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Key Points:

- Sediment $\delta^{18}O$ records show heightened hydroclimate variability during the Little Ice Age
- Discrepancies between tree rings and lake sediments from the Pacific Northwest stem from different seasonal and temporal sensitivities
- Charcoal records in the region indicate enhanced fire activity during periods of higher multi-decadal hydroclimate variability

Supporting Information:

Supporting Information may be found in the online version of this article.

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A Link Between Hydroclimate Variability and Biomass Burning During the Last Millennium in the Interior Pacific Northwest

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Abstract We present oxygen isotope and charcoal accumulation records from two lakes in eastern Washington that have sufficient temporal resolution to quantitatively compare with tree-ring records and meteorological data. Hydroclimate reconstructions from tree-rings and lake sediments show close correspondence after accounting for seasonal- to centennial- scale temporal sensitivities. Carbonate $\delta^{18}O$ measurements from Castor and Round lakes reveal that the Medieval Climate Anomaly (MCA) experienced wetter November-March conditions than the Little Ice Age (LIA). Charcoal records from Castor, Round, and nearby lakes show elevated fire activity during the LIA compared to the MCA. Increased multidecadal hydroclimate variability after 1250 CE is evident in proxy records throughout western North America. In the Upper Columbia River Basin, multidecadal wet periods during the LIA may have enhanced fuel loads that burned in subsequent dry periods. A notable decline in biomass burning occurred with Euro-American settlement in the late nineteenth century.

Plain Language Summary Paleoclimate reconstructions are based on proxy records that are sensitive to particular aspects of the climate system. We compare high-resolution lake sediment records with nearby tree-ring chronologies and instrumental data to explore hypotheses about climate variability. Here, we confirm that lake-sediment oxygen isotope ratios in the Upper Columbia River Basin are primarily sensitive to cool-season precipitation, whereas many tree-ring records are primarily sensitive to warm-season conditions. When lake records are compared with winter-sensitive tree-ring width chronologies, the reconstructions are similar. Oxygen isotopes indicate wet and stable winter conditions during the Medieval Climate Anomaly (900–1250 CE) and variable but generally dry conditions during the Little Ice Age (1450–1850 CE). Wet periods of fuel buildup, followed by drought, may have driven greater fire activity during the LIA. An abrupt decline in fire begins occurred Euro-American settlement, after the 1850s, and is attributed to loss of fuel connectivity and less ignition.

1. Introduction

Recent droughts and wildfire seasons in western North America are among the most severe in recorded history, driven by accelerating anthropogenic climate change (Higuera & Abatzoglou, 2021; Williams et al., 2020). Paleoclimate proxy evidence can provide context for current and projected climate-fire relationships (Marlon et al., 2012). Oxygen isotope ($\delta^{18}O$) records from lake sediments reflect changes in precipitation-evaporation balance, while charcoal accumulation records can identify shifts in fire activity. In northwestern North America, $\delta^{18}O$ of lacustrine carbonates primarily reflect cool-season ("winter," November–March) precipitation (Steinman et al., 2010), with more depleted $\delta^{18}O$ values indicating wetter conditions. This sensitivity to cool-season moisture is due to generally high precipitation and negligible evapotranspiration between November and March, and the corresponding influence on annual water balance (Steinman et al., 2013). Precipitation in the Upper Columbia River Basin (Figure 1) primarily comes from Pacific frontal storms during the cool-season, with substantial interannual/decadal climate variability resulting from hemispheric ocean-atmospheric teleconnection patterns; namely, the El Niño Southern Oscillation (ENSO) and the Pacific Decadal Oscillation (PDO) (McAfee & Wise, 2016). Positive ENSO (El Niño) and PDO conditions (indicating warm anomalies in the eastern tropical

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Pacific and northeastern mid-latitude Pacific, respectively) tend to deflect storm tracks southward, leading to decreased precipitation in northwestern North America; generally wetter cool-season conditions occur during negative ENSO/PDO intervals (Wise, 2010). $\delta^{18}O$ records from the region show generally wetter winters during the Medieval Climate Anomaly (MCA, 950–1250 CE) than during the subsequent Little Ice Age (LIA, 1450–1850 CE, Masson-Delmotte et al., 2013; Steinman et al., 2012, 2014; Shuman et al., 2018), whereas many tree-ring reconstructions suggest the MCA was marked by widespread summer drought across western North America (Cook et al., 2004).

Composites of charcoal data show higher fire activity during the MCA than in the LIA (Marlon et al., 2012), although there is considerable variability among sites (Walsh et al., 2015, 2023). Both charcoal and fire-scarred tree-ring records show abrupt changes in continental-scale climate/fire relationships associated with Euro-American settlement in the eighteenth and nineteenth centuries (Marlon et al., 2012). ENSO and the PDO have also influenced fire synchroneity in the eastern Cascades over the past several centuries, with severe fire years associated with El Niño/PDO + conditions (Heyerdahl et al., 2008). The amplitude of interannual and multidecadal climate variability has also been hypothesized to drive biomass burning, as wet periods generate fine fuels that subsequently burn during dry periods (Cooper et al., 2021; Walsh et al., 2015). A lack of multi-proxy sedimentary reconstructions which are sensitive to both hydroclimate and fire activity at sub-decadal timescales hinder a comprehensive understanding of the relationship between climate variability and biomass burning.

