**University of Nevada, Reno**

# Paleoecological Analyses of the Late Holocene Dry Period in the Northwestern Great Basin, Nevada

**A thesis submitted in partial fulfillment of the**

**requirements for the degree of Master of Science in**

**Geography**

**by**

**Cedar Briem**

**Dr. Scott Mensing Thesis Advisor**

**May, 2022**

The University of Nevada, Reno

THE GRADUATE SCHOOL

We recommend that the thesis prepared
under our supervision by

**CEDAR BRIEM**

entitled

**Paleoecological Analyses of the Late Holocene Dry Period in the Northwestern Great Basin, Nevada**

be accepted in partial fulfillment of the
requirements for the degree of

**MASTER OF SCIENCE**

Scott Mensing, Ph. D

*Advisor*

Adam Csank, Ph. D

*Committee Member*

Dave Rhode, Ph. D

*Graduate School Representative*

David W. Zeh, Ph.D., Dean

*Graduate School*

May, 2022

## Abstract

During the Pleistocene the Great Basin was filled by endorheic lakes that receded greatly during the Holocene. Several proxy records provide extensive evidence that the basin has gone through periods of amelioration from low precipitation followed by a return to dry conditions through the Holocene. Relative to the Pleistocene/Holocene transition and middle Holocene, aside from the Medieval Climate Anomaly, study of the late Holocene has received less attention.  In recent years evidence has emerged for a ca. millennial length drought termed the Late Holocene Dry Period (LHDP), between about 2800 and 1800 years ago. The LHDP has been proposed to follow a dipole climatic pattern associated with changes in precipitation linked to the Southern Oscillation Index (SOI) and described as a dry southwest and wet northwest in the United States. Here I present a 4000-year pollen record from northwestern Nevada, investigating the potential for the Late Holocene Dry Period to conform to the modeled dipole pattern in this part of the region. This site is located near a zone of ambiguity between wet and dry conditions in order to identify more definitively where the modeled dipole pattern is centered.

## Introduction

The hydrologic Great Basin is the largest endorheic basin in North America. The region is characterized by north/south trending basin and range topography. The Great Basin includes western Utah, southern Idaho, most of Nevada and portions of eastern California, Oregon and Wyoming (Fig. 1). This desert ecosystem experiences little precipitation throughout the year, cold winters, and hot summers. Water flowing into the basin from the Sierra Nevada forms several large closed-basin lakes, (e.g. Pyramid, Walker and Mono) but most basins are evaporative playas, remnants from extensive lake systems during the much wetter Pleistocene epoch. Faulting associated with basin and range topography, however, allows for groundwater fed seeps, springs and wet meadows to exist in valley bottoms even under these dry conditions. During dry periods, poor drainage produces alkaline soils, and in turn halophytic plant communities that are resistant to drought and saline conditions (Donovan et al., 1997). Due to arid conditions that facilitate preservation, the region is rich in archaeology, particularly in the vicinity of ancient wetlands.

