Holocene vegetation–fire–climate linkages in northern Yellowstone National Park, USA

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**Abstract**

Yellowstone National Park has been an important location for paleoecologic studies that focus on the use of charcoal data to reconstruct past fire activity and on the role of climate variations in shaping past vegetation and fire regimes. One hypothesis, which has been explored in other parts of the western U.S., is the idea that present-day summer-dry and summer-wet precipitation regimes were intensified during the early Holocene as a result of greater-than-present summer insolation and its effect on atmospheric circulation patterns. In Yellowstone, this hypothesis was previously examined at two sites, one in summer-wet and one in summer-dry precipitation regions. The records showed variation in both fire and vegetation history that supported the hypothesis. We present a fire and vegetation history from Blacktail Pond, located in *Pseudotsuga* parkland in the transitional region. The Blacktail Pond data indicate the following ecological history: prior to 12,000 cal yr BP, the site supported tundra vegetation and fire episodes were infrequent. Between 12,000 and 11,000 cal yr BP, *Picea–Pinus* parkland was established and fire activity increased; these changes are consistent with increasing temperature, as a result of rising summer insolation. From 11,000 to 7600 cal yr BP, the presence of a closed forest of *Pinus* and some *Picea* is attributed to high levels of winter moisture, but high fire activity indicates that summers were drier than at present. After 7600 cal yr BP, the presence of forest and steppe vegetation in combination with high fire activity suggest that middle-Holocene conditions were warm and dry. The decrease in *Picea* and *Betula* in the last 4000 cal yr indicates continued drying in the late Holocene, although fire-episode frequency was relatively high until 2000 cal yr BP. The pollen data at Blacktail Pond and other low-elevation sites in the northern Rocky Mountains suggest a widespread vegetation response in summer-wet regions to effectively wetter conditions in the early Holocene and decreased moisture in the middle and late Holocene. In contrast, the more-variable fire history among the three sites implies either that (1) summer moisture stress and fire conditions are related to year-round moisture balance and not well predicted by the hypothesis, (2) the transitional area between summer-wet and summer-dry precipitation regimes experienced complicated shifts in effective moisture through time, and/or (3) fire-episode data have a limited source area that makes it difficult to separate local influences from regional climate changes in understanding long-term variations in fire-episode frequency.

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**1. Introduction**

The western United States is influenced by two atmospheric circulation systems at present, which in turn affect the seasonal distribution of precipitation (Whitlock and Bartlein, 1993). The southwestern United States receives most of its precipitation during the summer when heating of the continent causes onshore flow of moisture from the Gulf of California and the Gulf of Mexico and is referred to as a summer-wet precipitation regime (Mock, 1996). The northwestern United States experiences a summer-dry precipitation regime, as a result of the expansion of the northeastern Pacific subtropical high-pressure system in summer, which suppresses precipitation, and high levels of winter precipitation brought by westerly storm systems. Within the northern Rocky Mountains, the location of these precipitation regimes is strongly influenced by topography and its influence on convectional storms. In Yellowstone National Park (YNP), July/January precipitation ratio is higher in northern YNP, and lower in the southern and central region and at high elevations (Whitlock and Bartlein, 1993) (Fig. 1).

Pollen and charcoal records in the northern Rockies suggest that these precipitation regimes were amplified during the early Holocene (Fall et al., 1995; Millsbaugh et al., 2004; Brunelle et al., 2005). Summer-wet areas became wetter and summer-dry areas became drier, and this is attributed to the amplification of the seasonal cycle of insolation and the attendant strengthening of the subtropical high-pressure system and monsoonal circulation (Whitlock and Bartlein, 1993). Millsbaugh et al. (2004) sought to test this hypothesis in YNP by comparing the environmental history of Slough Creek Lake (lat 44°55′28″N, long 110°21′10″W, elev. 1884 m) in the summer-wet region with that
of Cygnet Lake (lat 44°39′37″N, long 110°36′53″W, elev. 2530 m) in the summer-dry region. Higher-than-present fire activity at Cygnet Lake during the early Holocene supported the idea of effectively drier-than-present summers in summer-dry regions, and corroborated inferences based on pollen records from summer-dry regions in southern YNP and Grand Teton National Park (Whitlock and Bartlein, 1993). Concurrently, evidence of fewer fires and more mesophytic vegetation at Slough Creek Lake was consistent with predictions that summer-wet regions were wetter in the early Holocene.

In this paper, we present the vegetation and fire history from Blacktail Pond (lat 44°57′16″N, long 110°36′36″W, elev. 2012 m), located near the present transition of the two precipitation regimes in YNP, to further evaluate the summer-wet/summer-dry hypothesis. A 14,000-year-old pollen record was previously described by Gennett and Baker (1986) from a core taken in the marginal fen. Sharp lithologic and palynologic discontinuities in the original Blacktail Pond core and a questionable chronology based on bulk-sediment radiocarbon dates motivated reanalysis of the site. Our objectives were to (1) re-examine the vegetation and fire history from Blacktail Pond from a better-dated, more continuous lake-sediment core, and (2) compare the results with other paleoenvironmental records from YNP and the northern Rockies to better understand the regional vegetation and fire history as well as the evidence for past shifts in precipitation regimes.

The Blacktail Pond valley has a southwest–northeast orientation that formed as a late-Pleistocene meltwater channel. With ice retreat, Blacktail Deer Creek abandoned its original course and flowed north to the Yellowstone River, leaving a marshy environment and closed kettle lakes in valley, including Blacktail Pond (Pierce, 1979). Cosmogenic exposure dating of glacial boulders indicate an age of 14.3±1.2 10Be ka for moraines down valley in the Deckard Flats area to the west and 15.3±1.4 10Be ka for moraines up valley to the east. These ages imply that ice recession at Blacktail Pond occurred between about 14,000 and 15,000 cal yr BP (Licciardi and Pierce, 2008).

