Final Report

Multi-Century Droughts in Wyoming's Past: Evidence of Prolonged Lake Drawdown

PIs
Bryan N. Shuman, Assistant Professor, Univ. of Wyoming, bshuman@uwyo.edu,
Jacqueline J. Shinker, Assistant Professor, Univ. of Wyoming, jshinker@uwyo.edu,
Thomas A. Minckley, Assistant Professor, Univ. of Wyoming, minckley@uwyo.edu
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Publications and Presentations

Numerous presentations and related manuscripts have resulted from this project (detailed below). Current activity includes two manuscripts related to the funded project in preparation for submission to peer-reviewed journals. The first will be submitted to a short-format, high-impact journal (e.g., *Geology*) and includes initial findings of prolonged lake-level draw down related to long-term drought conditions that surpass historical and dendrochronological records. The second manuscript has been selected for a special volume of the *Annals of the American Association of Geographers*, and provides a long-term perspective on regional hydrology shifts in the headwaters of the North Platte River.

Related publications and presentations († high-school intern; *undergraduate; **graduate student author):

1. Paul Pribyl* and Bryan Shuman, Long-Term Perspectives on the Effects of Climate Change on Wyoming's Water Resources, 2009. Wyoming Undergraduate Research Day, University of Wyoming, May 2, 2009.
2. Robert Shriver* and Thomas Minckley, Fire history of the Snowy Range, WY over the past 16,000 years, 2009. Wyoming Undergraduate Research Day, University of Wyoming, May 2, 2009.
3. Victoria Perez† and Bryan Shuman, 2008. Sedimentary Evidence of Severe Prehistoric Droughts in Northern Colorado, EPCoR, Student Research Apprentice Program, University of Wyoming, July, 2008.
4. Thomas Minckley, Andrea Brunelle, Bryan N. Shuman, Jane M. Beiswenger, Elliott Lips, and Jacqueline J. Shinker, 2009. Asynchronous vegetation change along an elevational transect related to paleohydrology of Southeastern Wyoming, Association of American Geographers 105th annual meeting, 2009, March 22-27, 2009, Las Vegas, NV.
5. Jacqueline J. Shinker, Bryan N. Shuman, Thomas A. Minckley, 2009. Modern analogs of climatic controls on long-term drought in the North Platte River headwaters of Wyoming, Association of American Geographers 105th annual meeting, 2009, March 22-27, 2009, Las Vegas, NV.
6. Bryan N Shuman, Anna K. Henderson**, Thomas Minckley, Jacqueline J. Shinker, 2009. Evidence of multi-century to multi-millennial droughts in the Colorado River headwaters region during the past 8000 years, Association of American Geographers 105th annual meeting, 2009, March 22-27, 2009, Las Vegas, NV.
7. Jacqueline J. Shinker, Bryan N. Shuman, and Thomas A. Minckley, in prep. Climatic Shifts in the Availability of Contested Waters: A Long-term Perspective from the

Headwaters of the North Platte River. Annals of the Association of American Geographers.
8. Bryan N. Shuman, Paul Pribyl*, Anna K. Henderson**, Jacqueline J. Shinker, and Thomas A. Minckley, in prep. Multi-century to multi-millennium droughts in the Upper Colorado River headwaters during the Holocene.
9. Anna K. Henderson**; Grant Elliot**; Vania Stefanova; Bryan N. Shuman; Yongsong Huang. 2008. Comparison Between Mid-Holocene and Twentieth Century Climatic Change and Alpine Treeline Fluctuations in the Western U.S. Based on Compound-Specific Hydrogen Isotopes, Tree Rings, Pollen, and Macrofossils. American Geophysical Union, Fall Meeting 2008, abstract #PP41B-1442.
10. Anna K. Henderson and Bryan N. Shuman. In Prep. Temperature, Moisture, and Tree-Line Fluctuations at the Headwaters of the Colorado River over the Past 8000 Years. Geology.

Abstract
Wyoming has historically experienced prolonged periods of drought, which have had significant economic and social impacts. Yet, the severe droughts of the late 20th century are not unprecedented in the long-term context of climate variability, meaning droughts in the past may have exceeded recent dry periods in both magnitude and duration. Evidence from tree-ring and archeological records indicate that past centuries have contained multi-decadal “megadroughts” far more severe than any drought of the past 150 years. Using direct measurements of prehistoric shoreline elevations of lakes in Wyoming and Colorado, we show centennial-to-millennial scale drawdowns of lake levels that far surpass historic and dendrochronological records. Calculation of hydrologic budgets based on the inferred lake levels indicates that the drawdowns were produced by reductions in the balance of precipitation and evaporation of 0.3 to 0.7 mm/day. The spatial patterns and timing of past lake levels suggest episodes of widespread aridity, similar in magnitude and extent to droughts in AD 1954, 1960, 1988, and 2002, but which persisted from >8000 to <5000 years ago. Additional multi-century droughts were also documented, and resulted in changes in reduced tree cover in regional forests.