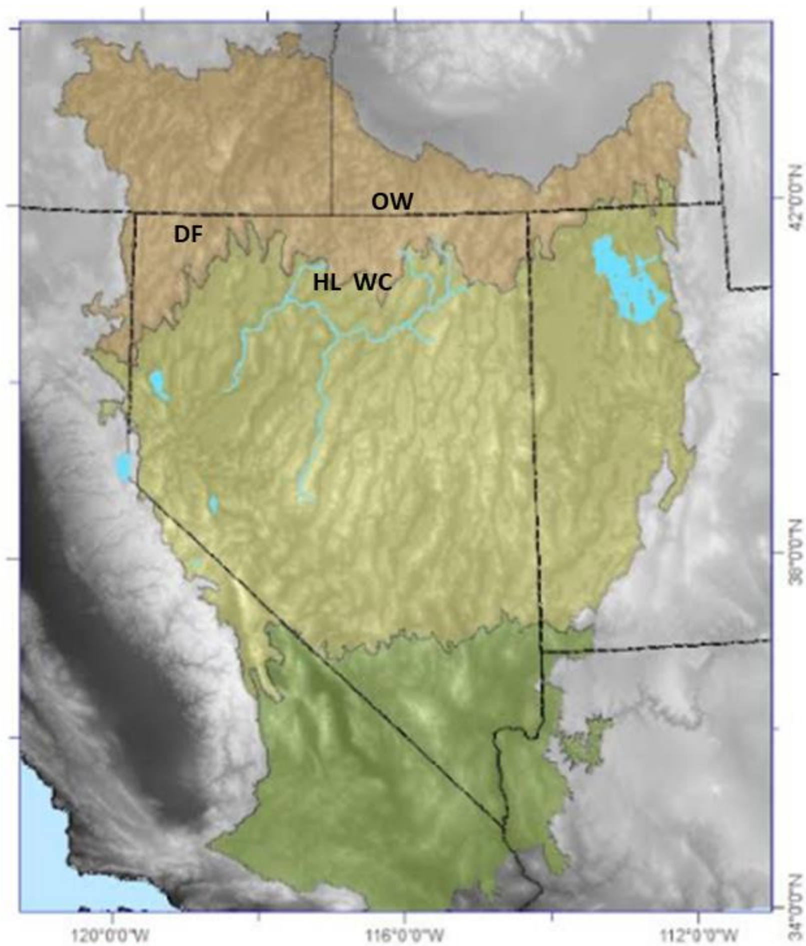


Fig 1. Ecoregions map of the Great Basin and attempted coring sites (appendix A); brown, northern, olive, central and green, southern. DF represents the location of the Dufurrena Ponds study site which is the basis of this study. Willow Creek (WC) Owyhee Wetlands (OW) and Hot Lake (HL) were also cored for this study, however due to extremely low sedimentation rates and low pollen concentration these sites were not fully analyzed. See appendix A for detail on sites.

The climate history of the Great Basin has been of interest ever since Antevs (1952) noted the ancient shorelines occupying many of the closed basins and referred to the middle Holocene as the ‘Altithermal’, a dry period from ca 7500-4500 BP (Grayson, 2011). This was before radiocarbon dating existed, so those studying the region were merely looking at extremely low-resolution sequences of time and generally correlating these with European sequences. Over the last 50 years, especially with the analysis of ice cores and use of AMS radiocarbon dating, there has been extensive research done on understanding the past and expounding on work done by early scientists like Antevs. With ice cores providing annual climate data piquing more and more interest among the scientific community, comparison to terrestrial proxies began to take place. Over the last 30 years there has been a focus on understanding the Pleistocene/Holocene transition (PHT) the Younger Dryas (YD) (Madsen et al. 2001, Miller and Gingerich, 2013, Goebel et al. 2011) and the Middle Holocene. There has been much less of a focus on the late Holocene (Grayson, 2011), however with the discoveries of the impacts of the Medieval Climate Anomaly (MCA) within the Great Basin (Stine 1990) and emphasis on other megadroughts in the southwest (Carter, et al., 2018; Cook, et al., 2010) there has been a shift in interest to the Late Holocene and the internal variability of this much shorter period relative to the Holocene as a whole.

It has long been thought that the late Holocene was a period of cool, wet conditions, (Grayson, 2011), however evidence for extensive, multi-centennial droughts is becoming increasingly abundant ((Madsen et al., 2005; Hockett, 2007; 2015; Mensing et al., 2008; Grayson, 2011), expressed through pollen, faunal and archaeological records throughout the region. Even more recently the region has experienced exceedingly dry conditions during the Medieval Climate Anomaly MCA (Stine 1994), potentially associated with the collapse of southwestern civilization (Benson et al., 2002). Such studies are making it clear that late Holocene climate change is more interesting than originally thought.

This project is further examining less understood periods of long-term dry periods in the Great Basin during the Late Holocene, referred to as the Late Holocene Dry Period (LHDP)

(Mensing et al. 2013). The LHDP is thought to have been a period of generally below average precipitation that persisted between about 2800 and 1800 years ago and extended across much of the Great Basin and potentially into southern California, however the timing and geographic extent are still not well defined. Mensing (2013) hypothesized that the pattern of drying during the LHDP conforms to the dipole pattern identified by (Redmond and Koch, 1991) and modeled by Wise (2010) (Fig. 2) that leads to a quasi-stable polar front across the north-central Great Basin, with polar front mesic conditions to the north and xeric conditions in the south.