Climate information is available from Mammoth, YNP, located 8 km west of Blacktail Pond, and from Tower Falls, 18 km southeast of Blacktail Pond. During the period from 1948 to 2007, mean annual temperature was 4.6 °C at Mammoth and 2 °C at Tower Falls, and mean annual precipitation was 38 cm and 42 cm. Blacktail Pond and Slough Creek Lake lie within the area of high July/january precipitation ratios (summer-wet), which results from penetration of summer convectional storms into the low elevations of northern YNP. In contrast, Cygnet Lake in central YNP is characterized by a lower July/january precipitation ratio and the greater influence of the subtropical high-pressure system in suppressing moisture (Fig. 1).

Present vegetation in northern YNP is arrayed by elevation and substrate, and controlled dominantly by winter and spring precipitation and its influence on moisture availability during the growing season (Despain, 1990). Steppe dominated by Artemisia tridentata (big sagebrush), Chrysothamnus nauseosus (rabbitbrush), and Festuca idahoensis (Idaho fescue) is abundant below about 1700 m elevation. Montane conifer forests occur between about 1700 and 3000 m elevation, with Pinus flexilis (limber pine) and Juniperus scopulorum (Rocky Mountain juniper) in low-elevation forests (1700 to 1900 m elev), Pseudotsuga menziesii (Douglas-fir) (1900–2000 m elev), Pinus contorta (lodgepole pine) at higher elevations (2000–2400 m elev), and Picea engelmannii (Engelmann spruce), Abies bobjia (subalpine fir) and Pinus albicaulis (whitebark pine) (2400–2900 m elev) in high-elevation forest and parkland. Alpine tundra lies above about 2900 m elevation. Pinus contorta forest dominates on infertile rhyolitic soils, grassland and steppe grow on nutrient-rich calcareous glacial till, and Pseudotsuga and mixed conifer forest prevail on andesite and other substrates (Despain, 1990).

Blacktail Pond lies within Artemisia steppe with Pseudotsuga and Pinus contorta on adjacent rocky slopes depending on substrate. Small patches of Abies and Picea grow in nearby valleys drained by cold air, and stands of Populus tremuloides (quaking aspen) occur in areas of seepage. Salix spp. (willow), Scirpus americanus (three-square
bulrush), Carex spp. and Typha latifolia (broad-leaved cat-tail) are found along the lake margin, and submerged aquatic plants include Chara, Utricularia (bladderwort) and Myriophyllum (water-milfoil).

2. Methods

Sediment cores, 6.20 m in length, were retrieved from the southwestern basin of Blacktail Pond in 3.45 m of water with a 5-cm-diameter Livingstone square-rod piston sampler (Wright, 1984). Cores BTP06A and BTP06B were extruded in the field, wrapped in plastic wrap and aluminum foil, and transported to the Paleoeocology Lab at Montana State University where they were refrigerated. Core BTP06A was the primary record, but gaps in recovery were filled in with core BTP06B. An 85-cm-long short core was also retrieved using a 7-cm-diameter Klein piston corer to recover the mud-water interface and the uppermost sediment. The short core was sampled in the field at 1-cm intervals into plastic bags and refrigerated.

Organic and carbonate content of the core was determined from loss-on-ignition analysis (Dean, 1974). At 4-cm intervals, 1-cm³ samples were collected to a depth of 5.44 m. Samples were dried at 90 °C for 24 h and weight loss was measured after heating to 550 °C for 2 h to remove organics and 900 °C for 2 h to remove carbonates. Sediment magnetic susceptibility, a function of magnetic mineral content, was measured to determine variations in erosional input to the lake (Gedye et al., 2000). Samples of 3-cm³ volume were measured at 1-cm intervals from 0 to 2.70 m depth and at 0.5-cm intervals from 2.70 to 4.70 m depth using a Bartington MS2 dual frequency susceptibility meter. The results are presented in cgs × 10⁻⁶.

Pollen analysis was undertaken on sediment samples of 1-cm³ volume taken at 8-cm intervals to a depth of 4.44 m. Extraction used the methods of Bennett and Willis (2002), except that acetylation was replaced by the use of Schulze solution (Doher, 1980). Pollen residues were mounted in silicone oil and identified at 400× magnification. Between 300 and 500 terrestrial pollen and spores per sample were identified to the lowest taxonomic level possible by comparison with reference slides and published pollen identification keys (e.g. Moore and Webb, 1978; Kapp et al., 2000). Based on modern phytogeography, diploxylon-type Pinus grains were attributed to P. contorta, and haploxylon-type Pinus grains were assigned to P. albicaulis or P. flexilis. A ratio of diploxylon/haploxylon Pinus types was plotted based on grains with intact distal membranes. Grains that were undetachable because of damage were counted as ‘Degraded.’ Terrestrial pollen percentages were based on the sum of total terrestrial pollen and spores; percentages of aquatic and fen taxa were based on the sum of all pollen and spores. A tracer of Lycopodium spores was added to each sample to calculate pollen concentration (grains cm⁻³), and these values were divided by deposition time (yr cm⁻¹) to calculate pollen accumulation rates (PAR; grains cm⁻² yr⁻¹).