Here, we present high-resolution $\delta^{18}O$ and charcoal records from Castor Lake (48.54°N 119.56°W; 594 m a.s.l.) and Round Lake (48.61°N 119.12°W; 654 m a.s.l.) that span the last 1200 years (Figure 1) and compare them to instrumental climate data and nearby tree-ring records. This approach allows us to better understand the climatic controls on sedimentary $\delta^{18}O$ records, which, when paired with corresponding charcoal accumulation data, improves our understanding of the climatic and non-climatic drivers of fire in this semi-arid western ecosystem.

2. Materials and Methods

2.1. Study Area

Castor and Round lakes lie in stagnant-ice depressions formed during the late-Pleistocene recession of the Cordilleran Ice Sheet in the Upper Columbia River Basin (Kovanen & Slaymaker, 2004; Figure 1). These sites are surrounded by parkland of *Pinus ponderosa*, *Pseudotsuga menziesii and Abies grandis*, with *Artemisia tridentata* present in forest openings and nearby steppe. Fifty percent of annual precipitation (<400 mm/yr at both sites) falls between November and March (PRISM Climate Group https://prism.oregonstate.edu). Near the lakes are three *P. ponderosa* stands (SUG, 48.60°N −119.70°W 844 m a.s.l; RRR 48.51°N −118.75°W 1,156 m a.s.l; SND 48.59°N −119.14°W 965 m a.s.l) that were previously analyzed for standard total ring width, earlywood width, latewood width and blue intensity as part of a paleoclimate investigation (Dannenberg & Wise, 2016) (Figure 1).

2.2. Coring and Sampling

Freeze cores (Besonen et al., 2008) were retrieved from Castor Lake (core B-18) and Round Lake (core B-18) in February 2018 to recover the mud-water interface and uppermost sediments. The stratigraphy of the Castor Lake freeze core was spliced to that from an existing hammer core (Castor A-03, Nelson et al., 2011) and the Round Lake record was correlated to the stratigraphy of a longer Livingstone piston core taken in 2017 (Figure S1 in Supporting Information S1).

2.3. Lithology and Chronology

One cm^3 samples were taken from each core at 0.5-cm intervals and were analyzed for bulk density and carbonate composition according to the method of Heiri et al., 2001. A chronology was developed via Bchron v. 4.7.6 for both lakes using ^{137}Cs radioisotopes (nCastor = 3 nRound = 1), radiocarbon dates (nCastor = 2 nRound = 4), the Mount Saint Helens Wn tephra layer in Castor Lake (1480 CE, Mullineaux, 1996; not successfully identified at Round Lake) (Figure S2 and Table S1 in Supporting Information S1).

2.4. Isotopic Analysis

Samples for $\delta^{18}O$ were processed according to the methods of Nelson et al. (2011). Samples were extracted with dehydrated phosphoric acid at 70°C under vacuum and measured with a Kiel-III preparation device coupled to a

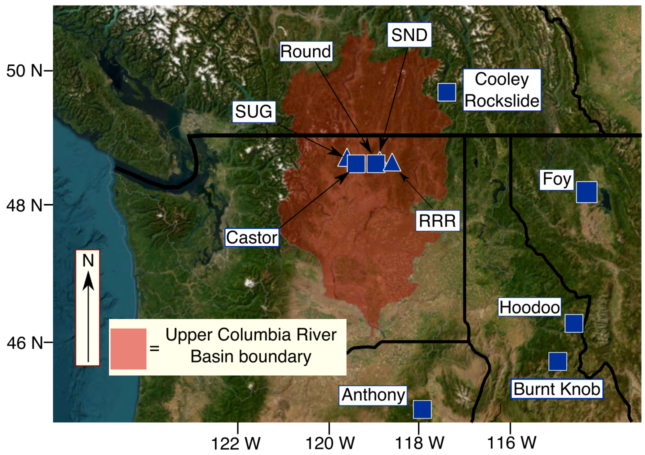


Figure 1. Location of Castor and Round Lakes within the Columbia River Basin (red shading) and other regional proxy records.

Finnigan MAT 252 gas-ratio mass spectrometer at the University of Arizona with 1σ precisions of 0.1‰ for $\delta^{18}O$ on repeated measurements of NBS-19 and NBS-18 standards.

2.5. Charcoal Analysis

Samples for charcoal analysis were taken at contiguous 0.5-cm intervals. 1 or 2 cm^3 samples of sediment were disaggregated in sodium hexametaphosphate and bleach, sieved through a 125-μm mesh screen, and counted under a binocular microscope at <10X magnification following Whitlock and Larsen (2001). Charcoal counts for both lakes were converted to charcoal accumulation rates (CHAR, particles/cm^2/yr^1). The CHAR time series were interpolated to 7-year timesteps, the median timestep of the Castor Lake record (and greater than that of Round Lake). Decadal to sub-decadal fire-return intervals that characterize these dry forests were too short to detect individual fire episodes in the CHAR time series, and we instead relied on the trends in CHAR to describe changes in fire activity (Walsh et al., 2023).