Statement of Problem
Understanding the full range of drought variability is important for informing long-term water resource planning in Wyoming in the future. By assessing prehistoric shoreline elevations of lakes in the North Platte watershed, we are able to extend knowledge of drought episodes beyond the range of historic and tree-ring records to provide a more complete assessment of the range of variability in water availability in the region. Based on evidence of past lake-level variations, these natural reservoirs experienced prolonged draw downs equal to a reduction in the regional hydrologic balance (precipitation minus evapotranspiration) of 0.3 to 0.7 mm/day for periods of centuries to millennia during the past 11,000 years. Such hydroclimatic changes were as severe as during years like AD 2002, and indicate the potential for shifts to severely dry hydrologic regimes that can persist well beyond societal planning horizons.

Objectives
In much the same way that data from local meteorological stations can be compared to assess weather patterns, arrays of lakes (via sediment deposits and proxy data such as pollen) can be

studied to reconstruct past climate conditions. Submerged shorelines are indicative of periods of drier-than-present conditions (e.g. Dearing, 1996; Shuman and Finney, 2006). These paleoshorelines are buried under sediment deposited during subsequent wet periods providing a record of past hydrological conditions (i.e., water level). By identifying and dating past lake-shoreline features, we reconstructed the histories of lake water levels in Wyoming, particularly the North Platte River drainage. Through the mapping of the subsurface shorelines from numerous lakes, we were then able to determine regional patterns of water-level change. We compare these past hydrologic patterns with modern climatological data (e.g., Mock and Brunelle-Daines, 1999; Shinker et al., 2006) as a means to better understand the climate processes that are associated with reduction in lake levels. Our objectives are to assess the:

1. Potential that regional water supplies have undergone multi-century fluctuations;
2. Spatial extent of ancient, long-term droughts in Wyoming;
3. Potential climatic controls and land-surface feedbacks associated with droughts in the region; and
4. Impacts of long-term drought on water resources and forest composition.

Methodology

Surveys of lakes throughout Wyoming (and the Colorado headwaters of the Platte River) were conducted with 1) ground-penetrating radar (GPR) to identify past shifts in shoreline position via sediment geometry; 2) sediment coring to date past shoreline deposits; and 3) pollen analysis of sediment cores taken from the basin centers to reconstruct past vegetation composition during long-term droughts. In addition, modern climate analogs of past drought conditions were analyzed to determine potential influences of climate on past low lake-level events.

<u>Ground-penetrating Radar</u>

Previous studies have demonstrated that small lakes, such as kettle and moraine-dammed lakes in glaciated areas can produce consistent records of climate-controlled lake-level fluctuations (e.g., Digerfeldt et al., 1992; Shuman et al., 2001; 2002). In such lakes, the water table of the surrounding aquifer is exposed at the surface, and the lake level generally reflects the climate-controlled water budget of the aquifer (Almendinger, 1993). Therefore, stratigraphic analyses of such lakes can provide accurate records of paleoclimatic change. We collected and analyzed 137 shore-to-basin GPR profiles to detect changes in the geometry of the sediments that indicated past shoreline elevation, and thus, confirm the regional availability of moisture through time. When lake levels are low, sandy and macrophyte-rich substrates expand toward the center of the lake and sedimentation slows near shore. As a result, sandy layers and hiatuses (erosion surfaces) extend from shore, older sediment units become truncated at these hiatuses, and deepwater sediments "pinch out" towards shore.

<u>Sediment Cores</u>

In addition to GPR data, our results derive from sediment cores collected in ten lakes (Hidden Lake, Lily Lake, and Boettcher Lake in Jackson Co., Colorado; American and Creedmore Lakes in Larimer Co., Colorado; East Allen, Long and Little Windy Hill Lakes in Carbon Co., Wyoming, Little Brooklyn Lake in Albany Co., Wyoming; and Lake of the Woods in Fremont Co., Wyoming). Shuman (2003) showed that differences in sedimentary characteristics among sediment cores collected at different depths within a single lake can be used to determine lake-level changes. Cores were collected in multiple sections with a modified Livingstone piston corer with individual polycarbonate barrels for each drive, or section of core. Polycarbonate barrels were detached from the piston device, capped and returned to the University of Wyoming for description, subsampling and analysis. Core density and magnetic susceptibility were determined on whole core sections using a GeoTek Multi-Sensor Core Logger. Sections were then subsampled for loss-on-ignition (LOI), radiocarbon dating, pollen, and macrofossil analysis. Detailed plots were created of sediment age and elevation that represent the water-level history. Loss on ignition, magnetic susceptibility, and grain-size analysis were assessed to indicate shifts in sediment composition and grain size indicating changes in shoreline positions. AMS radiocarbon dating of plant macrofossil and bulk sediment material was used to establish a chronology of each sediment core analyzed. Pollen extraction from sediment cores followed standard methodology (Faegri et al., 1989). Pollen samples were initially analyzed at 16 cm intervals to determine when present-day forests established. Subsequent samples were examined from “drought” and “non-drought” periods for determination of ecological responses to past drought events.

