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# Regionalization of fire regimes in the Central Rocky Mountains, USA

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ABSTRACT

Fire is one of the most important natural disturbances in the coniferous forests of the US Rocky Mountains. The Rocky Mountains are separated by a climatic boundary between 40° and 45° N, which we refer to as the central Rocky Mountains (CRM). To determine whether the fire regime from the CRM was more similar to the northern Rocky Mountains (NRM) or southern Rocky Mountains (SRM) during the Holocene, a 12,539-yr-old sediment core from Long Lake, Wyoming, located in the CRM was analyzed for charcoal and pollen. These data were then compared to charcoal records from the CRM, NRM and SRM. During the Younger Dryas chronozone, the fire regime was characterized as frequent at Long Lake. The early and middle Holocene fire regime was characterized as infrequent. A brief interval from 4000 to 3000 cal yr BP, termed the *Populus* period, had a frequent fire regime and remained frequent through the late Holocene at Long Lake. In comparison to sites from the NRM and SRM, the fire regime at Long Lake was most similar to the SRM during the past 12,539 cal yr BP. These results suggest the disturbance regime in the CRM has a greater affinity with those of the SRM.

## Introduction

Driven by factors such as temperature, precipitation, humidity, wind and fuel availability (Westerling et al., 2003), fire is a dynamic force shaping forest composition and is considered one of the most important natural disturbances in the coniferous forests of the western United States (US). Understanding these variables is important for determining how fire regimes may vary in response to climate change (Dale et al., 2001). One of the few ways we can learn about the interactions between fire and climate is to look at past fire regimes as a baseline against which to measure modern changes. Fire histories obtained through the examination and quantification of charcoal preserved in lake sediments are particularly useful because of their long temporal span. Unlike tree rings, which offer annual resolution but are generally age-limited to the past few hundred years, charcoal records preserved in lake sediments have the ability to reconstruct a fire history over millennia (Long et al., 1998). Charcoal records are also useful in that they can identify long-term shifts in fire regimes during periods of major climate change (Brunelle and Whitlock, 2003). To understand the fire ecology of a system, sediment-based fire reconstructions are compared to determine how fire regimes respond as climate changes through time (Minckley and Shriver, 2011; Minckley et al., 2012).

The US Rocky Mountain region is normally divided into either the northern Rocky Mountains Range (NRM) or southern Rocky Mountains Range (SRM). The central Rocky Mountains Range (CRM) are defined here as the geographical location also known as the Wyoming Basin that separates the NRM and SRM (Baker, 2009) (Fig. 1). In this context, the CRM can be viewed as the transition zone between the Great Basin, the Great Plains, the NRM, and the SRM (Brunelle et al., 2013). The CRM is of particular interest because currently precipitation in the CRM and NRM is influenced from westerly storms originating from the northern Pacific Ocean in the winter, and both experience summers that are relatively warm and dry (Mock, 1996; Shinker, 2010; Wise, 2010). However, it is unclear whether the CRM has been influenced by these same precipitation patterns through time or how different precipitation patterns may influence fire regimes in the CRM.

The SRM typically experience precipitation patterns out of phase with the NRM; based on the observation that when the NRM are anomalously wet, the SRM are anomalously dry (Dettinger et al., 1998; Wise, 2010). Within this dipole, the CRM historically has followed the moisture patterns of the NRM (Mock, 1996; Baker, 2009; Shinker, 2010). The dipole fluctuation in precipitation between the NRM and SRM is associated with El Nino–Southern Oscillation cycles (Wise, 2010), which are known to influence wildfire occurrence and severity in particular regions in the United States (Westerling et al., 2003).

Past fire regimes in the NRM have been researched more heavily than those of the SRM, with even fewer fire reconstructions along the transition zone between the two regions (Minckley et al., 2007, 2012; Brunelle et al., 2013). Based on climatic association, it is not understood whether the CRM has a distinct fire regime, or whether its fire regime is more similar to the NRM or SRM. Dettinger et al. (1998) proposed a climatic boundary that separates the NRM and SRM between 40° and 45° N latitude, but this climatic boundary was likely not stationary

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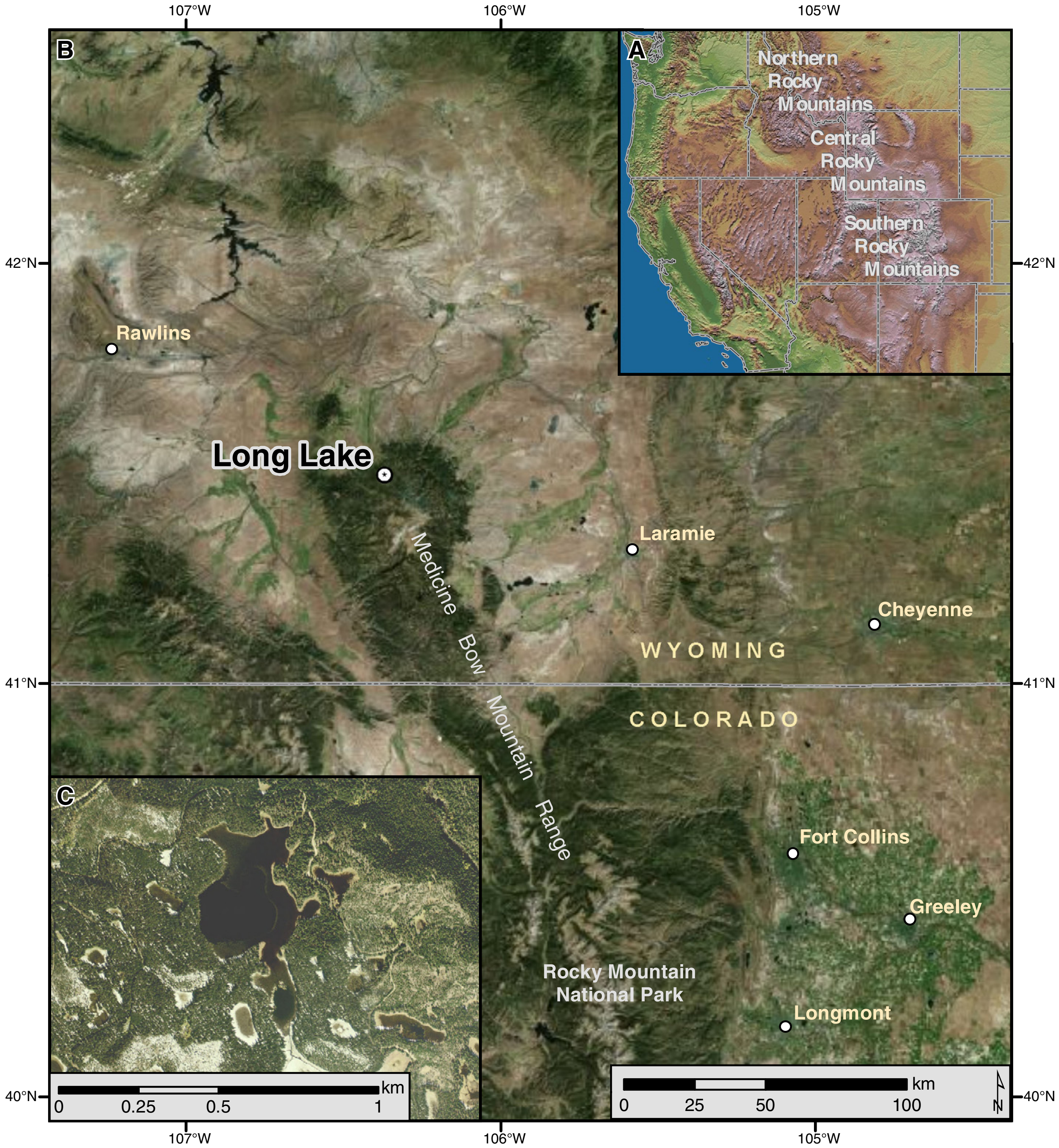