To reconstruct a local fire history at Blacktail Pond, macroscopic charcoal was analyzed from contiguous samples of 50-cm⁻³ volume. Samples were soaked in 20 ml of 5% sodium hexametaphosphate and 20 ml of 6% bleach for 24 h, before washed through a 125 μm mesh sieve. The mesh size was chosen because particles >125 μm diameter are not transported far from their source and thus provide information on local fire history (Whitlock and Millsapagh, 1996; Whitlock and Larsen, 2001). Charcoal particles were tallied in samples taken at 1-cm intervals from 0.02 to 2.70 m depth and at 0.5-cm intervals from 2.70 to 4.70 m depth. The rationale was to maintain as constant a deposition rate (yr cm⁻¹) as possible through the record, drawing on information from the previous study. Charcoal concentrations (particles cm⁻³) in the short core were calculated from 5-cm³ samples at 1-cm intervals, and sedimentation rates were determined from the ²¹⁰Pb chronology. CHAR in the short core was determined by dividing charcoal concentrations (particles cm⁻³) by deposition time (yr cm⁻¹).

Statistical treatment of the long-core charcoal data used CharAnalysis software (Higuera et al., 2008; http://charanalysis.googlespeccom/). CharAnalysis offers an array of approaches for peak-detection to reconstruct “local” fire history and diagnostic tools to help determine if peak detection is warranted and what parameters are most reasonable. Charcoal concentrations were interpolated into contiguous 25-year bins (the median resolution of the record) in order to sample over equally spaced time intervals through the record. Charcoal accumulation rates (CHAR; particles cm⁻² yr⁻¹) were determined by dividing re-sampled concentrations (particles cm⁻³) by re-sampled deposition times (yr cm⁻¹). CHAR data were separated into two components

Table 1
Uncalibrated radiocarbon dates and calibrated ages for Blacktail Pond

<table>
<thead>
<tr>
<th>Depth (cm)</th>
<th>Coreb</th>
<th>Depth in BTP06A (cm)</th>
<th>Uncalibrated ¹⁴C age (¹⁴C yr BP)</th>
<th>Calibrated age (cal yr BP) with 2 sigma rangec</th>
<th>Material dated</th>
<th>Lab numberd</th>
</tr>
</thead>
<tbody>
<tr>
<td>85</td>
<td>BTP06A</td>
<td>Same</td>
<td>2138±39</td>
<td>2126 (2199–2201)</td>
<td>Wood</td>
<td>AA70023</td>
</tr>
<tr>
<td>181–184</td>
<td>BTP06A</td>
<td>Same</td>
<td>8010±60</td>
<td>8870 (8682–9021)</td>
<td>Insect chitin or aquatic plant</td>
<td>N76635</td>
</tr>
<tr>
<td>268</td>
<td>BTP06A</td>
<td>Same</td>
<td>6730±40</td>
<td>7597 (7560–7667)</td>
<td>Charcoal</td>
<td>Hall et al. (1997)</td>
</tr>
<tr>
<td>343</td>
<td>BTP06A</td>
<td>Same</td>
<td>8485±40</td>
<td>9501 (9450–9537)</td>
<td>Charcoal</td>
<td>N76636</td>
</tr>
<tr>
<td>384</td>
<td>BTP06B</td>
<td>Same</td>
<td>9444±57</td>
<td>10683 (10515–10799)</td>
<td>Charcoal</td>
<td>AA0024</td>
</tr>
<tr>
<td>410</td>
<td>BTP06B</td>
<td>412.5</td>
<td>10,414±71</td>
<td>12317 (12061–12422)</td>
<td>Twig</td>
<td>AA70025</td>
</tr>
</tbody>
</table>

a Depth below mud-water interface.

b Core from which sample was taken.

c Depth of sample in BTP06A following stratigraphic correlation.

d Calibrated ages derived from CALIB 5.0.1 (Stuiver et al., 2005). The two sigma range is given in parentheses.

<table>
<thead>
<tr>
<th>Material dated</th>
<th>Lab numberd</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wood</td>
<td>AA70023</td>
</tr>
<tr>
<td>Insect chitin or aquatic plant</td>
<td>N76635</td>
</tr>
<tr>
<td>Charcoal</td>
<td>Hall et al. (1997)</td>
</tr>
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<td>Charcoal</td>
<td>N76636</td>
</tr>
<tr>
<td>Charcoal</td>
<td>AA0024</td>
</tr>
</tbody>
</table>

Table 2
Short core ²¹⁰Pb concentrations, age determinations, and age model for Blacktail Pond

<table>
<thead>
<tr>
<th>Depth (top cm)</th>
<th>²¹⁰Pb dpm g⁻¹</th>
<th>Age (cal yr BP)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>1</td>
<td>24.75</td>
<td>54</td>
</tr>
<tr>
<td>2</td>
<td>20.37</td>
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<td>3</td>
<td>15.74</td>
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<td>14.06</td>
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</tr>
<tr>
<td>14</td>
<td>7.21</td>
<td>9</td>
</tr>
<tr>
<td>15</td>
<td>5.36</td>
<td>15</td>
</tr>
<tr>
<td>16</td>
<td>6.3</td>
<td>23</td>
</tr>
<tr>
<td>17</td>
<td>7.01</td>
<td>31</td>
</tr>
<tr>
<td>18</td>
<td>5.51</td>
<td>40</td>
</tr>
<tr>
<td>19</td>
<td>7.3</td>
<td>49</td>
</tr>
<tr>
<td>20</td>
<td>7.36</td>
<td>59</td>
</tr>
<tr>
<td>21</td>
<td>5.25</td>
<td>68</td>
</tr>
</tbody>
</table>

Blacktail Pond short core age model (cal yr BP).