Modern Climate Analogs

Comparison of the lake-level data with maps of climate anomalies allowed for the examination of potential influences on spatial patterns of hydroclimatic change (e.g. Shinker et al., 2006). The spatial and temporal variability of modern and past drought events can provide information on conditions at the surface and in the atmosphere that lead to prolonged drought. Analysis of modern climate processes provides an important framework for considering mechanisms related to lake-level fluctuations and vegetation changes (Harrison et al., 2003; Shinker et al., 2006). Data from the NCEP-NCAR Reanalysis Project (Kistler et al., 2001) were used to link climatic controls on variations in lake levels and vegetation using a modern-analog approach (Mock and Brunelle-Daines 1999; Shinker et al., 2006) that incorporates modern climate data to represent surface and upper-level circulation conditions likely to support prolonged droughts. Composite anomalies were calculated to compare recent extreme dry years to long-term mean conditions within the climate system. Once calculated, composite-anomaly maps were made to show the relationship between large-scale atmospheric circulation patterns and surface climate responses (Yarnal 1993; Shinker et al., 2006; Shinker and Bartlein 2008).

Calculation of Impacts on Water Resources

We calculated the change in precipitation (P) minus evaporation (E), ΔP-E, at our two of our primary study sites (Lake of the Woods, Wyoming; Hidden Lake, Colorado) to measure the impact of past dry conditions on water resources. The two sites were chosen because their well-defined watersheds enabled us to approximate the moisture budgets of the lakes. To use inferred lake-level changes as a hydroclimatic indicator, we assume that changes in lake volume depend on the annual balance of watershed inputs (precipitation) and outputs (evaporation and groundwater leakage). We assume that groundwater leakage has remained constant through time although reduced hydrostatic head during periods of low lake levels should reduce levels of groundwater outflow, and thus make our ΔP-E estimates conservative. To calculate long-term ΔP-E, we estimate elevational shifts in the wave base of each lake (based on the depths of sand layers and erosion surfaces), and assume that changes in the elevation of the lake surface were equal in magnitude. We then calculate the associated change in lake volume by accounting or lake size and bathymetry. We assume the estimated change in lake volume represents a change in the annual balance of inputs and outputs of the entire watershed and therefore divide by the watershed area and 365 days to obtain a ΔP-E value in mm/day comparable to historic observations.

Results

Lake-level Variations

At multiple lakes throughout the region, we have identified evidence that shorelines were lower than today for prolonged periods in the past 11,000 years (Fig. 1, 2). GPR profiles show dense paleoshoreline deposits and erosion/non-deposition surfaces; sediment cores contain sand layers with very low accumulation rates as expected if near-shore wave-energy interacted with these substrates. For example, at Creedmore Lake in Larimer Co., Colorado, near the headwaters of the Laramie River, we found evidence that the lake was lower than its drought-induced low level in May 2008 from ca. 7900-3700 years before present (BP)(Fig. 1). Similar evidence was found at lakes from the southern reaches of the Platte River watershed in Jackson Co., Colorado, to the Wind River Range in Fremont and Sublette Counties, Wyoming (Fig. 2).

An important set of results show that Lake of the Woods, Fremont County, Wyoming, which is at the joint headwaters of the Snake-Columbia, Green-Colorado, and Wind-Bighorn-Missouri River systems, was substantially lower than today before 11,300 yrs BP, from 8900-2700 yrs BP, from 1900-1100 yrs BP. Sediment cores from the lake show three packets of dense sandy sediment, which interrupt intervals of deep-water sediments (olive silt), which date to these periods (Fig. 3). We infer that the packets represent paleoshorelines based on the geometry of the packets (i.e., their consistent appearance in GPR data from around the lake's margins, and their development only near shore), the shift from silts to sand (i.e., from low to high energy environments) and the low net sedimentation rates of the sand layers (i.e., potentially associated with extensive near-shore sediment winnowing). From 8900 to 2700 yrs BP, the net sedimentation rate within core 2A (at 194-167 cm below the modern lake surface) averaged 4.3 cm/kyr, and was as low as 1.9 cm/kyr from 8900 to 6200 yrs BP. Such low sedimentation rates are inconsistent with high rates of deposition during floods, which is a primary alternative explanation for the sand deposits.

The most recent dense sediment layers also coincide in time with periods of frequent drought in local tree-ring data (Cook and Krusic 2004), and the combination of lake and tree-ring data indicate that recent centuries were probably some of the wettest in the past 8000 years (Fig. 4). Core 2A from Lake of the Woods contains a dense paleoshore deposit at ca. 1100 yrs BP when dendroclimatic evidence indicates >60 drought years in a century. Earlier dense layers indicate that conditions there were likely at least as dry from ca. 8900 to 2700 yrs BP, and before 11,300 yrs BP. Similarly, at the southern end of our study area, at Hidden Lake, Colorado, a core collected near shore contains high-density shoreline deposits with very low net sedimentation rates before 1200 years BP when tree-ring drought reconstructions reveal repeated periods with >50 drought years per century. The lake record indicates that earlier periods were even drier or had more frequent extreme droughts, particularly from 3700-2000 yrs BP and 8400-4400 yrs BP (when the water level was too low for sediment to accumulate at the core location). Notably both lakes were low from ca. 8400-4400 yrs BP, but the details of their histories may otherwise vary, which is also consistent with the spatial variability of most historic droughts and the tree-ring data.