**Figure 1.** Location of study site. A) Map showing the western United States and the location of the northern, central and southern Rocky Mountains. B) Map showing site location in the Medicine Bow Mountains in southeastern Wyoming. C) 2006 NAIP (National Agriculture Imagery Program) imagery of Long Lake, WY.

through time (see also Schoennagel et al., 2005; Wise, 2010; Lyle et al., 2012). Results from Schoennagel et al. (2005) suggest that the CRM, like the NRM, may be more strongly influenced by weather systems from the Pacific Northwest and less influenced by weather systems from the Southwest. Analysis by Wise (2010) suggests a narrow climatic boundary (40°–42° N latitude) west of the continental divide. Finally, Shinker (2010) showed wedge-shaped clusters of similar monthly: annual precipitation patterns between 40° and 43° N that span the CRM, which is supportive of the interpretation of an unclear climatic boundary proposed by both Dettinger et al. (1998) and Wise (2010).

Here we present a 12,539-yr-long, fire–vegetation–climate reconstruction from Long Lake, Wyoming (Fig. 1), a lower-treeline site located in a mixed conifer forest in the Medicine Bow Mountain Range. Long Lake lies within the proposed climatic boundary separating the NRM and SRM and may help inform aspects of climatic sensitivity and how transitional climate boundaries may impact fire regime changes through the Holocene. Our objectives are 1) to determine whether the climatic transition zone has been stable throughout the Holocene and if not, how a shift of the transition zone affects the fire regime of the CRM; and 2) to determine the affinity of the fire regime from the CRM to the fire regimes of the NRM or SRM throughout the Holocene. We hypothesize that the climatic boundary has shifted through the Holocene and these shifts have significantly influenced the fire regime of the CRM. In addition to evaluating other sites from the CRM (Minckley et al., 2012; Brunelle et al., 2013), we compare our results with fire records from the US Rocky Mountain region to better understand possible regional climatic controls and their relationship with changes in fire regimes.

## Site description

Long Lake, Carbon County, Wyoming (41° 30.099′ N, 106° 22.087′ W, elevation 2700 m) lies within a closed drainage basin situated behind a terminal Pinedale moraine within the Medicine Bow River drainage (Atwood, 1937) (Fig. 1). Long Lake has a small watershed with a surface area of approximately 12 ha (US Forest Service, unpublished data), a maximum water depth of 10 m, and no inlet or outlet stream (Carter, 2010). The site was chosen because of its closed drainage basin where evidence of erosional events or disturbance events, such as fires, would largely be limited to local sources within the watershed. Interpolations from the nearest weather station indicate January and July precipitaion averages of 33 cm and 69 cm, respectively. Interpolated temperatures for Janurary average −9.7°C and July temperatures average 11°C (NRCS, *unpublished data*).

The forest canopy at Long Lake is dominated by lodgepole pine (*Pinus contorta* Dougl. ex Loud. var. *latifolia* Engelm. ex Wats.) with intermingled subalpine fir (*Abies bifolia* (Hook.) Nutt.) and Engelmann spruce (*Picea engelmannii* Parry ex. Englem.). Dominant understory species include whortleberry (*Vaccinium scoparium*), Oregon grape (*Mahonia aquifolium*), pipsissewa (*Chimaphila umbellata*), buttercup (*Ranunculus* sp.) and common juniper (*Juniperus communis*). The lake margin contains various grasses (Poaceae), and sedges (Cyperaceae), as well as water birch (*Betula occidentalis*) locally in mesic swales. Hydrophytes include Rocky Mountain pond lily (*Nuphar lutea*) and alpine pondweed (*Potamogeton alpinus*). Currently, no quaking aspen (*Populus tremuloides*) are found at Long Lake, but the ecotone lies roughly 150 m downslope from the lake along the toe of a Pinedale-age moraine.

## Methods

### *Field work*

In September 2007, a 4.85-m-long core (LL07D) was collected from the depocenter of the lake (10 m) from an anchored platform using a Livingstone corer. A 30-cm short core (LL07C) that captured the uppermost sediments was also collected using a Klein corer. Core lithology of LL07D was described in the field. Once extruded, each drive from the long core was wrapped in plastic wrap and aluminum foil. The short core was sampled contiguously in the field at 1-cm increments, which were placed in individual whirl-pak bags. All sediments were then transported to the University of Utah RED (Records of Environment and Disturbance) Lab, and refrigerated at 2°C, prior to further analyses.

### *Chronology and lithology*

Age–depth relationships for Long Lake were determined using seven AMS-$^{14}$C dates from conifer needles from LL07D, and one AMS $^{14}$C date from LL07C (Table 1). The LL07C date, along with charcoal data from LL07C, was used to align LL07D and LL07C. Because close alignment of both cores indicated that the long core captured the entire record, we present analysis solely from LL07D. Radiocarbon dates were converted to calibrated years using CALIB 4.1 (Stuvier et al., 1998) and age–depth relationships were determined to calibrated years before present (cal yr BP; AD 1950 = year 0) with a smoothing spline using a classical age–depth model (CLAM) for the entire record (Blaauw, 2010). The interpolated basal age of the record was 12,539 cal yr BP (Fig. 2).

**Table 1**
Long Lake Radiocarbon dates from LL07D and LL07C. An age model was constructed using a smoothing spline. See text for explanations.

| Depth (cm) | UGAMS# | Label ID | Source/Material | Age (14C yr BP) | Age (cal yr BP) with 2-sigma range |
|---|---|---|---|---|---|
| 29 | 3249 | LL07D | *Pinus contora* needle | 50 ± 35 | 31–139 |
| 88 | 2773 | LL07D | *Pinus contorta* needle | 1730 ± 35 | 1549–1714 |
| 156 | 3032 | LL07D | *Pinus contorta* needle | 3510 ± 30 | 3698–3864 |
| 232 | 2774 | LL07D | *Pinus contorta* needle | 6460 ± 45 | 7275–7435 |
| 249 | 3031 | LL07D | *Abies lasiocarpa* needle | 8110 ± 50 | 8976–9152 |
| 323.5 | 2775 | LL07D | *Pinus flexis* needle | 9630 ± 50 | 10,774–11,180 |
| 449 | 3478 | LL07D | *Abies lasiocarpa* needle | 10325 ± 50 | 11,975–12,386 |

The uppermost sediments of LL07D were composed of a flocculent mix of mud and water. From 12 to 15 cm, sediments were composed of green gyttja. From 15 to 199 cm, sediments were composed of brown gyttja and gradually shifted to a darker brown gyttja from 200 to 241 cm. A visible 7-cm organic peat layer was identified between 241 and 247 cm. From 247 to 433 cm, sediments were composed of green-brown gyttja. From 434 to 454, the sediments were a lighter brown color and mostly sand and clay. The remaining 31 cm were a gray color and comprised silty clay and sand.

