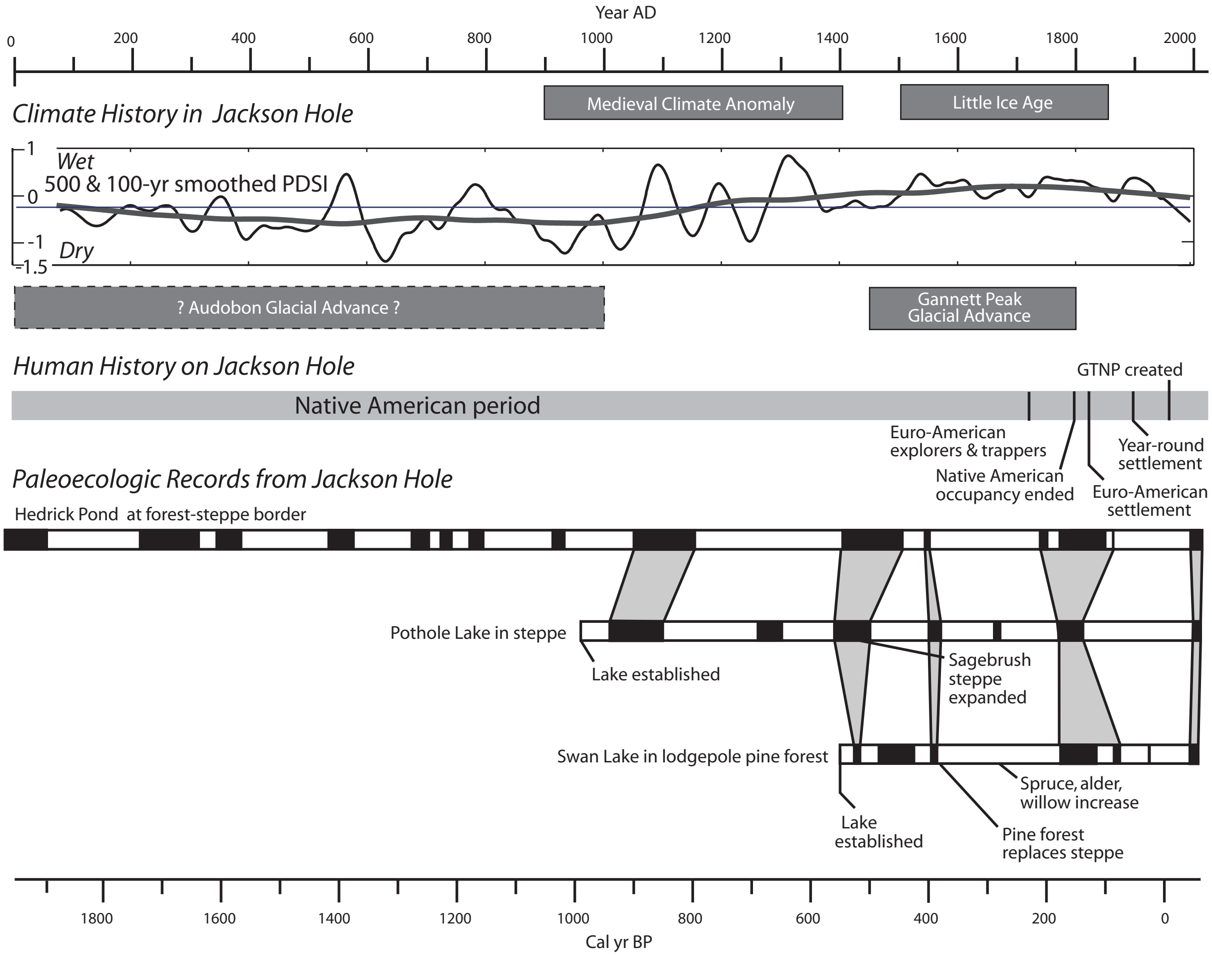


Jacobs & Whitlock, Figure 5



Jacobs & Whitlock, Figure 6