Overall, we find that all of the lakes we studied were commonly low from >7900 to <5000 years ago when sedimentary isotopic data indicate high regional temperatures (Henderson et al., 2008; in prep.). To sustain these low levels, P-E must have dropped by 0.3 mm/day at Lake of the Woods and by 0.7 mm/day at Hidden Lake. These estimates are consistent with climate model simulations of the region for 6000 yrs BP (Diffenbaugh et al., 2006), and indicate regional aridity as intense as in AD 2002.

Modern Climate Analogs of Past Drought Conditions

Evidence of prolonged prehistoric periods of low lake levels across Wyoming indicate persistent dry conditions that were similar to dry conditions in recent years. Years from the modern record that exhibit similar (in magnitude but not in duration) dry conditions as seen in the lake-level record are 1954, 1960, 1988, and 2002. Figure 5 shows the composite-anomaly maps for late spring/early summer (May, June, and July) months of the selected modern analog years. May, June, and July were selected to represent conditions during peak spring snowmelt and peak precipitation time (May) as well as summer months when evaporation is likely to be high. The modern analogs of ancient Wyoming aridity are characterized by lower-than-normal precipitation (Figure 5a), persistent reduced moisture availability through 850mb specific humidity (Figure 5b), enhanced sinking motions via 500mb vertical velocity (Figure 5c) leading to a mechanistic suppression of precipitation, and drier-than-normal soil moisture conditions (Figure 5d) in late spring and early summer months.

Pollen Analysis

A comparison of pollen percentages between drought and non-drought periods suggests millennial scale droughts had an impact on forest composition (FIG 6). Pine percentages decreased during drought period (median value 67%) when compared to non-drought periods (median value 69%). Median spruce percentages were 1% lower (3%) during drought period compared to non drought periods (4%). Fir percentages were indistinguishable between drought and non drought periods. Shrub and herbaceous taxa increase, illustrated by the change in sagebrush percentages, which had median values of 19% during drought periods and 17% during non drought periods. Further refinements of these results are needed to determine the statistical significance of these results. However, our results indicate the ecological significance of the ancient prolonged droughts inferred from the lake-level data.

Significance

The results of our study suggest that prolonged multicentennial to millennia scale drought, while not frequent, are common in the North Platte watershed indicating the region has not yet experienced the full range of possible drought conditions. Minimally, there were at least three major periods of drought centered on 3500, 1500 and 750 cal yr BP. GPR data from Lake of the Woods and Hidden lakes, suggest these drought periods could have been characterized by a series of shorter strong drought events with interspersed wet periods. Modulating drought periods might explain the high variance seen in the pollen percentage data during these times as forests responded to climate changes. The droughts in the past appear to have been widespread events most similar to conditions seen in during the AD 2002 anomaly. Conservatively, we calculate that if conditions like AD 2002 persisted over the timescales of drought in the past, perennial water supplies in the North Platte watershed, for example, could disappear. Platte River flows of ~25% of normal in AD 2002 were likely sustained by base groundwater flows that must have been significantly reduced during the past to produce the sustained low lake levels.

Information Transfer

Results from this research were presented through several scientific symposia and conference presentations including:

- EPCoR, Student Research Apprentice Program, University of Wyoming, July, 2008;
- American Geophysical Union, Fall Meeting, San Francisco, CA, December, 2008;
- Wyoming Undergraduate Research Day, University of Wyoming, May 2, 2009 (2 presentations);
- EPCoR, Student Research Apprentice Program, University of Wyoming, July, 2008; and
- Association of American Geographers 105th annual meeting, 2009, March 22-27, 2009, Las Vegas, NV (3 presentations).

Student Support

The funded project supported training and mentorship of five students, one high school student, three undergraduate students, and one graduate student.

- Victoria Perez, a high school student from Denver, CO was supported through the EPSCoR Student Apprentice Research Program (SRAP) which supports the involvement of under-represented high school students in research project. Ms. Perez's involvement in the project included training in field collection and lab analysis of sediment samples from Creedmore Lake, and a presentation of research results at a symposium (see Information Transfer above).
- Joshua Fredrickson, a Geography undergraduate student was funded through the project to be trained in summer field collection of lake sediment cores. As a result of his involvement with this project Mr. Fredrickson will be working on an independent study project in the summer of 2009 to analyze climate data associated with recent low stream flow events in the Platte and Colorado River drainages.
- Paul Pribyl, a Geology and Geophysics undergraduate student was funded through the project to be trained in lab analysis of grain-size analysis and loss on ignition in support of sedimentary analysis. Mr. Pribyl's training resulted in an independent study project that received additional funding through the NSF EPSCoR and Wyoming NASA Space Grant Programs. Results from Mr. Pribyl's research will be presented at the University of Wyoming Undergraduate Research Day (see Information Transfer above).
- Robert Shriver, a Botany undergraduate student, was funded through the project to be trained in lab analysis of sedimentary material. Mr. Shriver's involvement in the project lead to an independent study project funded through NSF EPSCoR and an undergraduate research grant through the Ruckelshaus Institute of Environment and Natural Resources to analyze charcoal and macro-botanical fossils from sediment cores. Mr. Shriver's research will be presented at the University of Wyoming Undergraduate Research Day (see Information Transfer above).
- Anna Henderson, a Ph.D. graduate student (mentored by Shuman) in Geology and Geophysics at the University of Minnesota (Shuman's former institution) was responsible for analyses of cores at Hidden, American, Lily, and Boettcher Lakes. Henderson has used funding from this project to obtain radiocarbon dates for detailed lake-level analyses from Lily Lake (extending back ~14000 years) for comparison with results from Hidden Lake. She has also generated a detailed temperature reconstruction for northern Colorado over the past 8000 years based on sediment isotopes from American Lake.