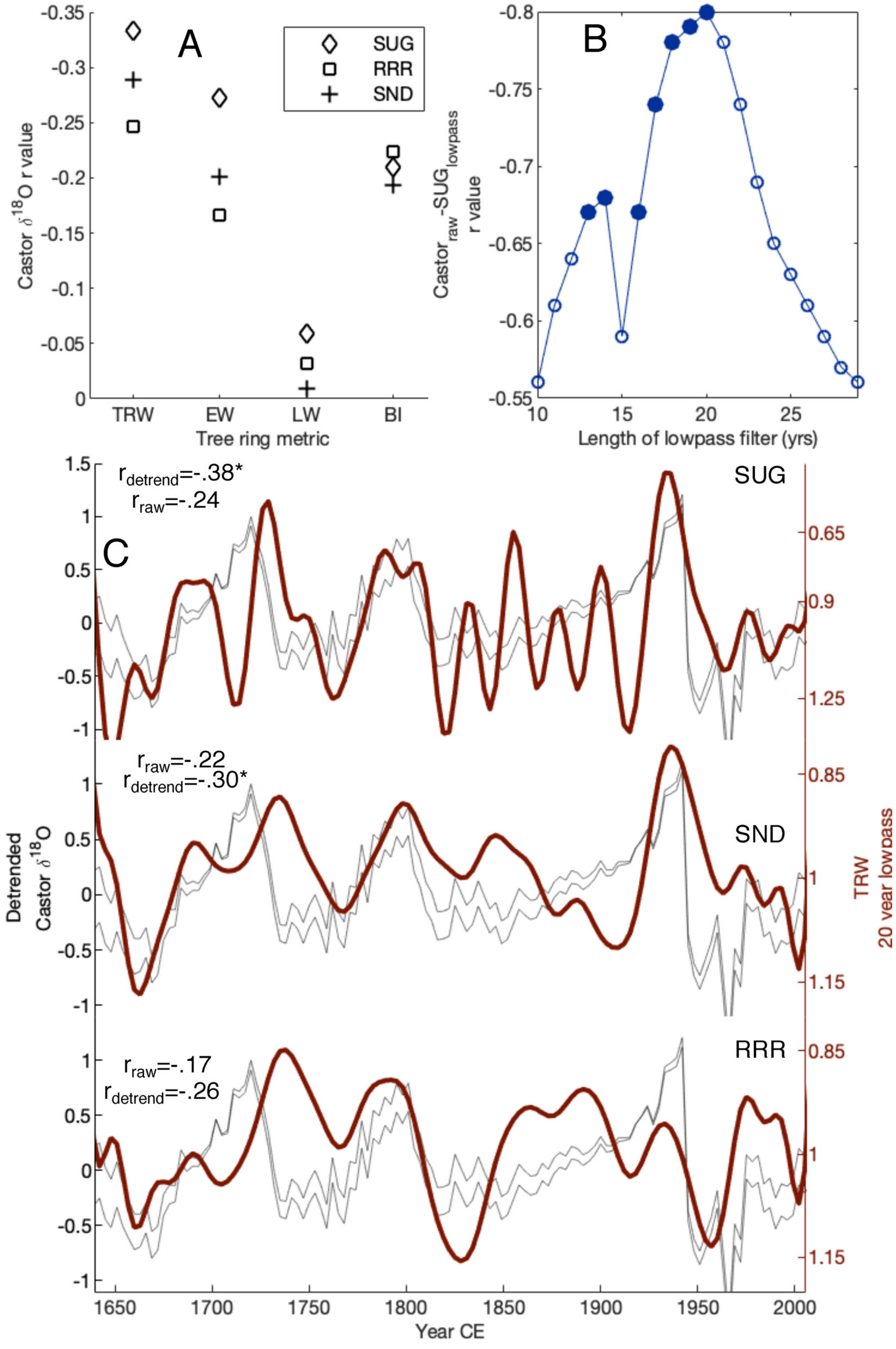
2.6. Statistical Analysis

Comparison of modern tree-ring and meteorological data (1895–2012) was conducted by averaging the 9–4-km resolution PRISM climate model grid cells centered on each site (Figure S3 in Supporting Information S1). April 1 snow water equivalence (SWE) data from the Upper Columbia River Basin are from Pederson et al. (2011), covering the period 1936–2006 (Figure S4 in Supporting Information S1).

For Castor Lake, Pearson's correlations between 1900 and 2016 were conducted on annually resolved $\delta^{18}O$ measurements (Figures 2a and 2b). For comparison to tree-ring stands SUG, SND, and RRR between 1600 and 2016, correlations were carried out by interpolating the lowpass-filtered tree-ring chronologies to a 3-year resolution (Figure 2c, Figure S4 in Supporting Information S1). Detrending of the Castor and Round Lake $\delta^{18}O$ records for comparison with tree-ring chronologies was carried out using first and third degree polynomials (Figure S4 in Supporting Information S1). Autocorrelation was accounted for by adjusting the effective degrees of freedom of each time series (Hu et al., 2017).