Age=0.1959 * depth² + 1.8103 * depth – 56.

a Depth below mud surface.

b Concentrations provided by Dr. James Budahn at the U.S. Geological Survey, Denver, CO.
(Long et al., 1998): a slowly varying trend often referred to as background charcoal (BCHAR), which represents gradual variations in regional fire activity and/or charcoal production per fire, and peak charcoal (PCHAR), the high-frequency variability representing local fire episodes (i.e., one or more fires occurring within the time span of the bin) and noise. BCHAR was determined with a 500-year lowess smoother, robust to outliers. PCHAR was determined by subtracting BCHAR from CHARM. The noise component of PCHAR values within 250 yr of every sample was modeled with a Gaussian mixture model.

Fire events were identified when PCHAR values exceeded the 95th percentile of the noise distribution. Fire frequencies (number of episodes 1000 yr$^{-1}$) were smoothed with a 2000-year moving window. CHARM peak episodes that had maximum charcoal counts with a >5% chance of coming from the same Poisson distribution as the minimum charcoal count in the preceding 75 yr were disqualified from consideration as fire episodes. Fire-episode magnitude (particles cm$^{-2}$ episode$^{-1}$) is an index of the amount of charcoal produced and varies with fire size, severity, and proximity (Whitlock et al., 2006).

Fig. 2. Age–depth model for Blacktail Pond core BTP06A. Dashed line represents inferred chronology before 12,000 cal yr BP.

Fig. 3. Lithology, radiocarbon dates, magnetic susceptibility, and organic and carbonate content for BTP06A.
Fig. 4. Pollen percentages for selected taxa and total pollen accumulation rate (PAR) from Blacktail Pond.
Charcoal data from Slough Creek and Cygnet lakes were reanalyzed to facilitate comparison with the Blacktail Pond data. Charcoal concentrations from Slough Creek Lake were re-sampled in 26-year bins and those from Cygnet Lake were re-sampled in 20-year bins, because these were the median resolutions of those records. In Millsapgh et al. (2004), CHAR data were binned to 10-year intervals, and the data were log-transformed. In addition, the original study identified fire episodes as CHAR values above BCHAR (i.e., a threshold ratio of one), rather than defining a threshold based on residuals. This approach identified more peaks, especially in the late-glacial interval when CHAR and CHAR variability were low. Despite our use of a binning interval based on the median deposition time, the use of residuals rather than ratios, and the elimination of statistically insignificant peaks for the Cygnet and Slough Creek lake records, the overall trends in BCHAR and charcoal peak frequency, especially in the Holocene, did not change substantially from Millsapgh et al. (2004).

3. Blacktail Pond results

3.1. Chronology

The Blacktail Pond chronology was based on a series of 230Pb dates for the short core, and four AMS 14C dates of terrestrial plant material and identification of a 0.5-cm thick Mazama ash layer at a depth of 2.68 m for the long core (Tables 1 and 2; Fig. 2). The long and short cores were correlated based on similarities in the charcoal stratigraphy and chronology. A late-glacial ash layer was reported in the core described by Bennett and Baker (1986) but was not found in cores BTP06A or BTP06B. One age determination from 1.81 to 1.84 m depth was excluded from the age-depth model because it was out of sequence and judged too old. The material dated was originally thought to be terrestrial insect chitin but may have come from aquatic zooplankton that incorporated ancient carbon.

A range of possible calibrated dates and probability distributions were determined for every radiocarbon date using CALIB 5.0.1 (Stuiver et al., 2005). Monte Carlo sampling was used to generate a cubic smoothing spline through 2000 dates randomly sampled from each probability distribution, and the final age-depth model was based on the median ages of all the runs (Higuera et al., in press). Because no datable organic matter was found below the clay/gyttja boundary (ca. 12,000 cal yr BP), an age of 14,000 cal yr BP was conservatively assigned to 6.2 m depth, although the bottom date could be as old as 15,300 cal yr BP, based on the cosmogenic exposure dating of nearby moraines (Liciardi and Pierce, 2008). Age determinations from the short core were based on a second-order polynomial (Table 2).

For purposes of comparison, new age models were developed for Cygnet and Slough Creek lakes, based on recalibration of the original radiocarbon dates (Stuiver et al., 2005) and development of Monte Carlo age-depth models (Higuera et al., 2008). The new chronologies were similar to the published ones, with the new chronology from Slough Creek Lake differing less than 400 yr at all depths from the original, and that from Cygnet Lake differing less than 550 yr at all depths (Millsapgh et al., 2000, 2004).

3.2. Lithology

Core BTP06A was divided into six lithologic units (Fig. 3). From 6.20 to 4.12 m depth, the sediment consisted of gray clay of low organic content (~2%) and low carbonate content (~1.3%). The sediment from 4.70 to 4.12 m depth had higher sediment magnetism than the rest of the core (5.8 to 329.0 cgs×10^−6), implying considerable mineral input. The second unit, from 4.12 to 3.80 m depth, contained dark-brown fine-detritus gyttja with low to moderate magnetic susceptibility (~3.6 to 6.3 cgs×10^−6), high organic content (~40%), and low carbonate content (~2.5%). The increased organic composition of this unit implies a more productive lake than before, and the decreased magnetic susceptibility indicates reduced mineral input. From 3.80 to 2.56 m depth, the sediments consisted of light brown marl (freshwater carbonate) with gastropod shells, interbedded with layers of dark brown fine-detritus gyttja without shells. Sediment magnetic susceptibility was low (~3.2 to 0 cgs×10^−6) with the exception of the Mazama ash layer at 2.68–2.69 m depth (2.7 cgs×10^−6). Organic and carbonate contents (~22% and 20%) were relatively high and suggest high lake productivity and authigenic marl precipitation. The fourth unit from 2.56 to 1.08 m depth was dark-brown fine-detritus gyttja with shells, interbedded with light brown marl with shells. Magnetic susceptibility was low (~3.5 to 0.8 cgs×10^−6), organic content was high (~40%), and carbonate content was low (~6%), implying that the lake was productive but with less marl. From 1.08 to 0.52 m depth was light-brown marl with shells along with interbedded dark-brown fine-detritus gyttja with shells. Magnetic susceptibility was low (~2.7 to 0.1 cgs×10^−6), and organic (~22%), and carbonate (~21%) were high. The upper unit from 0.52 m depth to the top of the long and short cores was composed of gyttja with shells, with low magnetic susceptibility (~3.7 to 0 cgs×10^−6), high organic content (~33%) and low carbonate content (~13%).