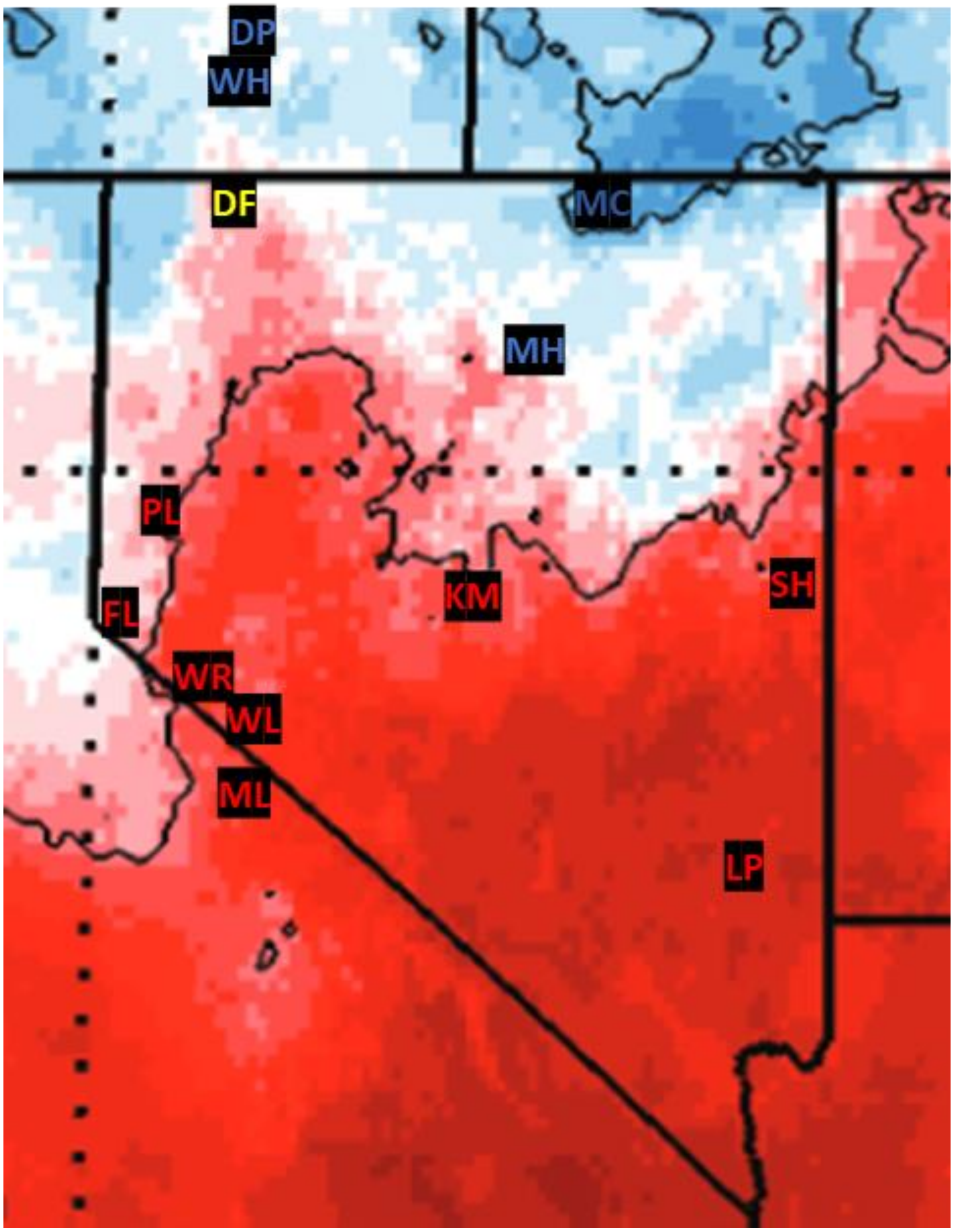


Fig 2. Map of the correlation coefficients between the Jun-Nov. SOI and Oct-Mar precipitation between 1926 and 2007, following Wise, 2010 and study sites discussed in the text. Regions in blue have higher than average precipitation, those in red have lower than average precipitation and white has no correlation. Thin black line represents the 90% confidence interval. DF, the primary site in this study, is in yellow, shows that the record dry during the period 2800 – 1800