We calculate 60-year moving variances (in the case of lake-sediment proxies) by linearly interpolating data to the minimum timestep justified by the temporal resolution of each data set (3 years for $\delta^{18}O$ data sets in Castor and Round lakes, 6 years in $\delta^{18}O$ Foy Lake, MT) and measuring the variance of each proxy in a moving 60-year window. 60-year intervals were used to accurately capture multidecadal climate phenomena; however, window lengths between 48 and 72 years did not substantially alter results. Pearson's correlations between proxies (Table S2 in Supporting Information S1) were conducted by interpolating data to the same 6-year time-step over the period covered by each pair of proxies. Correlations between the charcoal accumulation record and the $\delta^{18}O$ moving variances were conducted by interpolating the moving variance time series to the same resolution as the charcoal records. To account for non-linear relationships, we used Spearman's ranked correlation and compared the charcoal record to the 60-year moving window that ends at the beginning of the charcoal sampling interval (rather than the window centered on the charcoal sampling interval). This alignment was done to evaluate hydroclimate conditions *prior* to each charcoal datapoint. Correlations between charcoal records and SUG, SND, and RRR were conducted using the lowpass filtered tree-ring width records interpolated to a 3-year time step (the approximate median charcoal sampling interval between 1650 and 1910).

To test for significant differences between the MCA and LIA in the 60-year moving variance time series, two-sample Kolmogorov-Smirnov tests were used. The presence of serial autocorrelation invalidates the assumption of independent observations and can lead to a spurious rejection of the null hypothesis that the two time series come from the same distribution. We use the methods of Lanzante (2021), which developed a Monte Carlo approach with a first-order autoregressive model to account for autocorrelation and improve the robustness of results.



A
SUG
RRR
SND
Castor δ18O r value
TRW
EW
LW
BI
Tree ring metric
B
Castor raw-SUG lowpass r value
Length of lowpass filter (yrs)
C
r detrend=-.38*
r raw=-.24
SUG
r raw=-.22
r detrend=-.30*
SND
r raw=-.17
r detrend=-.26
RRR
Detrended Castor δ18O
TRW 20 year lowpass
Year CE

Figure 2.

3. Results

Castor and Round lake water is evaporatively enriched with respect to the global meteoric water line (Figure S5 in Supporting Information S1). Sediments from Castor and Round lakes spanning the last 1200 years primarily consist of millimeter-scale laminae alternating between light-colored carbonate-rich and darker-colored organic-rich sediments. Both sequences consist of >25% $CaCO_3$ throughout. $\delta^{18}O$ values vary between −6.5 and −2‰ for Castor Lake and −14 and −8‰ for Round Lake over the past 1200 years. $\delta^{18}O$ values for both lakes were on average more enriched during the LIA (−4.3 and −11.3 at Castor and Round lakes, respectively) than during the MCA (−5.0 and −11.8). Pronounced periods of $\delta^{18}O$ enrichment occurred between approximately 1010–1070 CE, 1330–1430 CE, and 1710–1740 CE at both lakes (Figure 4a).

The Castor Lake $\delta^{18}O$ record is approximately annually resolved between 1900 and 2016 CE, as indicated by ^{137}Cs-derived dates over the past century (Figure S2 in Supporting Information S1). This resolution allows for quantitative comparison of results with instrumental data and nearby tree-ring records (Schoenemann et al., 2020). In the tree-ring data, cool-season precipitation is most highly correlated with total ring-width, earlywood, latewood, and blue intensity chronologies at SUG and has the lowest correlation with trees in the RRR stand (Figure S3 in Supporting Information S1). SWE is strongly correlated to cool-season precipitation at each study site (Figure S6 in Supporting Information S1). Greater sensitivity to cool-season moisture in the SUG and SND stands indicates these chronologies come from moisture-limited trees (Cluster 1 according to Coulthard et al., 2021). RRR trees, which exhibit a weak but statistically significant negative relationship with regional SWE (Figure S4 in Supporting Information S1), may be more limited by energy rather than by moisture, a trait commonly seen in the Cascade Range to the west (Cluster 3, Coulthard et al., 2021). Castor Lake $\delta^{18}O$ values also exhibit statistically significant correlations ($p < 0.1$) between 1900 and 2016 with cool-season and annual precipitation but not with warm-season precipitation (Figure S7 in Supporting Information S1). The SUG total ring-width record most closely matched Castor Lake $\delta^{18}O$ data (Figure 2a, Figure S4 in Supporting Information S1). Castor Lake $\delta^{18}O$ data also show high correlations with earlywood and blue intensity, and the lowest correlations with latewood, a warm-season precipitation indicator (Figure 2a). Given the shared sensitivity to cool-season precipitation (Figures S2 and S4 in Supporting Information S1) and correlation between recent tree-ring width and ^{18}O, tree-ring width is the most appropriate metric to compare to the sedimentary records (e.g., Figures 2b and 2c).