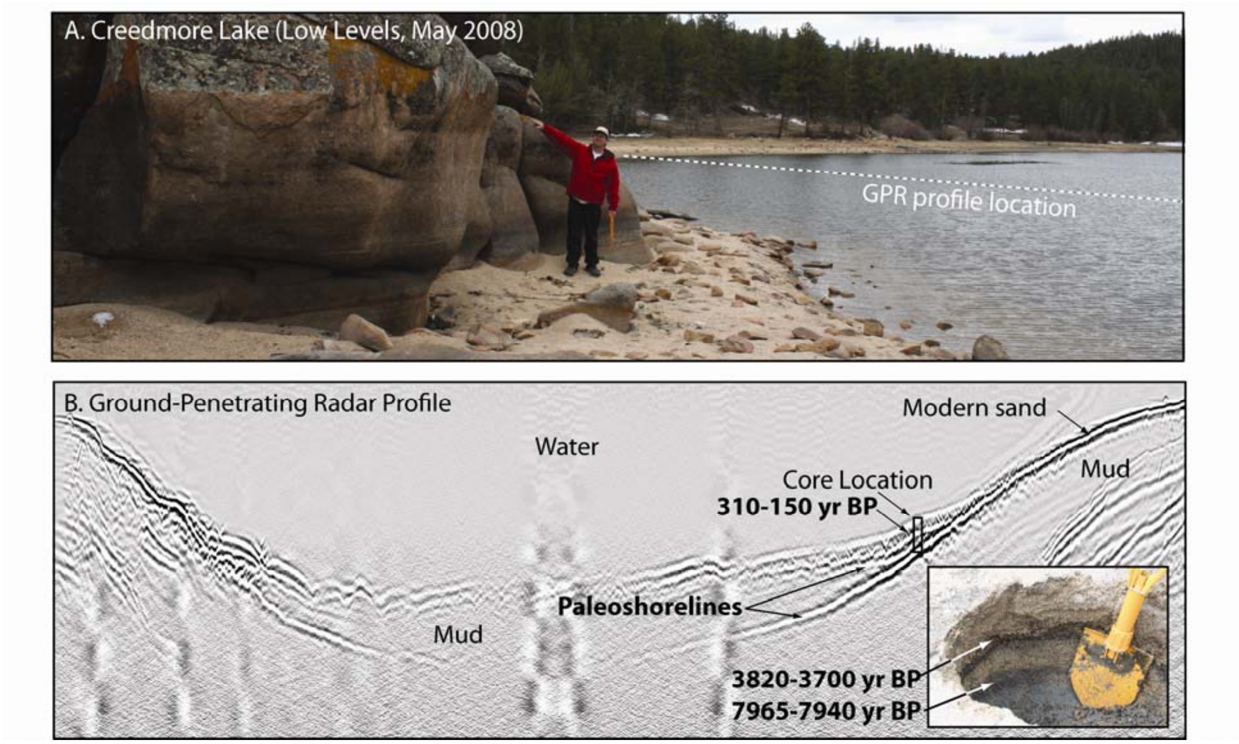

Figure 1. Recent low water levels at Creedmore Lake in May 2008 (A) illustrate the hydrological impacts of the past decade of drought. Sub-surface geology (B), however, captured by ground-penetrating radar (GPR) and sediment core data reveal that the lake has been much lower in the past. In fact, despite water-levels as high as the lichen line on the rocks (A) as recently as AD 1999, no lake sediment has permanently accumulated in the current sandy beach zone since ca. 3750 years before present (BP) (BC 1800) – and then only briefly (see inset photo of a shovel pit from the beach). Paleoshorelines submerged within the lake date from ca. 7950-3750 yrs BP when sand was deposited nearly to the center of the lake (see lower paleoshorelines in B), and to before ca. 200 yrs BP. Bold numbers in B indicate ages and positions of radiocarbon ages on sedimentary features.