3.3. Pollen

The record was divided into five zones using a constrained cluster analysis of the terrestrial pollen percentages (Fig. 4) (Grimm, 1987). Pollen data in each zone were compared with modern pollen rain from studies in the YNP region (Bright, 1966; Baker, 1978; Whitlock, 1993; Fall, 1994) and modern pollen accumulation rates (PAR) from the Rocky Mountains and eastern Canada (Fall, 1994; Ritchie and Lichti-Federovich, 1967) to reconstruct the vegetation. Pollen percentages and PAR are listed as zone averages unless otherwise noted.

3.3.1. Zone BP-1 (4.44–4.28 m depth; 13,000–12,000 cal yr BP)

Percentages of Poaceae (1.6%), Artemisia (28%), other herbs (5.2%), and Cyperaceae (4.1%) were high, those of Pinus (38%, mostly haploxylon-type) were moderate, and those of Picea (1.3%), Salix (4.2%), Populus (2.2%), Rosaceae (0.5%), Astarceae Tubifillore (2.8%), and Chenopodineae (2.5%) were low. High percentages (10%) of degraded grains were probably the result of subaerial exposure prior to deposition. Total nonboreal pollen percentages were high (52%) and PAR was low (87 grains cm⁻² yr⁻¹). The assemblage resembles modern pollen rain from alpine tundra in the Rocky Mountains, except that in modern assemblages, Poaceae is more abundant (7.7%), and Salix (13.1%) and Artemisia are less abundant (19%) (Fall, 1994). Modern pollen assemblages from alpine tundra in the Wind River Range and Yellowstone are dominated by diploxylon-type rather than haploxylon-type Pinus (Whitlock, 1993; Fall, 1994), reflecting the input of Pinus contorta pollen from lower elevations (Fall, 1994). Haploxylon-type Pinus in Zone BP-1 was most likely Pinus albicaulis, but P. flexilis may also have been a contributor. Populus tremuloides stands likely grew near the site, since 1 to 2% Populus pollen indicates local occurrence (Bright, 1966); Salix was also present (Fall, 1994). PAR values in Zone BP-1 fall within the range of modern values from arctic-subarctic Canada (Ritchie and Lichti-Federovich, 1967).

3.3.2. Zone BP-2 (4.24–3.92 m depth; 12,120–11,110 cal yr BP)

Percentages of Picea (7.8%), Juniperus-type (1.5%), Betula (3.1%), Poaceae (3.4%), Artemisia (24%) and Cyperaceae (4.6%) were high. Pinus values were moderate with more haploxylon-type than diploxylon-type identified. Pollen of Salix, Populus, Rosaceae, Astarceae Tubifillore, and Chenopodineae were present in low amounts (~2%). Nonboreal pollen percentages were moderate (35%), and PAR averaged 663 grains cm⁻² yr⁻¹. The assemblage resembles samples from modern subalpine parkland between alpine tundra and mixed conifer forest in the Wind River Range, WY (Fall, 1994). Modern samples from Pinus albicaulis parkland feature higher percentages of diploxylon-type Pinus grains (63–93%) and lower amounts of Picea...
and Betula. PAR values of Zone BP-2 fall within the range of modern forest-tundra ecotone of arctic–subarctic Canada (Ritchie and Lichti-Federovich, 1967). The data suggest a period of subalpine parkland.

3.3.3. Zone BP-3 (3.92–2.76 m depth; 11,110–7680 cal yr BP)

Pinus (85%) values were the highest of the record, and identifiable grains were nearly equal amounts of diploxylon-type and haploxylon-type. Picea pollen was also present in moderate values (5%), and pollen of Abies, Betula, Salix, Populus, and Poaceae was present in 2%. Artemisia was lower (7%) in this zone than any other, as was nonarboreal pollen (12%). PAR was relatively high (2620 grains cm$^{-2}$ yr$^{-1}$). This zone resembles modern surface samples from closed subalpine forest in Yellowstone but with lower levels of Abies and haploxylon-type Pinus than at present (Baker, 1976). Forests at this time were dominated by Pinus and possibly Picea in wetter settings.

3.3.4. Zone BP-4 (2.76–1.50 m depth; 7680–4080 cal yr BP)

Pinus percentages (66%), largely of diploxylon-type, increased, and Pseudotsuga and Poaceae pollen were present in low but steady amounts. Picea and Abies were present in low but steady levels. Artemisia percentages were relatively high (17%), and Betula and Chenopodiineae percentages were higher than in Zone BP-3. Overall, nonarboreal pollen increased to 24% and PAR averaged 2534 grains cm$^{-2}$ yr$^{-1}$. This zone resembles modern pollen samples from montane forests in the northern Rocky Mountains (Fall, 1992). The decrease in PAR and arboreal pollen percentages from values in Zone BP-3, the shift to Pinus contorta and Pseudotsuga, and the increase in Artemisia, Betula, Chenopodiineae, and Poaceae imply conifer forest and steppe. The substrate constraints on modern vegetation in YNP suggest that conifers grew on the upland rocky areas, and Artemisia steppe was present in the valley.