Residence time of lake water causes serial autocorrelation in carbonate $\delta^{18}O$ values, effectively smoothing hydroclimate reconstructions (Steinman & Abbott, 2013). To quantify the effect of the isotopic "memory" of lake water, lowpass filters of different lengths were applied to the SUG total ring-width record, and the smoothed chronology was regressed against the unfiltered Castor $\delta^{18}O$ record. A 20-year lowpass filter of the total ring-width data produced the most accurate match (Pearson's $r = -0.80$ $p < 0.1$) (Figure 2b, Figure S8 in Supporting Information S1). Higher cutoff frequencies retain climate variability that is removed by the residence time of lake water, while lower cutoff frequencies excessively smooth the tree-ring chronology (Figure S8 in Supporting Information S1). Importantly, this correspondence empirically supports the modeled relationship between cool-season precipitation and lake sediment $\delta^{18}O$ values, showing that lake water residence time effectively integrates approximately 20 years of (primarily cool-season) precipitation (Steinman et al., 2010).

Relatively short lifespans of individual trees and the removal of age-related growth signals hinder the detection of low-frequency climate signals (Helama et al., 2017). Detrended Castor and Round Lake $\delta^{18}O$ records show higher correlations with each tree-ring chronology than the original time series (Figure 2c, Figure S4 in Supporting Information S1). Hence, while residence time of lake water prevents sedimentary $\delta^{18}O$ records from preserving high-frequency variability, centennial-scale variability preserved in lake sediment records can be removed during the compositing of tree-ring chronologies.

Charcoal accumulation rates (CHAR) were generally low in both lakes from the beginning of the record to approximately 1000 CE. Between 1000 and 1500 CE, CHAR increased to maximum values of ~10 particles

Figure 2. (a) Correlations between unfiltered Castor Lake annual $\delta^{18}O$ record (1900–2012) and unfiltered total ring-width, earlywood, latewood, and blue-intensity chronologies from three sites in the eastern Washington (Dannenberg & Wise, 2016). (b) Correlation coefficients between the unfiltered Castor $\delta^{18}O$ data set (1900–2012 CE) and SUG ring-width record with lowpass filters of different lengths. Solid circles represent datapoints for which $p < 0.1$. (c) 20-year lowpass filtered tree-ring chronologies (thick red lines) and detrended Castor Lake $\delta^{18}O$ values (thin black lines indicate first and third degree polynomial detrending). Asterisks next to r values indicate statistical significance ($p < 0.1$).