### *Charcoal analysis*

To reconstruct local fire history, macroscopic charcoal was analyzed from contiguous samples from LL07D. Contiguous subsamples of 5 cm$^3$ were soaked in sodium hexametaphosphate, a disaggregant, and sieved through 125 and 250 μm wire mesh screens. Charcoal >125 μm suggests local fires within the watershed because particles of this size do not travel far from their source (Clark, 1988; Gardner and Whitlock,

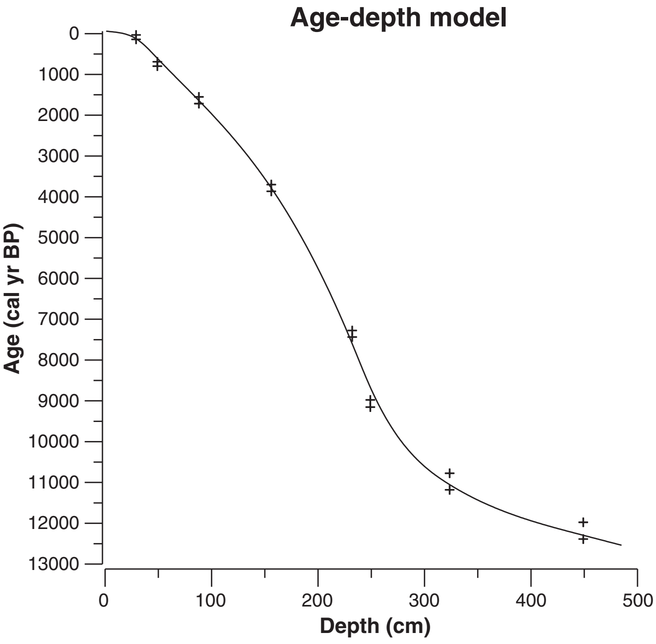

**Figure 2.** Age–depth model for Long Lake. Age model plot depicts calibrated AMS $^{14}$C ages versus depth plots using CLAM (Blaauw, 2010). The "+" symbols indicates the range of two-sigma calibrated ages (cal yr BP) (see Table 1).

2001). The total charcoal counts were converted into charcoal concentrations (particles/cm$^3$) and then transformed to charcoal influx (CHAR; particles/cm$^2$/yr). Charcoal concentrations were binned into 5-yr intervals to capture the highest resolution portion of the fire record using CharAnalysis (Higuera et al., 2009; Huerta et al., 2009).

The interpolated charcoal time-series was decomposed into two components: the slow moving background component, assumed to represent continual input of charcoal from varying local and extra-local fire activity; and a peaks component, which represents the relatively instantaneous charcoal input into the lake from a single or a series of fire events during the interpolated time span of each sample (Fig. 3). The background component was determined by using a 500-yr lowess smoother, robust to outliers. Fire return interval (FRI), the number of years between each fire episode, was smoothed using a 1000-yr moving window. Fire episode magnitude, or peak magnitude (particles/cm$^2$/episode), represents the amount of charcoal produced above the background charcoal level for each fire episode detected and may vary with fire size, severity, and proximity (Higuera et al., 2009; however see Minckley and Shriver, 2011 for an alternate interpretation of peak magnitude and fire severity). Here peak magnitudes are used as a proxy for severity to facilitate inter-site comparisons with published literature.

For our regional comparisons, we reanalyzed 9 fire histories from Hoodoo Lake, Baker Lake, Pintlar Lake and Burnt Knob Lake (Brunelle et al., 2005), Cygnet Lake (Millspaugh et al., 2000 (NOAA)), Slough Creek (Millspaugh et al., 2004 (NOAA)), Little Windy Hill Pond (Minckley et al., 2012), Hunters Lake and Chihuaheños Bog (Anderson et al., 2008). Charcoal data from these published records were treated similarly to the Long Lake dataset. However, instead of binning charcoal data into 5-yr intervals, we used the median sedimentation rate values determined using CharAnalysis to best represent the sedimentation rate of each site (Higuera et al., 2009; Huerta et al., 2009). We then calculated z-scores for each dataset by taking the standard deviation of each FRI from each site calculated by CharAnalysis for inter-site comparisons so that the sites could be compared for changes in trend (Fig. 6). We used the same temporal scale for each dataset to match the temporal scale of the Long Lake record.

### Pollen analysis

Pollen analysis was conducted at 4–8 cm intervals. One-cm$^3$ samples were processed with standard acid–base reduction methods from Faegri et al. (1989). *Lycopodium* tablets were added to each sample as an exotic tracer during processing for calculation of pollen influx rates. Minima of 300 terrestrial pollen grains were counted per sample using light microscopy at 500× magnification. Pollen counts were converted into pollen percentages based on the abundance of each pollen type relative to the sum of terrestrial grains in each sample (Fig. 4). *Pinus* subgenus *Pinus* and *P.* subgenus *Strobus* pollen were assigned to *Pinus contorta*-type and *Pinus flexilis*-type based on the modern phytogeography and macrofossils identified in the cores. *Pinus* grains without distal membranes were identified as *Pinus* undifferentiated, and total *Pinus* represents the sum of *P.* subgenus *Pinus* and *P.* subgenus *Strobus* and undifferentiated *Pinus* grains. *Abies* pollen was referred to as *Abies bifolia* and *Picea* pollen was referred to as *Picea engelmannii* based on the modern phytogeography and macrofossils. Macrofossils were identified concurrently with charcoal counts. Pollen percentage data are presented as zonal averages unless otherwise indicated. Pollen zones were calculated using CONISS (Grimm, 1987) and we used the same zone boundaries for the charcoal record and regional comparisons.

## Results

### *LL-I: Younger Dryas Chronozone (YDC) (depth 485–385 cm, 12,539–11,800 cal yr BP)*

#### *Pollen*

In LL-I, low arboreal pollen percentages with *Pinus-flexilis*-type (1%), *Pinus-contorta*-type (4%) and total *Pinus* pollen percentages (19%) represented most of the arboreal contributions of this zone until ~12,200 cal yr BP when *Picea* pollen percentages increased to over 13% (Fig. 4). Cupressaceae (6%) and *Betula* (3%) pollen percentages were relatively low. *Artemisia* pollen percentages (41%) dominate the LL-I pollen assemblage. Herbaceous taxa were common with high

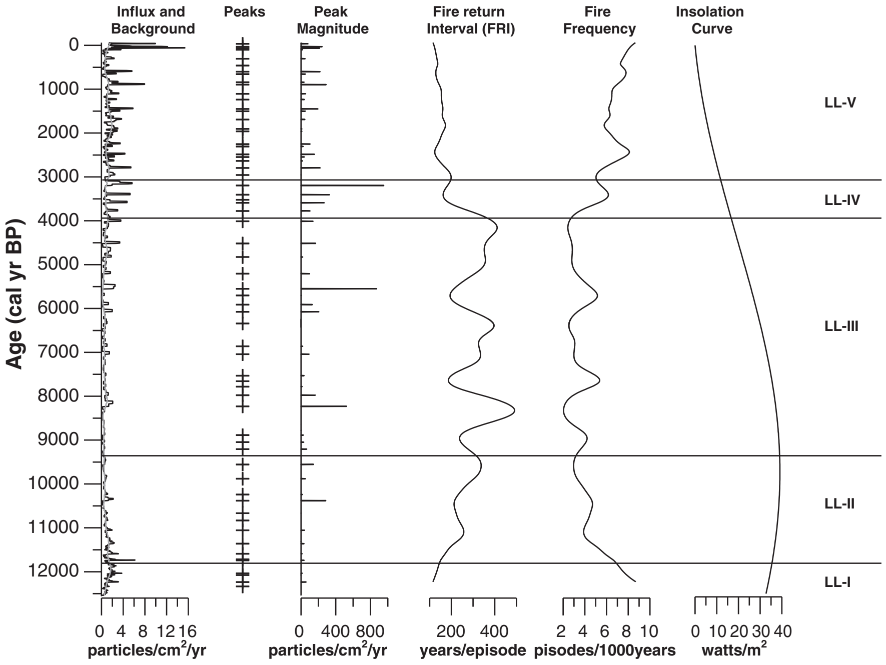

**Figure 3.** Fire history with charcoal influx (black) and background (gray). Peaks are indicated by the '+' symbol as indicated by CharAnalysis. Peak magnitude (particles/cm$^2$/yr) is used to illustrate the magnitude of each peak detected. Fire return interval (FRI) illustrates how many years are between each fire episode. The insolation curve is representative of the changing climate and the changing fire regimes associated with the climate change.