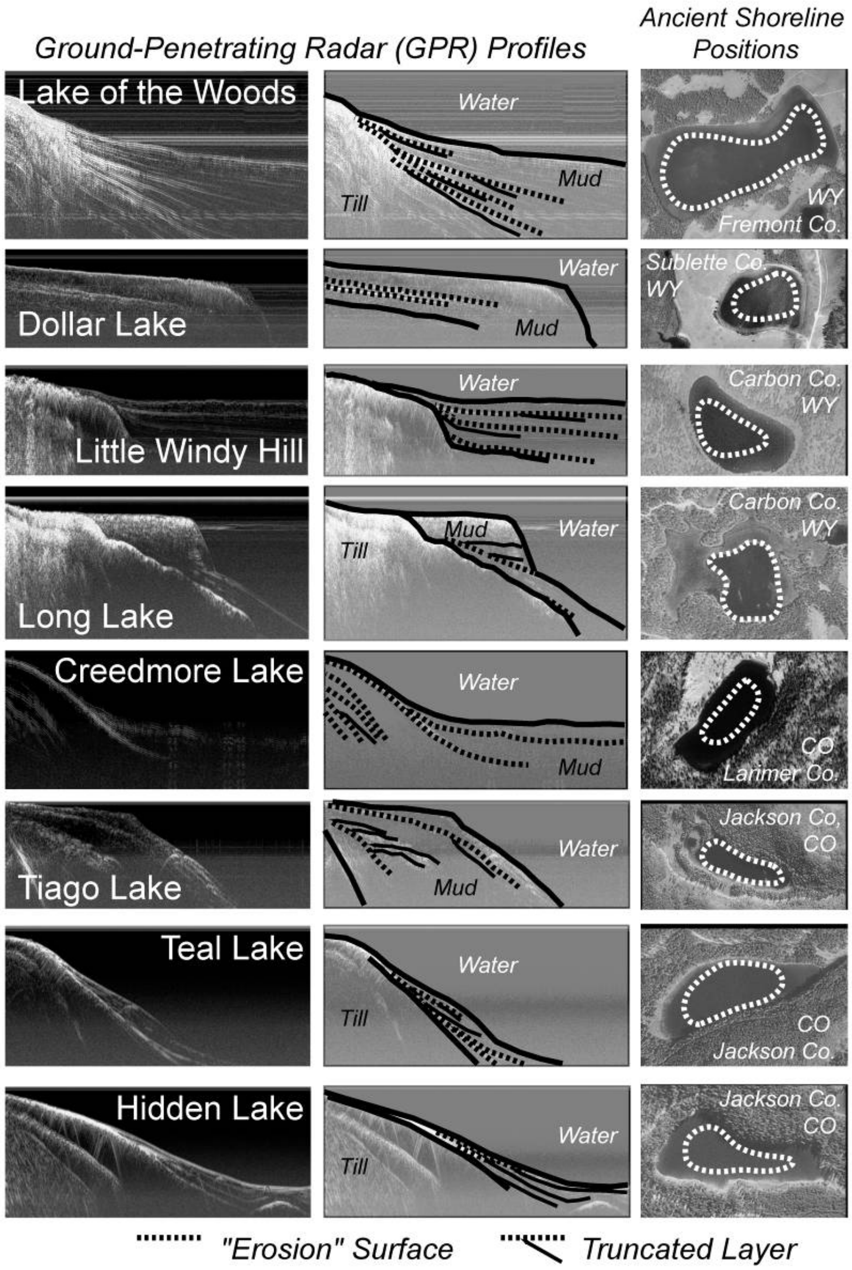

Figure 2. Lakes throughout the region contain submerged erosion surfaces at their margins that indicate prolonged periods of low water-levels. Representative ground-penetrating radar profiles from a geographically-diverse selection of lakes are shown. White indicates areas of high-density contrast within the vertical radar profiles. The middle column shows the interpretation of the profile with black lines denoting the submerged lake sediments, dashed lines marking erosion surfaces, and thin black lines showing truncated layers. At the right, the inferred position of the most prominent ancient shorelines (based on the erosion surfaces). Where dated at Lake of the Woods, Little Windy Hill, Creedmore, and Hidden Lakes, the inferred shoreline positions were occupied from >5000 to <3000 years ago (except during a few multi-century wet periods during this time).