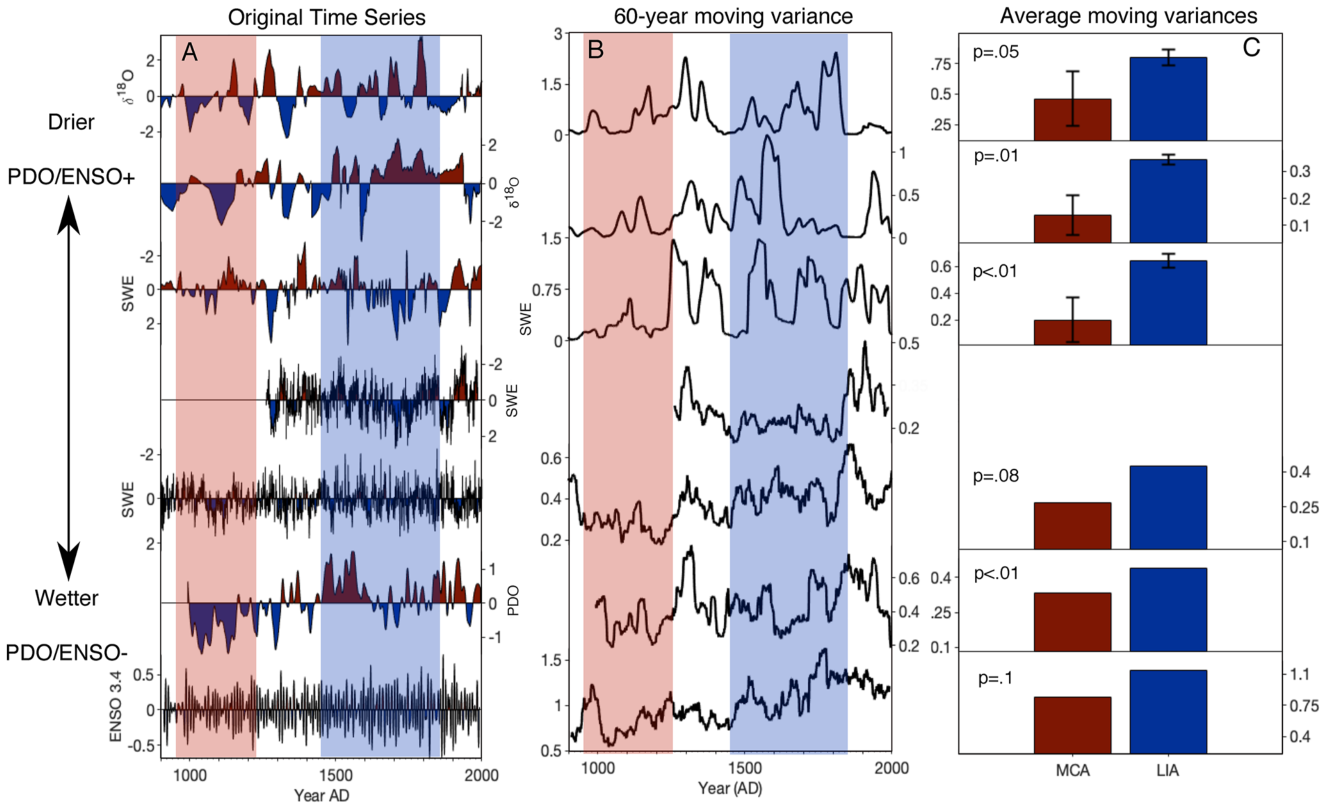


Figure 3. (a) Round and Castor lakes $\delta^{18}O$ records (this study), Foy Lake, MT (Schoenemann et al., 2020), Upper Columbia River Basin and Southern Upper Colorado snow water equivalence reconstructions (Pederson et al., 2011), Western North America tree-ring based Pacific Decadal Oscillation reconstruction (MacDonald & Case, 2005), North American tree-ring El Niño Southern Oscillation reconstruction (Li et al., 2011) (all treated with 20-year smoothing). (b) 60-year moving variances of the same proxies. Red and blue shading indicates the Medieval Climate Anomaly (900–1250 CE) and Little Ice Age (1450–1850 CE), respectively. (c) Average 60-year moving variance for each proxy record. *P*-values indicate results of 2 sample Kolmogorov-Smirnov tests Error bars on lake sediment records represent 97.5–2.5 percentile age model uncertainty (Castor and Round Lake) and proxy uncertainty (Foy Lake).

cm^2/yr and declined in the nineteenth century (Figure 3). CHAR values are not significantly correlated to $\delta^{18}O$ records from either lake, nor to any tree-ring chronology (Figure S9 in Supporting Information S1). However, CHAR is significantly correlated to the 60-year moving variance of $\delta^{18}O$ at each lake (Figure S10 in Supporting Information S1).

4. Discussion

4.1. Hydroclimate Variability in Western North America

Low $\delta^{18}O$ values during the MCA in the Castor and Round lake records are consistent with predominantly PDO/IPO negative conditions (e.g., wetter winters in northwestern North America). This is further consistent with a PDO reconstruction from two long lived tree-ring chronologies in southern California and Alberta (MacDonald & Case, 2005). Tree-ring based April 1 SWE reconstructions from the Upper Colorado River Basin do not extend into the MCA (Pederson et al., 2011); however, those from the southern Colorado River basin indicate drier conditions during the MCA than the LIA, reflecting the north-south dipole pattern in ENSO/PDO-induced precipitation anomalies (Pederson et al., 2011; Sung et al., 2014). While proxy syntheses aimed at reconstructing temperature show generally warmer conditions during the MCA (Trouet et al., 2013; Viau et al., 2012), a coherent picture of hydroclimate variability in western North America over the past 1200 years is difficult to derive from existing proxy data, with few records showing significant correlations with one another (Figure 4a, Table S2 in Supporting Information S1).

A consistent feature of high-resolution hydroclimate reconstructions across North America is enhanced multi-decadal variability during the LIA compared to the MCA (Figures 4b and 4c). Snowpack reconstructions