3.3.5. Zone BP-5 (1.50–0 m depth; 4080 cal yr BP to present)

Moderate Pinus percentages (24%) of mostly diploxylon-type, persistent Pseudotsuga (2%), and Artemisia (14%) characterize this zone. Poaceae (2%) and total nonarboreal pollen (21%) values were higher than before. PAR values averaged 2050 grains cm$^{-2}$ yr$^{-1}$ and were highest at the top of the record. This zone marks the establishment of the modern vegetation with expanded Artemisia and Poaceae steppe in the Blacktail valley.

3.4. Charcoal

BCHAR was initially very low but increased to 0.04 particles cm$^{-2}$ yr$^{-1}$ at 12,000 cal yr BP (Fig. 5). Values rose further to 0.43 particles cm$^{-2}$ yr$^{-1}$ at 11,000 cal yr BP and remained relatively constant, averaging 0.18 particles cm$^{-2}$ yr$^{-1}$ until 2000 cal yr BP. In the last 2000 yr, BCHAR decreased to an average of 0.10 particles cm$^{-2}$ yr$^{-1}$. Charcoal peaks (i.e., fire episodes) were not detected before 12,000 cal yr BP. Of the 64 significant episodes identified in the last 12,000 cal yr, the two largest episodes occurred between 11,000 and 10,000 cal yr BP and had magnitudes of 87 and 79 particles cm$^{-2}$ episode$^{-1}$. Other fire episodes averaged 4.5 particles cm$^{-2}$, and large episodes were dated at 6750, 3400, 2950, 2850, 2550, 1800, and 1550 cal yr BP. The large peak at the top of short core was dated to fires in Yellowstone in AD 1988. Fire frequency averaged 6 episodes 1000 yr$^{-1}$ between 12,000 and 11,000 cal yr BP, dropped to 4 episodes 1000 yr$^{-1}$ at 10,500 cal yr BP, and then increased to a maximum of 8 episodes 1000 yr$^{-1}$ at 8500 cal yr BP. After that, fire frequency decreased to 6 episodes 1000 yr$^{-1}$ and, between 2000 cal yr BP and present day, it decreased further to 3 episodes 1000 yr$^{-1}$. The Blacktail Pond area burned extensively in 1988, and the short core had high CHAR values at the top of the record dating to this event (Fig. 5).
4. Discussion

The fire and vegetation reconstruction at Blacktail Pond was compared with those from Cygnet and Slough Creek lakes to provide more information on the postglacial history of YNP and better evaluate the summer-wet/summer-dry hypothesis (Fig. 6). We also compared the YNP reconstructions with a summer-dry site in northern Idaho (Burned Knob Lake [lat 45°42'16"N, long 114°59'13"W, elev. 2258 m], Brunelle and Whitlock, 2003) and summer-wet sites in the Wind River Range (Rapid Lake [lat 42°42'09"N, long 109°10'17"W, 3436 m], Fall et al., 1995) and northwestern Montana (Pintler Lake [lat 45°50'27"N, long 113°26'26"W, elev. 1925 m], Brunelle et al., 2005) (site locations in Fig. 1). In addition, submillennial fire-history variations at Blacktail Pond during the last 4000 yr were compared with other paleoenvironmental records from northern Yellowstone (Fig. 7).

Pollen and charcoal records throughout YNP and the northern Rocky Mountains indicate an initial late-glacial period of tundra or meadow vegetation, negligible fire activity, poorly developed soils, and unstable slopes (Whitlock et al., 2008a). The vegetation is floristically poorly characterized, but it is consistent with colder-than-present conditions. Warming after 12,000 cal yr BP was likely caused by rising summer insolation and shrinkage of local glaciers. The lengthening growing season allowed trees to move into deglaciated regions, and the vegetation to shift from tundra to subalpine parkland to closed forest over the span of a few millennia. Lower-than-present winter insolation in the late-glacial period implies that winters were cold and possibly effectively wetter than at present (Bartlein et al., 1998).

In the summer-wet region of northern YNP, subalpine parkland of Picea, Pinus albicaulis, Artemisia developed between 13,000 and 12,000 cal yr BP. Pollen records from summer-dry regions in southern

Fig. 7. Comparison of wet/dry oscillations in the late Holocene are based on the Palmer Drought Severity Index for Grid Point 100 (Cook et al., 2004), a multi-proxy climate record from Crevice Lake (Whitlock et al., 2008a); CHAR data from Blacktail Pond core BTP06A and short core, and fire-related sedimentation events (Meyer et al., 1995), which imply dry periods in northern Yellowstone National Park. Large-magnitude fires (black circles) at Blacktail Pond are identified. The Medieval Climate Anomaly based on the local Palmer Drought Severity Index is noted.
Mountains featured an increase in northern Idaho and other summer-dry sites in the northern Rocky Mountains, and this likely reflects warmer conditions and greater fuel biomass suitable for burning (Marlon et al., 2006).