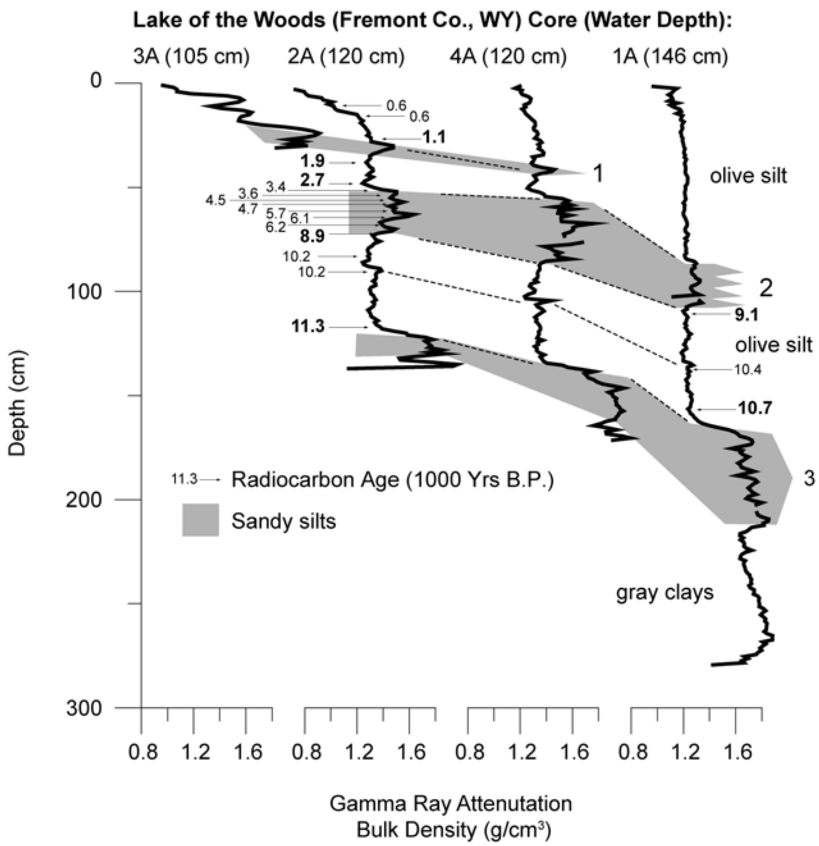

Figure 3. Density profiles from cores collected near the margin of the Lake of the Woods show three packets of dense, sandy shoreline sediments (gray). Bold numbers indicate radiocarbon ages bracketing these paleoshorelines deposits in thousands of years before present.

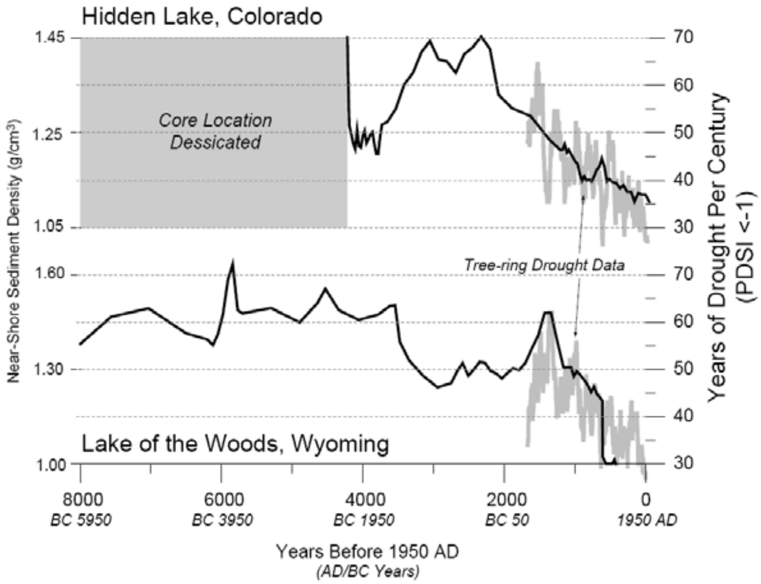

Figure 4. Lake sediment cores track the low-frequency (long-term) trends in regional drought frequency, and show that the past few centuries have been the wettest period in >8000 years. During intervals when tree-ring evidence records frequent droughts (years with PDSI <-1) per century, cores collected near the margins of Hidden Lake and Lake of the Woods contain dense (sandy) shoreline deposits, which accumulate because the water level of each lake is lower than today during droughty periods. The results indicate periods of 2000-4000 years with >60 drought years per century. Gray box indicates the period when Hidden Lake was too low for sediments to accumulate at the core location (and thus more frequent drought years than during any period in the past 4400 years). Tree-ring data for the lake locations was obtained from Cook and Krusic (2004).