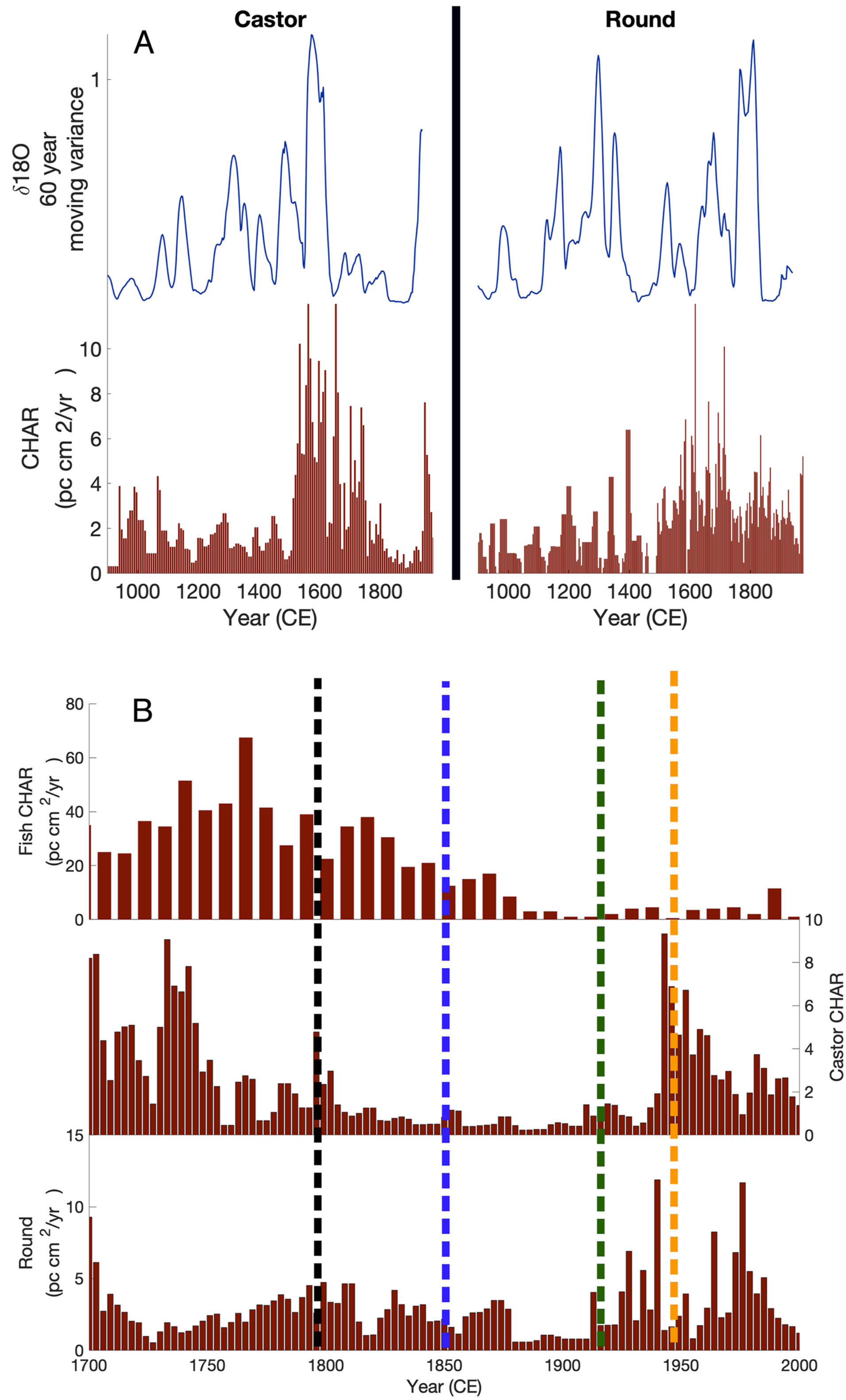


Figure 4. (a) Charcoal accumulation rate (CHAR) and 60-year moving average of variances of $\delta^{18}O$ from Castor and Round lakes over the past millennium. (b) CHAR from Fish, Castor, and Round Lake between 1700 and 2000 CE. Black line indicates the first documented smallpox case (Boyd, 1999) among Native American groups in the region, blue line indicates the establishment of Euro-American grazing practices in the region (Walsh et al., 2018), green line represents onset fire suppression policies and orange line represents post-WWII increase in fire suppression efficacy.

from lake sediments (Foy Lake, Schoenemann et al., 2020) and tree-rings (Pederson et al., 2011) all document comparatively high-amplitude wet/dry cycles during the LIA. An ENSO reconstruction derived from North American tree-rings shows enhanced multidecadal variability over the past 500 years, driven by tropical Pacific forcing (Li et al., 2011; Figure 4). A prominent shift to more variable conditions in the eastern tropical Pacific after ~1500 CE is well documented (Rustic et al., 2015) and is consistent with higher amplitude wet/dry cycles in the western United States. Additionally, the LIA was marked by increased strength in the teleconnection between the tropical Pacific and precipitation in western North America (Dee et al., 2020). A stronger teleconnection between the tropics and mid-latitudes may also explain why high-resolution records of hydroclimate phenomena show enhanced variability during the LIA while centennial-scale proxy compilations derived from pollen records fail to capture distinct transitions between the MCA and LIA (Shuman et al., 2018; Viau et al., 2012).

4.2. Climate and Biomass Burning in the Upper Columbia River Basin

Charcoal accumulation rates in Castor, Round, Fish, and Doheney lakes (Walsh et al., 2018, 2023) were low in the MCA and increased during the LIA, when winter conditions were generally drier than before (e.g., MacDonald & Case, 2005; Mushet et al., 2023; Steinman et al., 2012; Steinman et al., 2014) and multidecadal hydroclimate variability was high (Figure 3 and Figure S10 in Supporting Information S1). Nearby sites in northern Idaho (Baker Lake, 2,300 m a.s.l, Hoodoo Lake, 1770 m a.s.l, Burnt Knob Lake, 2,250 m a.s.l Figure 1) and Montana (Foy Lake 1006 m a.s.l Figure 1), also show increased charcoal accumulation during the LIA compared to the MCA (Brunelle & Whitlock, 2003; Brunelle et al., 2005; Power et al., 2006). Raw CHAR values from Anthony Lake in northwestern Oregon (44.95°N, −118.20°W, 2,174 m a.s.l.) show little systematic trend over the past 1000 years (Long et al., 2019). Two charcoal records from subalpine forests in the Upper Columbia River Basin which experience multi-centennial fire return intervals (Figure 1, Cooley and Rockslide lakes, 1,515 m a.s.l. and 1,539 m a.s.l. respectively, Figure 1) show dissimilar trends, but both document a decrease in fire activity after 1500 CE (Gavin et al., 2006). In summary, sites from the Upper Columbia River Basin which experienced short fire-free intervals prior to Euro-American settlement (Round, Castor, Fish, and Doheney lakes) show increased fire activity during the LIA, while the response of nearby montane forest sites generally had fewer fires. The decrease in fire activity in dry forest stands in contrast to regional (Walsh et al., 2015) and continental-scale (Marlon et al., 2012) syntheses that indicate high fire activity in the MCA but not in the LIA.