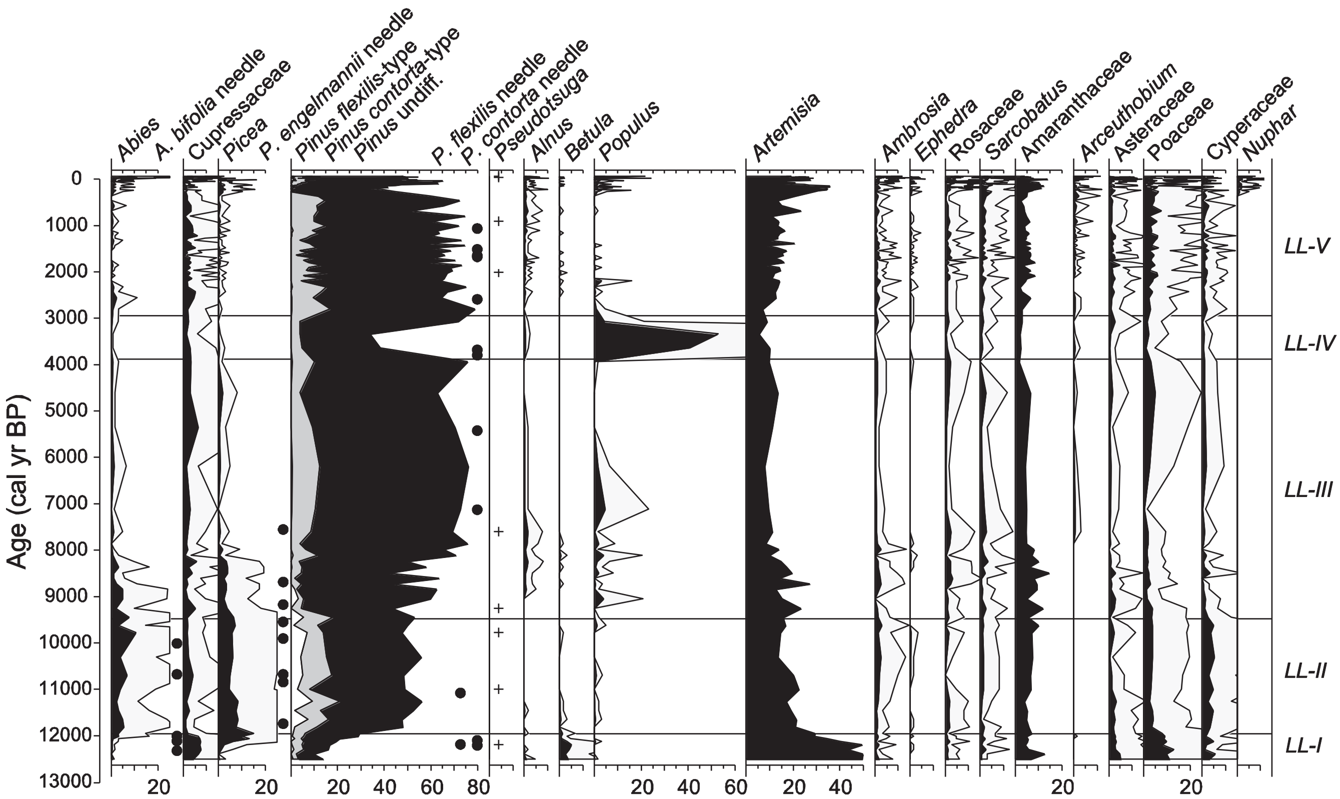

**Figure 4.** Pollen percentage and macrofossil data plotted against time for Long Lake, WY. Gray shading indicates 5× exaggeration of pollen percentage data. A '+' symbol indicates the presence of pollen at trace amounts. Black circles indicate identified macrofossils.

percentages of Poaceae (10%) and Amaranthaceae (~6.5%) pollen. Cyperaceae pollen percentages were low (3%). Initial forest constituents include *Abies bifolia*, *P. contorta*-type and *P. flexilis*-type based on macrofossils.

### *Charcoal*

Four fire episodes were identified with a mean fire return interval (FRI) of 131 yr (Fig. 4). Peak magnitudes were variable between 0.1 and 58.5 and averaged 18.0 particles/cm$^2$/episode.

### *LL-II: the early Holocene (depth 385–258 cm, 11,800–9400 cal yr BP)*

### *Pollen*

Pollen percentages for subalpine species, *Abies* (5%) and *Picea* (7%) increased during LL-II. *Pinus* pollen percentages also increased to 50%, with *Pinus flexilis*-type and *Pinus contorta*-type pollen abundances averaging 5% and 10% respectively. Shrub and herbaceous pollen abundances decreased in this zone with *Artemisia* pollen percentages decreasing (18%), along with Cupressaceae (2%), Poaceae (4%), and Asteraceae (2%). Cyperaceae pollen percentages increased to 4%. *Abies bifolia*, *Picea engelmannii* and *P. flexilis*-type needles were present.

### *Charcoal*

LL-II had 13 fire episodes with a mean FRI of 246 yr. Peak magnitudes ranged between 0.3 and 144.0 and averaged 48.0 particles/cm$^2$/episode.

### *LL-III: the middle Holocene (depth 258–160 cm, 9400–4000 cal yr BP)*

### *Pollen*

Total *Pinus* pollen was the dominant pollen type during LL-III, averaging 68%. *Abies* pollen percentages averaged a peak of 4% around 9000 cal yr BP. *Pinus flexilis*-type (1%) and *Pinus contorta*-type (6%) pollen percentages decreased in this zone. *Picea* pollen was initially present (4%) but decreased to trace levels through the zone. Cupressaceae (3%) pollen percentages also decreased. *Populus* pollen increased (1%) after 9000 cal yr BP. *Artemisia* pollen percentages (14%) along with Amaranthaceae (7%), Asteraceae (1%), Poaceae (2%) pollen percentages were all lower than previous. Cyperaceae (1%) pollen percentages, as well as riparian species, including *Salix* (<1%) and *Alnus* (<1%) increased. Short-term increases of *Artemisia* pollen percentages and those of aquatic pollen types were notable in the 7-cm thick organic layer (241–247 cm; 8600–8200 cal yr BP). *Pinus flexilis*-type increased to 4% while *Pinus contorta*-type decreased to 2% during this shift. *Abies* pollen increased to 5% and *Picea* pollen decreased to 3%. Around 9000 cal yr BP total *Pinus* pollen decreased to 36%, while Amaranthaceae (14%), Asteraceae (3%), Poaceae (2%), and Cyperaceae (4%) all increased. Aquatic and riparian species, including *Salix* (2%), and *Alnus* (<1%) also increased.

### *Charcoal*

LL-III had 21 fire episodes with a mean FRI of 320 years, which was the least frequent of the record (Fig. 3). Peak magnitudes for the 21 events ranged between 0.1 and 871.0 and averaged 124.0 particles/cm$^2$/episode. Two out of the 21 fires (5500 and 8230 cal yr BP) had peak magnitudes >500 particles/cm$^2$/episode.