cal yr BP, the proposed Late Holocene Dry Period. Sites that stay wet are in blue, and sites that record dry during the LHDP are in red. DP (Diamond Pond) (Wigand, 1987), WH (Wildhorse Lake) (Mehringer, 1985), MH (Middle Humboldt River) (Tausch and Chambers, 2004), and MC (Mission Cross Bog) (Mensing et al., 2008) all show a wet signal during the LHDP. FL (Fallen Leaf Lake) (Kleppe, et al., 2011), ML (Mono Lake) (Stine 1990), WL (Walker Lake) (Adams, 2007), PL (Pyramid Lake) (Mensing 2004), LP (Pahranagat Lake) (Theissen et al., 2019), WR (Wassuk Range) (Millar et al., 2019), KM (Kingston Meadow) and SH (Stonehouse Meadow) (Mensing et al., 2013) all record dry during the LHDP.

One significant point of the hypothesis is that it suggests that the dipole pattern might have once persisted for multiple centuries. Droughts of great duration have occurred through time (Carter et al. 2018), so dry periods of this length are certainly not an impossibility. This persistent pattern is consistent with current global circulation models (GCM) suggesting a persistently drier southwest and wetter northwest by 2071-2099 (NOAA NCDC / CIS-NC). Evidence suggests that the influence of lower sea surface temperatures and changing pressure regimes in the Pacific could influence long term drought in the central Great Basin (Kennett et al. 2007) expressed along a latitudinal gradient. Recently, evidence has shown the possibility of periods of drought in the Late Holocene (Mensing et al. 2013; Millar et al., 2019; Kleppe et al., 2019). All four sites that fall in the blue, northern portion of the dipole (Fig. 2) record wet conditions during the LHDP while sites that fall in the red record dry conditions during the LHDP.

The goal of this project is to further explore the geographical and temporal extent of the LHDP and to identify the latitudinal gradient where conditions change from wet to dry by reconstructing the paleoecology, and by inference the paleoclimate of the last 4000 years, of a set of sites along a south to north latitudinal gradient across north-central Nevada. This thesis specifically examines the northern most site of that transect, a wetland located on the Sheldon-Hart Mountain National Wildlife Refuge near Dufurrena Ponds in northwest Nevada adjacent to the Oregon border (Fig. 1).

Although permanent natural lakes are often the preferred sites for collecting sediment cores for palynological paleoecological analyses, there are several reasons why this study is working with wet meadows. First and most obvious is that in valley bottoms, where droughts would be expected to be most severe and have the greatest impact on human activity, there are virtually no natural lakes in the region beyond the large remnant Pleistocene closed basin lakes fed by the Sierra Nevada. Second, the drought tolerant nature of Great Basin plants makes them resistant to all but the most severe and long-lasting droughts, and therefore not a sensitive indicator of other dry periods. Wetland plants on the other hand are extremely sensitive to changes in water table and can be used as a proxy for changing hydrologic conditions. Spring-fed wetlands, found in nearly every Great Basin valley offer a place for ancient plant material, pollen, and charcoal to be preserved via sedimentary deposition, making them some of the more ideal sites for paleoecological study. Pollen preserved from cores obtained from Great Basin wetlands and playas are the main proxy for this study. Ancient pollen assemblages inform us what was growing on the land at the time and by extension can tell us something about the climate.

**Site description**

Dufurrena Ponds

The Dufurrena Ponds are located at +41.8544°, -119.0111° (41° 51' 16" N, 119° 0' 39.8" W), elevation 1470 m (4,823 feet) Northwest of Winnemucca, NV (Fig. 1) on the Sheldon-Hart Mountain National Wildlife Refuge near the border between Nevada and Oregon. The wetland system includes an extensive area of natural wet meadows fed by a hot spring along the southern edge, and a low gradient drainage system that flows from Hart Mountain (2100 m, 6800') to the southwest. A series of artificial ponds were built to the north and west of the wetland. The geology of the region consists of basalt plateaus, dormant volcanics and ancient lake beds. The upland terrain slopes gently away from the wetland in a series of basalt flows that form low cliffs around the wetland. Soils are typically young, and poorly developed but the wetlands contain an abundance of organic material (Kasbohm, 2012). Apart from grazing in the early 1900's the adjacent springs have remained relatively undisturbed.