The period from 12,000 to 6000 cal yr BP defines the early-Holocene summer insolation maxima when summer temperatures were higher than present (Bartlein et al., 1998). Between 11,000 and 7600 cal yr BP, the increased organic and carbonate content of the Blacktail Pond sediments indicates greater limnologic production. In particular, marl production in the early Holocene suggests strengthened summer conditions (i.e., more sunlight, warmer temperatures, and drier conditions; Meyers and Ishiwatari, 1993). The transition from subalpine parkland to forests with Pinus, Picea, and some Betula at Blacktail Pond occurred at the same time as a shift to forests of Pinus, Juniperus, and Betula at Slough Creek Lake. Higher levels of Picea at Blacktail Pond than at Slough Creek Lake, however, imply locally cooler conditions, perhaps as a result of greater cold air drainage into the Blacktail Pond region from the Blacktail Deer Plateau to the south. At Cygnet Lake, the early Holocene was marked by the expansion of Pinus contorta forest, which persisted with little change up to the present day. Non-ryolite sites in southern YNP and Grand Teton National Park show an expansion of xerophytic forest taxa (Pseudotsuga and Populus) (Whitlock, 1993), which is consistent with the idea that summer-dry regions experienced warmer and effectively drier conditions than before. Burnt Knob Lake in the subalpine zone of northern Idaho and other summer-dry sites in the northern Rocky Mountains featured an increase in Pseudotsuga, beginning at 11,000 to 9500 cal yr BP that persisted until 8000 to 4500 cal yr BP (Brunelle et al., 2005). The vegetation data are consistent with effectively longer growing seasons in summer-dry regions during the early-Holocene summer insolation maximum.

Fire frequency at Blacktail Pond rose abruptly at 12,000 cal yr BP to 6 episodes 1000 yr\(^{-1}\). It declined slightly between 11,000 and 9000 cal yr BP and reached a maximum of 8 episodes 1000 yr\(^{-1}\) between 9000 and 7500 cal yr BP. The reconstruction resembles those at Cygnet Lake and Burnt Knob Lake (summer-dry sites) on multi-millennial times scales, because all show highest fire frequency between 11,000 and 8000 cal yr BP, but on millennial and shorter time scales, the sites show differences in the timing of maximum fire occurrence in this interval. The early-Holocene fire history at Slough Creek Lake (summer-wet) is obscured by a gap in the sedimentary record between 9500 and 8500 cal yr BP (Fig. 5), which artificially depresses fire frequency. In general, however, fire frequency was generally low (2–4 episodes 1000 yr\(^{-1}\)) in the early Holocene, as it was at Pintler Lake (summer-wet) in northwestern Montana (Brunelle et al., 2005). Thus, the high fire activity and marl precipitation indicate that Blacktail Pond experienced warmer and effectively drier summers in the early Holocene than before or at present, similar to sites from the summer-dry precipitation regime.

From 7600 to 4000 cal yr BP, Pinus and Pseudotsuga became abundant on rocky substrates near Blacktail Pond, although minor amounts of Picea may have persisted in cool ravines. Artemisia steppe was more extensive around the lake than before or at present. A similar transition to xerophytic vegetation also occurred at Slough Creek Lake (summer-wet) as Pseudotsuga and Poaceae increased. The shift suggests that effective summer moisture was lower than before, as a result of reduced winter snowfall and/or weakened monsoons. Fire activity at Blacktail Pond decreased from previous high levels to 6 episodes 1000 yr\(^{-1}\) and maintained that level until 2000 cal yr BP. Slough Creek Lake registered 7 fire episodes 1000 yr\(^{-1}\) at 7500 cal yr BP and 8 episodes 1000 yr\(^{-1}\) by 4000 cal yr BP. Cygnet Lake (summer-dry) maintained a fire frequency of 7–8 episodes 1000 yr\(^{-1}\) until 4000 cal yr BP. The high activity at all sites suggests little differentiation of fire regimes in summer-wet and summer-dry precipitation regions in the middle Holocene. Likewise, Burnt Knob Lake (summer-dry) in the northern Idaho indicates moderate fire activity and xerophytic forest between 8000 and 3000 cal yr BP, as does Pintler Lake (summer-wet) in northwestern Montana and Rapid Lake (summer-wet) in the Wind River Range. Thus, during the middle Holocene, effectively warmer-than-present summers prevailed throughout the northern Rocky Mountain region.

From 4000 to 2000 cal yr BP, the expansion of Artemisia steppe and parkland of Pseudotsuga and Pinus contorta at both Blacktail Pond and Slough Creek Lake (summer-wet) and the decline of Picea suggest increased aridity. A period of high marl production at Blacktail Pond between 2900 and 1300 cal yr BP implies warmer summer conditions and possibly lower lake levels. Fire frequency at Blacktail Pond remained high (~5 episodes 1000 yr\(^{-1}\)), although it gradually decreased through this period. Slough Creek Lake experienced increased fire activity at this time (up to 8 episodes 1000 yr\(^{-1}\)). The higher fire activity at Slough Creek Lake may be related to the greater importance of convectional storms and lightning ignitions and the more-open landscape for fire spread there than at Blacktail Pond. Highest fire activity was also noted at Pintler Lake (summer-wet), where it was associated with an expansion of Pinus contorta forest (Brunelle et al., 2005). At Cygnet Lake (summer-dry), a sharp decline in fire frequency occurred after 4000 cal yr BP from 7 to 2 episodes 1000 yr\(^{-1}\). At summer-dry sites on non-ryolite substrates in southern YNP and Grand Teton National Park (Whitlock, 1993) and at Burnt Knob Lake, an increase in Picea and Abies is evidence of cooler effectively wetter conditions in the late Holocene. Like other YNP records, Cygnet Lake shows a trend of decreasing fire activity in the last 2000 yr.