### *LL-IV: the Populus period (depth 160–140 cm, 4000–3100 cal yr BP)*

### *Pollen*

From 4000 to 3100 cal yr BP, *Populus* pollen percentages increased from 1% to 31% and remained high for ~900 years. The increase in *Populus* pollen abundance was anomalous in western North America pollen diagrams, so these counts were verified by Carter, Brunelle and Minckley. All relative pollen abundances were lowered by the inclusion of *Populus* pollen percentages in the terrestrial sum. *Pinus* pollen percentages averaged 36%. *Artemisia* pollen decreased from 14% to 8%. *Pinus contorta*-type needles were identified in this zone.

### *Charcoal*

LL-IV had five fire episodes with a mean FRI of 277 yr. Peak magnitudes ranged between 0.2 and 953.0 and averaged 330.0 particle/cm$^2$/episode. The largest fire episode (3195 cal yr BP) occurred during this zone and had a peak magnitude averaging 953.0 particles/cm$^2$/episode. Two other noticeable fire episodes occurred during this zone (3405 and 3590 cal yr BP) with peak magnitudes >200 particles/cm$^2$/episode.

### *LL-V: the late Holocene (depth 140–0 cm, 3100 cal yr BP–present)*

### *Pollen*

Total *Pinus* pollen percentages increased to 57% but overall there was a decreasing trend in *Pinus* pollen abundance. *Pseudotsuga* pollen was intermittently present from 2000 cal yr BP to present. *Populus* pollen percentages decreased to 1%. *Artemisia* (19%) pollen percentages increased toward present. Cupressaceae (2%), Poaceae (4%) and Amaranthaceae (6%) pollen percentages were low within LL-V. *P. contorta*-type and *Pseudotsuga menziesii* (Douglas-fir) needles identified in this zone indicate local presence of these taxa.

### *Charcoal*

During LL-V there were 24 fire episodes with an average FRI of 149 years. Peak magnitudes ranged between 0.2 and 290.0, averaging 90.0 particles/cm$^2$/episode. Four of the 24 fires were >200 particles/cm$^2$/episode (30 cal yr BP, 65 cal yr BP, 600 cal yr BP, and 895 cal yr BP).

## Discussion

Located in the middle of the NRM, SRM, Great Basin and Great Plains, the CRM is a unique geographic region to study the sensitivity of fire regimes across the proposed north–south climate boundary of western North America (Dettinger et al., 1998; Shinker, 2010; Wise, 2010). This study presents the record from Long Lake and compares the fire history with other charcoal records across the US Rocky Mountains (Fig. 5) to determine if this climatic boundary shifted through the Holocene. The Long Lake record is also used to demonstrate whether the fire activity at Long Lake was more similar to the NRM or SRM throughout the Holocene and how this could relate to climate sensitivity within the climatic boundary zone (Fig. 6).

### *Holocene climate, vegetation and fire history of the Central Rocky Mountains*

### *LL-I: YDC (12,539–11,800 cal yr BP)*

Cold and dry conditions were present at Long Lake prior to 12,200 cal yr BP, as evident by an open parkland, abundant with *Artemisia* (most likely the herbaceous species *A. borealis*) and other low-lying herbs and shrubs, such as Poaceae, Amaranthaceae and Asteraceae (Fig. 4). Fires were relatively frequent, averaging 131 years between episodes, but of low magnitude (18 particles/cm$^2$/episode) (Fig. 3). Four fire events occurred through the first 740 years of the Long Lake record, indicating a relatively frequent FRI. Fuels were likely dominated by low-lying herbs and shrubs with low connectivity making low biomass a major factor controlling fire occurrence prior to 12,200 cal yr BP. Low background charcoal also suggests low fuel abundances and connectivity. Increasing abundance of *P. contorta*-type, *P. flexilis*-type and *Abies bifolia* macrofossil needles from 12,000 to 11,800 cal yr BP (Fig. 4) indicates infilling of the local forest and warming conditions. As the fuels on the landscape changed throughout the YDC from low-lying herbs and shrubs to a landscape with intermediate conifers, the FRI became more infrequent than previous (Fig. 3). However, fuels increased on the landscape as the local forest formed coinciding with the largest peak magnitude event during the YDC.

During the YDC in the CRM, specifically in the Medicine Bow Mountains, Little Windy Hill Pond and Little Brooklyn both record similar colder than present conditions prior to ~12,000 cal yr BP (Fig. 5). Little Windy Hill Pond recorded low fire activity with an infrequent FRI (Fig. 6), as a result of low fuel connectivity in the earliest part of the YDC. These sites suggest warming conditions and the development of local forests around 12,000 cal yr BP. The more infrequent fire regime recorded at Little Windy Hill Pond is counter to the frequent fire regime recorded at Long Lake. This suggests elevation and possibly fuels were the controlling factor for the local heterogeneity of the FRI during this time.

### *LL-II: the early Holocene (11,800–9400 cal yr BP)*

Early Holocene warming associated with increased summer insolation corresponded to the establishment of a closed mixed conifer forest

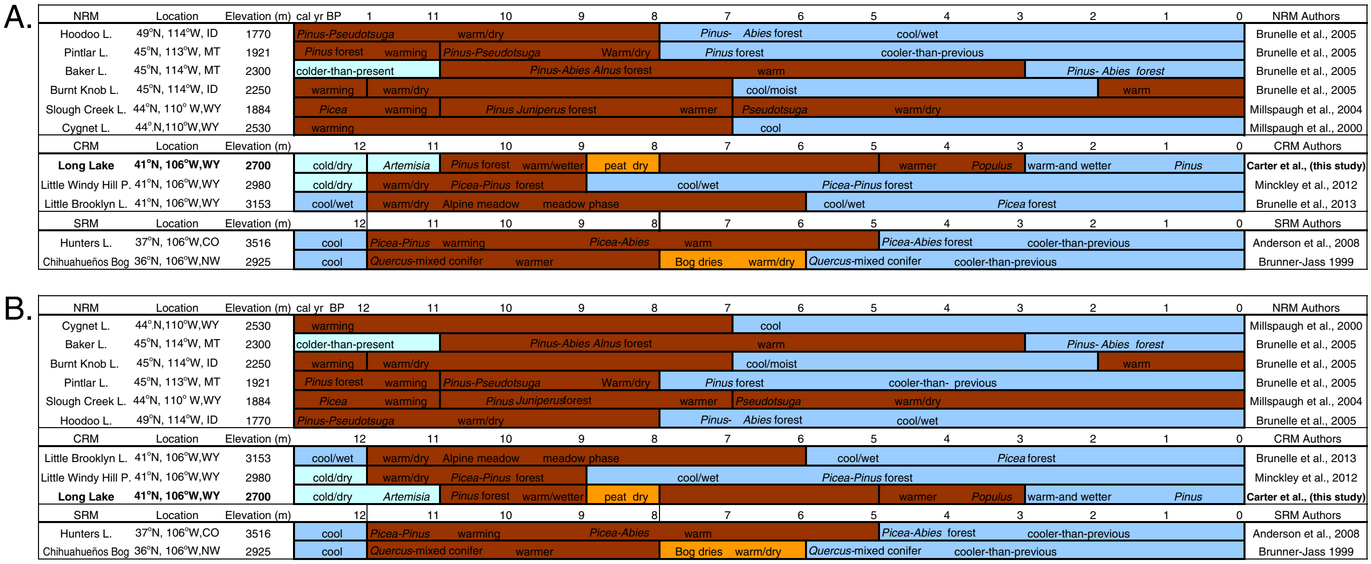

**Figure 5.** Regional comparison diagram beginning at 13,000 cal yr BP. A — Sites are organized by latitude, from north to south. B — Sites are organized by elevation, from high elevation to low elevation.