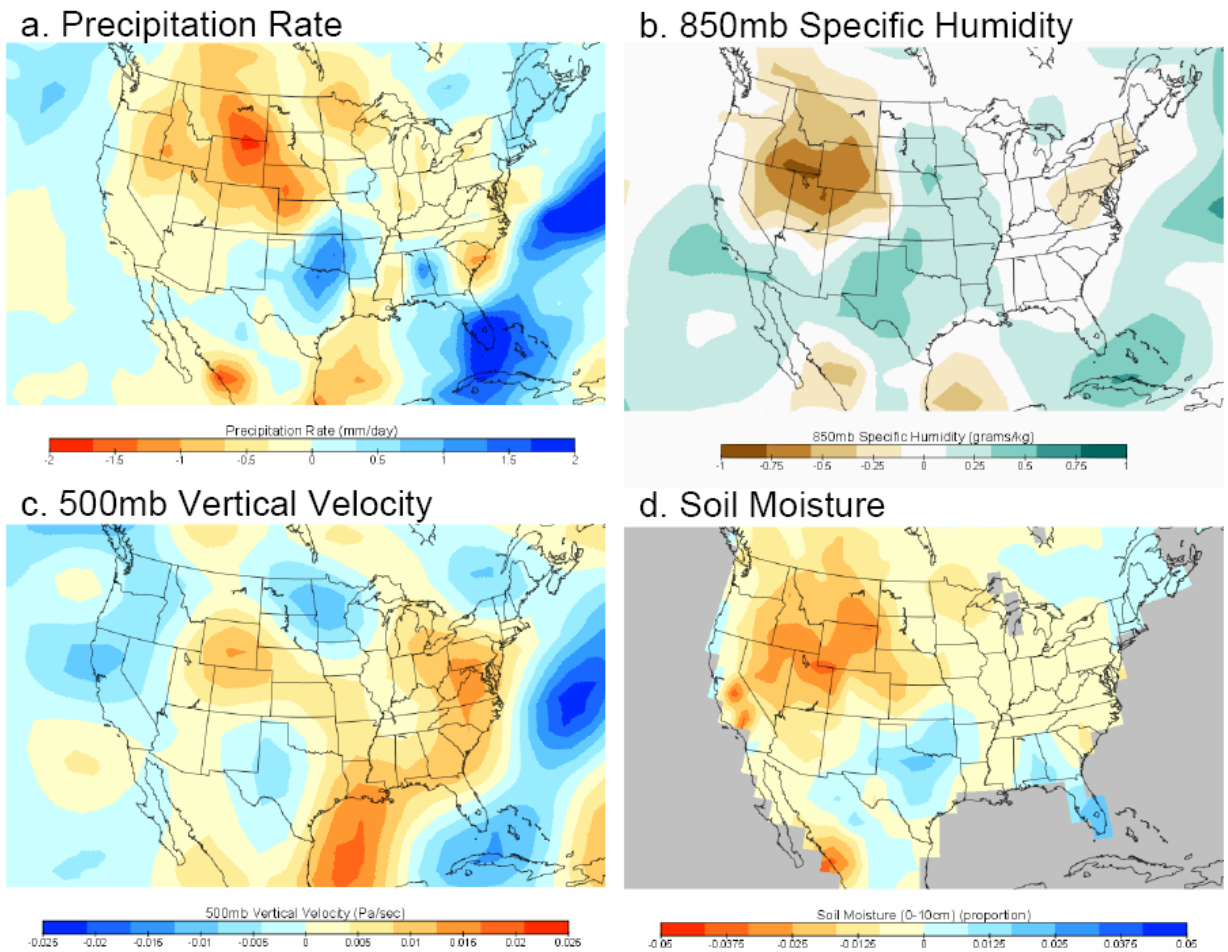

Figure 5. Composite-anomaly maps for summer (May, June, and July) of dry years (1954, 1960, 1988, and 2002, base period 1979-2000), illustrating modern analogs of climate conditions leading to basin-wide water deficits. Precipitation rate (a) showing lower-than-normal precipitation (orange); 850mb specific humidity (b) showing lower-than-normal moisture availability (brown); 500mb vertical velocity (c) showing greater-than-normal sinking conditions which suppress precipitation (orange); and soil moisture (d) showing lower-than-normal moisture at the surface (orange).

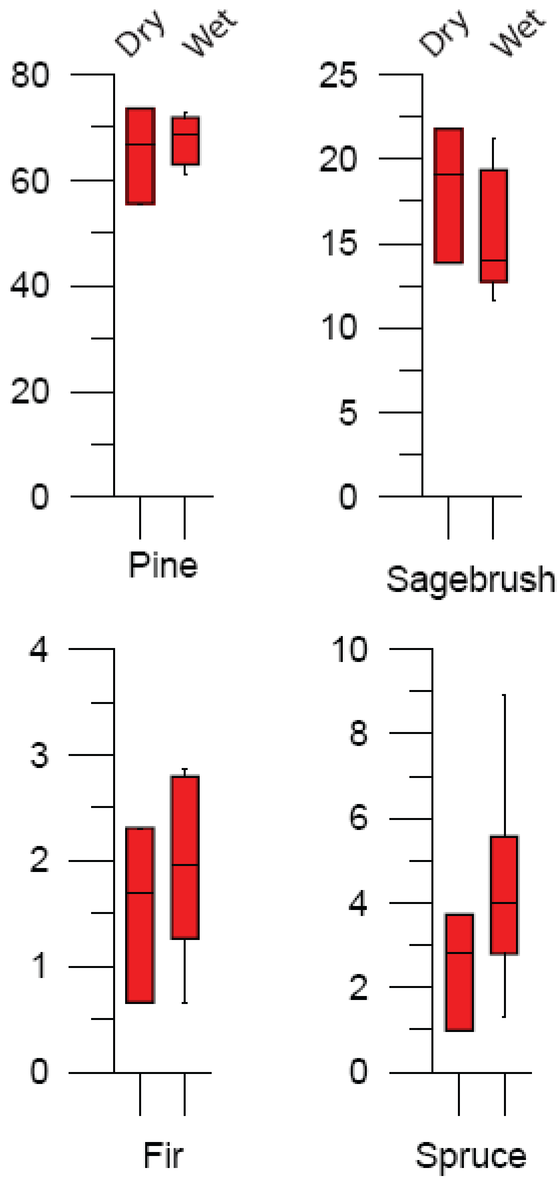

Figure 6. Box plots of Pine, Sagebrush, Fir and Spruce pollen percentages for millennial-scale drought periods centered on 3500, 1500 and 750 cal yr BP (left) compared to non-drought period (5000 cal yr BP to present) (right). Drought periods show greater variance in pollen percentages when compared to non-drought periods.

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