For comparison, a multi-proxy record of centennial-scale climate variability in the last 2650 yr is available at Crevice Lake (lat. 45° 00′ N, long. 110° 34′ 20″ W, elev. 1713 m), located 8 km north of Blacktail Pond (Whitlock et al., 2008b) (Fig. 1). Pollen, diatom, charcoal, geochemical, and stable isotope data were analyzed from this varved-sediment site to infer limnologic and vegetation variations (Fig. 7). The Crevice Lake record indicates the following environmental history: (1) limited bottom-water anoxia, relatively wet winters, and cool spring and summers from 2650 to 2100 cal yr BP; (2) dry warm conditions between 2100 and 850–800 cal yr BP when the lake was anoxic, winter precipitation was low, and fire frequency was generally high (5–7 episodes 1000 yr\(^{-1}\)) between 1350 and 1100 cal yr BP; and (3) improved winter precipitation compared with previous conditions, and lake stratification suggesting warmer springs from 250 to 150 cal yr BP, and (5) increased winter precipitation and moderate spring and summer conditions between 150 cal yr BP and the top of the record (AD 1908). Within dry interval 2 (2100–800 cal yr BP) was a period of very dry winters between 1350 and 1100 cal yr BP that overlapped with the Medieval Climate Anomaly, which has been variously dated between ca. 1300 and 650 cal yr BP in the western U.S. and Great Plains (e.g., Laird et al., 1996; Woodhouse and Overpeck, 1998; Fritz et al., 2000; Case and MacDonald, 2003; Pierce et al., 2004; Stevens et al., 2006). Likewise, local PDSI data show persistent dry conditions between 1350 and 800 cal yr BP, followed by an interval of alternating wet and dry extremes from 900 to 600 cal yr BP (Fig. 7). An 800-year tree-ring reconstruction from the Yellowstone area also indicates pronounced drought in the early 13th century (not shown, Gray et al., 2007).

In the Blacktail Pond long and short cores, CHAR values and, by inference, fire activity were high between ca. 1850 and 1400 cal yr BP and large-magnitude fire episodes occurred at ca. 1800 and 1550 cal yr BP. This period falls within the dry interval 2 at Crevice Lake, although the large fire episodes precede the Medieval Climate Anomaly. The fire episodes at 2800 and 2550 cal yr BP also are associated with dry conditions inferred from times of high fire-related debris flow activity
in northern YNP (Meyer et al., 1995). Low CHAR values between 1400 cal yr BP and –33 cal yr BP (i.e., AD 1988) mark a period of low fire activity at Blacktail Pond, and effectively wetter conditions between 800 and 50 cal yr BP were also noted at Crevice Lake and in the fire-related sedimentation records (Fig. 7).

5. Final remarks

The records from YNP illustrate the sensitivity of vegetation and fire activity to variations in seasonal water balance during the Holocene. Although the summer-wet/summer-dry hypothesis, as originally described by Whitlock and Bartlein (1993), focused on spatial and temporal variations in summer precipitation, the vegetation and the fire season is strongly controlled by winter and spring precipitation and its influence on summer moisture conditions (Despain, 1990). The vegetation history at Blacktail Pond closely matches that of Slough Creek Lake and suggests a progression from tundra in the late-glacial period to mesophytic forest in the early Holocene and dry open parkland and steppe in the late Holocene. Thus, the vegetation changes suggest wet conditions in the early Holocene followed by progressively drier conditions in the last 7000–8000 yr, as predicted for summer-wet sites, but a combination of variations in winter and spring precipitation and summer drought likely contributed to these changes. Summer-dry sites show the presence of xerothermic forest in the early and middle Holocene followed by mesophytic forest in the late Holocene, and this sequence implies effectively dry growing season conditions initially followed by cool wet conditions. Again, changes in winter/spring precipitation and summer drought were probably both important.

In contrast to the vegetation history, the fire-episode frequency shows considerable site variability. One explanation for lack of coherence may be that all three sites lie near the summer-wet/summer-dry transition and show a complicated response that reflects changes in the sharpness or location of the boundary through time. In the early and middle Holocene, the high fire-episode frequency at Blacktail Pond resembles that at Cygnet Lake and other summer-dry sites (although on millennial time scales the records are out of phase). At Slough Creek Lake, the early-Holocene fire-episode frequency was low (although there is a gap in the record at this time), and it rose steadily after 8000 cal yr BP. In the middle Holocene (ca. 8000 to 4000 cal yr BP), the fire-episode frequency was high at all sites and throughout the northern Rocky Mountains, reflecting drier- and warmer-than-present conditions. Fire activity declined dramatically at Cygnet Lake after 4000 cal yr BP, and at all sites after 2000 cal yr BP. The decrease in fire-episode frequency suggests effectively cooler summer conditions than before. Submillennial variations in fire activity at Blacktail Pond in the last 4000 yr suggest that large fire episodes occurred during dry periods embedded within this long-term cooling trend.

Another, equally likely explanation is that the summer-wet/summer-dry hypothesis is only one driver of whether or not a site experiences fire. Recent modeling and empirical studies of charcoal data indicate that the source area of overall CHAR is different from that of charcoal peaks, even for high-resolution macroscopic charcoal data (Higuera et al., 2007, in review). The studies suggest that CHAR is collected from a radius of tens of kilometers around the lake sampling site, and CHAR levels are even for high-resolution macroscopic charcoal data (Higuera et al., 2007, in review). The research was supported by funds from the Canon Foundation, Yellowstone National Park, and NASA student internship under GRNASM99G000001. The paper benefited from the comments of two anonymous reviewers.

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