Although the fire season in the dry forests of the Upper Columbia River Basin occurs between May and October, winter and spring precipitation influences soil moisture and fuel conditions (Halofsky et al., 2020; Wright & Agee, 2004). Tree-ring studies from the region tie recent fire activity to variations in ENSO and the PDO, which alters winter moisture patterns as well as summer temperatures (Hessl et al., 2004; Heyerdahl et al., 2008). At Castor and Round Lakes, the amplitude of multidecadal climate variability shows significant correlations with CHAR (Figure 3, Figure S10 inSupporting Information S1). The mechanism linking Pacific climate variability to fire is as follows: cool-season precipitation during La Niña/negative PDO phases leads to fuel production more densely vegetated landscapes. Subsequent droughts periods desiccate fuels, leading to more intense and regionally synchronous fire seasons. This relationship is most significant in high-frequency fire regimes (Gavin et al., 2006), and helps explain the contrast between Castor, Round, Fish, and Doheney Lakes and higher elevation sites from elsewhere in the west which experienced longer fire-free intervals (Figure 3).

The relationship between the moving variance of $\delta^{18}O$ and CHAR deteriorates after 1910 (Figure S10 in Supporting Information S1), demonstrating the effect of Euro-American land-use practices on fire-climate relationships in the region (Hessburg et al., 2021; Walsh et al., 2018). Humans helped shape fire regimes in the Columbia River Basin for thousands of years, through deliberate burning practices (Boyd, 1999; Walsh et al., 2018, 2023). The Interior Salish people, who lived in the study region, used fire to enhance valued plant resources, facilitate travel, and hunt game (Wynecoop et al., 2019). Castor and Fish lakes show decreasing CHAR during the nineteenth century, coincident with the arrival of settlers and disease in Upper Columbia River Basin (Boyd, 1998) (Figure 3b). By the mid-1850s, Euro-American settlement and loss of Native American burning practices Round, Castor, and Fish Lakes all show low CHAR (Figure 3b). Traditional land management practices were replaced by intensive agriculture and forestry in the late nineteenth century (Hessburg & Agee, 2003; Hessburg et al., 2005). Fire suppression efforts starting in the early twentieth century drastically lengthened the period between fires in dry forests that traditionally experienced frequent burning (Hessburg & Agee, 2003). At Castor and Round lakes, CHAR remained low until the mid-twentieth century when lake sediment and tree-ring records, as well as meteorological data, show an intense drought (Figures 2 and 3b), which would have diminished the effectiveness of fire suppression tactics (Westerling & Swetnam, 2003). The Castor Lake charcoal accumulation record indicates a possible fire event, which was likely confined to the area near the watershed, due to the absence of a similar peak at nearby Fish and Doheney Lake (Walsh et al., 2018, 2023). At Castor Lake, charcoal accumulation declines again after the 1950s, possibly reflecting improved fire-fighting technology and training, and increased investment in fire prevention after World War II (Dombeck et al., 2004; Pyne, 2010).

5. Conclusions

High-resolution $\delta^{18}O$ data from Castor and Round lakes show strong similarities to cool-season sensitive tree-ring proxies and winter precipitation data, consistent with proxy-system modeling studies (Steinman et al., 2010). Applying a 20-year lowpass filter to tree-ring width records greatly improved correlations between the two proxy types, as the residence time of lake water acts to buffer the isotopic response of carbonate sediments to interannual climate variability. Additionally, detrending the $\delta^{18}O$ data sets improves correlations with tree-ring data, as removal of age-related growth trends suppresses low-frequency signals in tree-ring records. Tree-ring and lake sediment studies are often biased to particular temporal windows, and better understanding the nature of these biases can improve inter-archive comparisons.

Castor and Round lakes $\delta^{18}O$ records indicate drier winter conditions during the LIA than the MCA. Although other high-resolution proxy records from western North America do not show consistent trends in mean-state hydroclimate conditions, an increase in multi-decadal (~60-year) variability during the LIA is consistent throughout the region. Records from the Upper Columbia River Basin also document an increase in fire activity during the LIA, coincident with enhanced multi-decadal precipitation variability. Increased hydroclimate variability leads to fuel accumulation during wet periods, followed by widespread burning during droughts. The arrival of disease and Euro-American settlement altered previously existing human-fire-climate relationships in the region. Thus, the use of hydroclimate and fire proxies from the same sedimentary sequence allows for thorough quantitative interrogation of the influence of hydroclimate on biomass burning over multidecadal timescales.

Conflict of Interest

The authors declare no conflicts of interest relevant to this study.

Data Availability Statement

Data from this project is available online at https://www.ncei.noaa.gov/access/paleo-search/study/38540. Tree-ring width measurements from the sites used in this study are available online at https://www.ncei.noaa.gov/products/paleoclimatology/tree-ring (records WA139, WA140, and WA141).

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