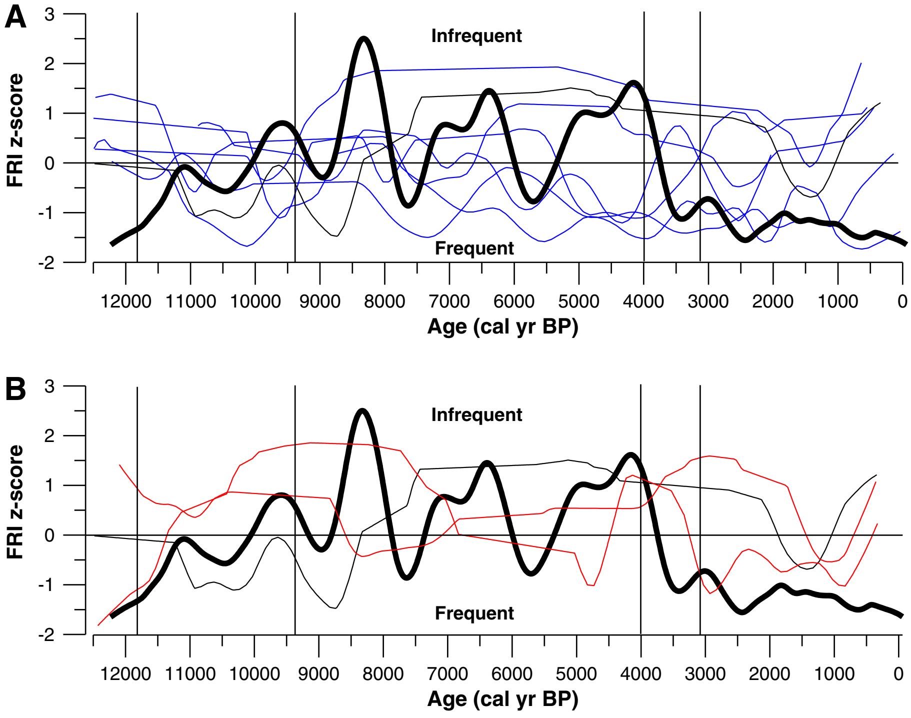

**Figure 6.** FRI z-score comparison diagram. A) Blue lines indicate NRM sites. Black lines indicate CRM sites, with the thick black line representing Long Lake. B) Red lines indicate SRM sites. Black lines indicate CRM sites, with the thick black line representing Long Lake. Z-scores below 0 indicate a frequent FRI, while z-scores above 0 indicate an infrequent FRI.

dominated by limber and lodgepole pines around Long Lake (Fig. 4). *Artemisia* and other understory vegetation, such as Poaceae and Asteraceae decreased as a result of the canopy closing. Fire episodes increased from previous, but were infrequent during the early Holocene, with an average FRI of 246 yr. Peak magnitudes increased to an average of 48 particles/cm$^2$/fire, which can be attributed to the increase of woody biomass around Long Lake. Increased forest density would have provided greater fuel connectivity for fire propagation; however the increase in summer insolation may have invigorated convective storms, which would have increased moisture availability and likely suppressed fire activity through increased fuel moisture (Brunelle et al., 2005). The increase in peak magnitudes and lengthened FRI suggests that fire severity increased as the system shifted from shrub–herb dominated to forest dominated (Baker, 2009).

Climatically in the CRM, Little Windy Hill Pond and Little Brooklyn record similar warming conditions, with drier conditions during the early Holocene. The infrequent FRI at Little Windy Hill Pond was similar to the FRI of Long Lake as a result of the development of a mixed conifer forest (Minckley et al., 2012). This suggests a stable climatic boundary may have established during the early Holocene in the CRM.

### *LL-III: the middle Holocene (9400–4000 cal yr BP)*

The record from Long Lake shows 9400–8000 cal yr BP was a time of considerable hydroclimatic variability resulting from the peak of Northern Hemisphere summer insolation (Kutzbach et al., 1998). From 9400 to 9000 cal yr BP, conditions were drier than previous, as indicated by relatively low *Pinus* and high *Artemisia* pollen percentages (Fig. 5). However around 9000 cal yr BP, an increase in *Pinus* pollen percentages (Fig. 4) that lasted ~200 yr, suggests climate conditions abruptly shifted to a wetter than previous state. Climate conditions shifted back to drier than previous conditions between 8800 and 8200 cal yr BP. A clearly visible 7-cm coarse organic layer in the Long Lake core, comprised of aquatic material, began ~8600 cal yr BP and ended ~8200 cal yr BP. Given the sediment cores were collected under 10 m of water, conditions had to be dry enough to cause the lake levels to drop low enough for macrophyte rooting to take place. *Pinus* percentages decreased and *Artemisia* pollen percentages increased, also indicating drier than previous conditions. Arid conditions lasted until ca. 8200 cal yr BP at Long Lake. From 8200 cal yr BP to ~4000 cal yr BP, wet conditions are inferred at Long Lake based on the highest percentages of *Pinus* pollen, mostly *P. contorta*-type, of the entire record and generally low *Artemisia* pollen percentages (Fig. 5). Jimenez-Moreno et al. (2011) interpret an increase of *Pinus* pollen percentages and decrease of *Artemisia* pollen percentages as representing increased summer precipitation. The absence of *Pseudotsuga* pollen and macrofossils from 7000 to 4000 cal yr BP at Long Lake also suggest wet conditions (Whitlock and Bartlein, 1993).

During the middle Holocene, fire episodes increased from previous but were still infrequent (average 320 yr/episode) likely of mixed severity (Fig. 3) (Minckley and Shriver, 2011). More severe fires, (greater peak magnitudes) occurred at Long Lake during the transitions from wet to dry conditions, likely when buildups and subsequent drying of fuels occurred. Swetnam and Betancourt (1998) demonstrated that in the southwestern US, prior to large fire events, wet conditions increase the production of fine fuels, but when the climate shifts to dry conditions, fuel moisture decreases resulting in large fires. For example, the termination of the dry interval between 8800 and 8200 cal yr BP was punctuated by a fire episode with a peak magnitude averaging 523 particles/cm$^2$/episode, suggesting a mid-to-high fire severity event. Charcoal data indicate the longest FRI for the entire Long Lake record (averaging 320 yr) may be explained by the shift from dry conditions in the early Holocene to effectively wetter than previous conditions in the middle Holocene. The interpretation of high charcoal influx (>500 particles/cm$^2$/yr) during transitions from wet to dry conditions is also applied to the fire episode at 5550 cal yr BP, when Long Lake shifted from a wet to dry period.

In the CRM, specifically in the Medicine Bow Mountains, both sites upslope experienced warmer and wetter than previous conditions at the onset of the middle Holocene (Fig. 5). Little Windy Hill Pond recorded a prolonged fire-free period between 7200 and 5600 cal yr

BP, believed to be a result of low effective moisture (Minckley et al., 2012). As a result, the FRI was more infrequent with less variability than that of Long Lake (Fig. 6). Even though conditions were wetter than those of the early Holocene, severe droughts in the Rocky Mountains occurred during the middle Holocene and lasted for centuries, which in turn disrupted the fire regime and vegetation composition (Shuman et al., 2010; Minckley et al., 2012). All sites upslope of Long Lake record a shift to dry conditions between 6000 and 5000 cal yr BP (see Brunelle et al., 2013).

### *LL-IV: the Populus period (4000–3100 cal yr BP)*

A significant change in the local forest composition around Long Lake occurred between 4000 and 3100 cal yr BP, with *Populus* replacing *Pinus* as the local dominant pollen type. The rise of *Populus* pollen percentages largely affected the relative abundance of *Pinus* pollen (Fig. 4). The high percentage of *Populus* pollen is significant because *Populus* pollen is not typically seen in great abundance because its preservation varies with pollen transport and lake chemistry (Sangster and Dale, 1964). *Populus* currently has the widest distribution of any tree in North America (Little, 1971), requires temperature ranges between ~— 10°C and 20°C (Thompson et al., 1999), and grows on moist soils in the US Rocky Mountains. Soil moisture is one of the biggest limiting factors of *Populus* (Burns and Honkala, 1990). Therefore, we interpret the shift in vegetation as a response to drier conditions at lower treeline, which is currently ≤150 m downslope from Long Lake. Another explanation may be a change in fire severity or frequency, promoting early succession plants. *Populus* is usually one of the first trees to establish after high-severity fire in mixed conifer forests (Baker, 2009). Fires of higher severity that kill both conifers and *Populus* trees favor resprouting and dominance of shade-intolerant *Populus* trees, which may explain its dominance during the *Populus* period (Kulakowski et al., 2004).

Peak magnitudes increased to the highest of the record (300 particles/cm$^2$/yr) and FRI became more frequent than the previous period (average 227 years/episode) around 4000 cal yr BP (Fig. 3); however, the FRI during this time is still representative of an infrequent FRI. Correlations between the pollen percentage data and increased peak magnitudes suggest fire severity was the greatest during the *Populus* period than any other time in the record based on the response of vegetation associated with these fire events.

In the CRM, Little Windy Hill Pond recorded a lowering of lake levels from 3800 to 3700 cal yr BP, indicative of more arid conditions. However at mid-elevations, arid conditions did not seem to cause a shift in vegetation composition. The record from Little Windy Hill Pond also recorded a prolonged fire-free period between 3700 and 1600 cal yr BP and an infrequent FRI (Fig. 6) during the *Populus* period. Little Brooklyn recorded cool and wet climatic conditions during the same time period.

The short *Populus* period is unique to Long Lake and suggests higher elevation sites were not as sensitive to this short arid period. Long Lake likely experienced the most significant shift in vegetational composition because of its proximity to the modern lower treeline boundary. The heterogeneity in FRI within the Medicine Bow Mountains during the *Populus* period was most likely controlled by the elevational differences in fuels on the landscape, but could also represent an unstable climatic boundary or a shift in the climatic boundary.

### *LL-V: the late Holocene (3100 cal yr BP–present)*

The late Holocene represents a return to wetter conditions similar to those prior to the *Populus* period. The presence of *Pseudotsuga* pollen and relatively high Amaranthaceae and Poaceae pollen percentages (Fig. 4) indicate lower than previous effective summer moisture, possibly as a result of reduced late-winter to summer precipitation (Huerta et al., 2009; Shinker, 2010). *Pinus* pollen percentages decrease over the past 3100 cal yr BP, while *Artemisia* pollen percentages generally increase (Fig. 4), suggesting a trend toward greater aridity towards present. The FRI became more frequent, averaging 149 yr/episode extending the trend of greater fire episode frequency during the *Populus* period (Fig. 3). The more frequent FRI could be a result of the relatively wetter than previous conditions increasing fuels on the landscape. Pollen data show greater variance during the late Holocene, which may indicate greater climatic variability. However pollen sample density was higher than the rest of the record during this time, so the increased variance may simply represent an artifact of sampling intensity (e.g., Liu et al., 2012). Increased fire activity observed for the last 300 yr may be a result of the increased climatic variability, or a result of increased anthropogenic influence (Carter, 2010).

In the Medicine Bow Mountains, Little Windy Hill Pond and Little Brooklyn both record cooler and wetter than previous conditions during the late Holocene (Fig. 5). Little Windy Hill Pond recorded an infrequent FRI during the late Holocene (Fig. 6). Even though Little Windy Hill Pond may have had greater fuel connectivity and abundance (Minckley et al., 2012), relatively wet conditions may have reduced the FRI. The heterogeneity in the FRI in the Medicine Bow Mountains suggests elevation or changes in vegetation were a greater controlling factor than potential changes in the climatic boundary.

## *Regional Holocene climate, vegetation and fire history from the Northern and Southern Rocky Mountains*

The sites that were used for the regional comparison from the NRM varied in species composition and elevations that range from 1770 to 2530 m elevation (Fig. 5). The regional sites from the SRM had a more consistent elevation in or above the subalpine forest zone, ranging from 2700 to 3516 m. This is significant to point out because, as we have suggested in the CRM, elevation may be a significant factor influencing fire regimes across the US Rocky Mountains.

### *LL-I: YDC (12,539–11,800 cal yr BP)*

In the NRM during the earliest part of the YDC, climatic conditions were mostly colder and drier than present (Fig. 5). All sites record more infrequent FRI's than the CRM sites, indicating climatic conditions were the driving factor during the YDC (Fig. 6). Brunelle et al. (2005) suggest that the infrequent FRI recorded at Hoodoo Lake, Baker Lake, Burnt Knob, and Cygnet Lakes was consistent with the modern fire regimes of subalpine environments, thus cold and dry conditions were the primary climate drivers of the fire regime during the YDC.

In the SRM, all sites show cold conditions during the earliest part of the YDC (Fig. 5). As a result, most of the sites including those from the CRM show frequent FRI's, suggesting climate conditions were the driving factor controlling fires (Fig. 6). Through the YDC, most FRI's show an increasing trend towards relatively more frequent (Fig. 6). Briles et al. (2012) suggest the initial low fire activity during the early YDC at Lily Pond, Colorado (38°N) and in the SRM was a result of cool–wet winters, and prolonged warm–wet summers. In zone LL-I, the fire regime at Long Lake was more similar to the frequent FRI reported in the SRM.

### *LL-II: the early Holocene (11,800–9400 cal yr BP)*

In the NRM, climatic conditions were consistently warmer than previous (Fig. 5). Most FRI's show trends toward more frequent FRI's during the early Holocene, while Long Lake and the other SRM sites show trends toward infrequent FRI's (Fig. 6). Brunelle et al. (2005) interpret variations in fire activity in the NRM to reflect variable precipitation patterns during the early Holocene. Interpreted climate conditions were warmer than previous in both the SRM and CRM (Fig. 5). Anderson et al. (2008) interpret the highest fire episode frequency during the early Holocene as changes in summer insolation and changes in vegetation composition. Briles et al. (2012) also interpret increased fire activity in the SRM during the early part of the early Holocene as a result of abundant fuels and effectively drier climatic conditions from increased high summer insolation. The fire regime in the CRM appears to be more similar to the fire regime of the SRM in zone LL-II.

### *LL-III: the middle Holocene (9400–4000 cal yr BP)*

In the NRM, conditions shifted from warm and dry in the earliest part of the middle Holocene to cool and wet conditions in the later part (Fig. 5). The fire regime of the NRM shows slight variability, however FRI's are more frequent than those of the CRM (Fig. 6). This could be a result of indirect climate effects from increased summer insolation causing some areas to become drier than present and other areas to become wetter than present (Whitlock et al., 2011). Variability in moisture availability may be related to changes in circulation patterns associated with enhanced seasonality as summer insolation increased after the YDC, which may have intensified precipitation regimes (Whitlock and Bartlein, 1993; Bartlein et al., 1998; Lyle et al., 2012).

In the SRM, climatic conditions shifted from warm and dry conditions to cool and wet conditions in the middle Holocene (Fig. 5). Moy et al. (2002) postulate that El Nino Southern Oscillation (ENSO) variability first became significant around 7000 cal yr BP, but may have been reduced during the mid-Holocene (Conroy et al., 2008). Johnson et al. (2013) interpret several SRM sites that all record significant increases in organic content and sediment around 6000 cal yr BP, coincident with the increasing strength of ENSO. FRI's also show considerable variability in the Rocky Mountains (Fig. 6), which could be a result of increased summer insolation or a result of elevational gradients and local effects. Briles et al. (2012) suggest the spatially variable fire activity in the SRM during the middle Holocene was due to fuels. FRI's tend to be more infrequent than frequent during the middle Holocene in the SRM and CRM sites (Fig. 6). In zone LL-III, the FRI in the CRM appears to be more similar to the infrequent fire regime recorded in the SRM.

### *LL-IV: the Populus period (4000–3100 cal yr BP)*

In the NRM, climatic conditions were still considerably variable (Fig. 5), which resulted in considerable scatter in the reconstructed FRI's (Fig. 6). Climatic conditions were also variable in the SRM. Hunters Lake follows the decreasing trend towards a more frequent FRI, while Chihuaheños Bog and Little Windy Hill Pond both record an infrequent FRI (Fig. 6). The *Populus* period corresponds with lower lake levels at Lake of the Woods, Wyoming (43°N) between 3470 and 3410 cal yr BP, suggesting regional aridity across south-central Wyoming (centered on ~41° N latitude) (Shuman et al., 2010). However, Johnson et al. (2013) suggest diatom assemblages shifted at Cumbres Bog (37°N) due to abrupt transitions in water depth from 4000 to 3800 cal yr BP and again at 3300–3000 cal yr BP, which they infer as shifts to cooler climatic conditions. We suggest that the diatoms may have shifted as a result of effectively drier conditions, or as a result of a possible southward shift in the climatic boundary. Long Lake's FRI was more similar to the frequent FRI's observed in the SRM records during zone LL-IV, although there remains significant heterogeneity amongst sites upslope from Long Lake and across the Rocky Mountains during this time period, suggesting a shift in the climatic boundary or possibly differences in fuel type caused by elevation.

### *LL-V: the late Holocene (3100 cal yr BP–present)*

In the NRM, climatic conditions were mostly cool and wet (Fig. 5). FRI's were still considerably variable during the late Holocene, but most sites had long FRI values, indicating a more infrequent FRI than Long Lake (Fig. 6). Around 1000 cal yr BP, all sites in the NRM trend towards infrequent FRI's.

In the SRM, climatic conditions were more variable than the NRM sites, while all sites in the CRM recorded cooler and wetter conditions. FRI's were also still considerably variable, however the Little Windy Hill Pond and the SRM sites all show a similar trend toward infrequent FRI's around 1000 cal yr BP, while Long Lake was the only site to trend toward a frequent FRI. Jimenez-Moreno et al. (2011) interpret cooler conditions at Tiago Lake (40° N) in north-central Colorado as a result of enhanced winter precipitation. Based on this interpretation, FRI shifted from already infrequent fire occurrences to more even infrequent events between 3000 and 1500 cal yr BP, shifting back to infrequent from 1500 to the present. Long Lake's FRI was more similar to the SRM sites than that of the NRM during zone LL-V. However, it appears that Long Lake is unique in the CRM and SRM, recording a trend toward a more frequent FRI, while Little Windy Hill Pond shows a trend toward an infrequent FRI. This could be a result of elevation and more localized topographic influences.

## Conclusions

### *Long Lake and the CRM*

The record from Long Lake, Wyoming indicates cold and dry conditions during the YDC with low-lying herbs and shrubs dominating the landscape. As a result, the FRI was frequent. Sites in the CRM also recorded colder conditions, with an infrequent FRI. This suggests that elevation was the primary factor controlling the fire regime in the CRM during the YDC. In the early Holocene, increases in *Pinus* pollen percentages at Long Lake indicate forest formation and suggests warming conditions. The FRI during the early Holocene became more infrequent as a result of the warming conditions. In the CRM, sites also recorded warming conditions and an infrequent FRI. This suggests a relatively stable climatic boundary during the early Holocene in the CRM region.

At Long Lake, the middle Holocene was dominated by pine forests, which indicate a continuation of warmer than previous conditions. However, several dry episodes occurred throughout this period based on decreases in *Pinus* pollen percentages and increases in *Artemisia* pollen percentages. The FRI was mostly infrequent during the middle Holocene. In the CRM, sites recorded warmer and wetter conditions with an infrequent FRI. This suggests a stable climatic boundary during the middle Holocene period in the CRM.

The *Populus* period represents a unique change in forest composition, with a switch from *Pinus* to *Populus* dominance around Long Lake and a frequent FRI. Sites in the CRM recorded an arid period during the *Populus* period, but did not record a change in vegetation composition and, as a result, the FRI remained infrequent at other CRM sites. This forest change suggests a change in climate and disturbance that affected lower treeline.

At Long Lake, a return of *Pinus* dominance in the late Holocene suggests conditions were wetter than the *Populus* period. However, there was a trend of decreasing *Pinus* pollen percentages and increasing *Artemisia* pollen percentages that suggests increasing aridity at lower treeline. The FRI at Long Lake was frequent. In the CRM, sites recorded cooler and wetter conditions with an infrequent FRI. This suggests elevation or topographic influences, and not shifts in large-scale climate boundaries were the driving factors in the CRM during the late Holocene.

### *Fire and climate in the NRM and SRM*

The paleoenvironmental records from the NRM suggest a cold YDC with an infrequent fire regime, while the paleoenvironmental records from the SRM suggests cold climatic conditions and a frequent fire regime. During the early Holocene, both the NRM and SRM indicate warming climatic conditions; however, the fire regime varied between the NRM and SRM. In the NRM, fires were relatively frequent, while the SRM fires were infrequent. The middle Holocene was a time of climatic and fire regime variability in both the NRM and SRM. In general the NRM sites recorded a more frequent fire regime than that of the SRM and CRM sites. The *Populus* period was a time of climatic variability in the NRM and SRM. There were no real comparisons to the paleoenvironmental records in the NRM; however, the fire regime from Long Lake and the CRM seems to be more similar to the fire regime of the SRM during the *Populus* period. In the late Holocene, a shift to cooler and wetter conditions in both the NRM and SRM resulted in a switch in the FRI to infrequent in the NRM and frequent in the SRM. Based on our analysis, the record from Long Lake has been more similar to the fire regimes of the SRM throughout the Holocene.

### *Climate boundary and future research*

The paleoenvironmental record from Long Lake illustrates the sensitivity of vegetation and fire activity relative to the climatic boundary between the NRM and SRM proposed by Dettinger et al. (1998) to lie between 40° and 45°N. During the entire Holocene period, the FRI at Long Lake is more similar to that of the SRM, suggesting the CRM is more closely influenced by SRM precipitation patterns. Schoennagel et al. (2005) suggest that the CRM may be more influenced by weather patterns from the Pacific Northwest, and not those from the Southwest. However, the records from Long Lake and the CRM demonstrate that the fire regime in the CRM has a greater affinity to those from the SRM, suggesting an association with moisture sourcing and timing from the Southwest. Because of this, the fire regime of the CRM may depend on the strength of the subtropical and temperature pressure systems that drive effective moisture from the south into the region.

Paleoecological reconstructions provide valuable baseline information on past fire regimes and climatic shifts. However, it's important to consider elevation and different vegetation dynamics, as they relate to fuels. Currently, the NRM is more heavily studied than the CRM and SRM and as a result, comparisons are difficult to interpret. Further paleoecological reconstructions are needed from these areas to help determine whether the changes in the regional climatic boundary serve as a control on fire occurrence. Future research is also needed to address the larger scale impacts of elevation and different fuel types across the entire US Rocky Mountains in order to further test the sensitivity of the proposed climatic boundary in the CRM.

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