Over the last 150 years the high desert steppe landscape has become significantly less biologically diverse (Dobkin and Sauder, 2004) due to agriculture, fragmentation, and invasive species. Overall the surrounding area is characteristic of most Great Basin environments being comprised of Sagebrush (*Artemisia, sp.*), Juniper (*Juniperus osteosperma*), Bitterbrush (*Purshia tridentata*), Mountain Mahogany (*Cercocarpus latifolia*), and at higher elevations Aspen (*Populus tremuloides*), Pines (*Pinus sp.*) and White Fir (*Abies concolor*). The site is too far north for Pinyon Pine (*Pinus monophylla*) to be present on the landscape (Grayson, 2011). Today the dominant plants surrounding the meadow are Greasewood (*Sarcobatus vermiculatus*), Saltgrass (*Distichlis sp.*) and Willow (*Salix sp.*) with virtually no other trees in the vicinity. In the meadow Sedge (*Carex sp.*) and Cattail (*Typha latifolia*) dominate. Forest taxa are only present in higher elevation mountains in the surrounding region. The Pine Forest Range (6800'), 30 km to the southeast, has *P. albicaulis* (Whitebark Pine) and *P. flexilis* (Limber Pine) (Charlet 1996). To the west, the predominant wind direction, about 70 km from Dufurrena Ponds in the Mosquito Range (5000’) are found *P. ponderosa* (Ponderosa Pine) as well as *Abies concolor* (White Fir), at elevations up to 6840’. White fir and Ponderosa pine are also present in larger quantities in the Warner Range of California, 90 km west of Dufurrena Ponds.

The wetland is about 150 m wide by 350 m long (5 ha in area) with a fringe of *Sarcobatus* towards the outer edge, giving way to sedge over most of the surface. Cattails (*Typha latifolia*) grow in isolated pockets of deeper water towards the center. The wetland was once larger, but is now bisected by a road built on fill, to the southwest about 120 m south of the coring location. The road now slows the flow of water through the wetland (flow comes from the southeast) however the core site is located far from the road and there was no evidence of disturbance in the wetland anywhere near the coring location. The site had a few centimeters of standing water at the time of coring. Archeological surveys conducted in association with construction of the Ruby Pipeline project along the Nevada-Oregon border found evidence of a rich cultural history including lithics and petroglyphs (Hildebrandt et al., 2016).

## Methods

### *Core recovery*

On December 21, 2020, two overlapping cores (DUF20-A and DUF20-B) were taken one meter apart from an unnamed wet meadow near Dufurrena Ponds in the Sheldon-Hart Mountain National Wildlife Refuge using the Livingstone coring method (Wright et al, 1984). We recovered 6.7 meters of sediment in each core, puncturing what we assume to be the Mazama Ash in the top of core section DUF20-B-L5, at 389-435m depth, spanning ~46cm, which seems reasonable considering the proximity to Crater Lake 280 km to the northwest. Only the upper 2.2

meters were used for this study. DUF20-A was recovered in seven sections and DUF20-B in eight sections. Cores were wrapped in plastic film in the field and placed into 1-m long, pre-split PVC rigid pipe, labeled, then taped securely for transport and storage. Cores were taken to the University of Nevada, Reno Nevada Paleoenvironments Lab and stored at 4°C. The cores can be used to discern a broad record of past vegetation and inform geomorphic changes through palynological study.

*Radiocarbon dating*

A total of 21 samples were submitted for radiocarbon dating. Samples were sieved with deionized water at 250 micron and were sieved at <70µm mesh to identify potential macrofossils (in the larger fragment) and isolate the smaller size fraction (<70µm) for humics. Material was subsampled from a total of 17 sample depths. Macrofossils sufficient for dating were found in five samples and four yielded dates. The dates for all remaining sample depths (13) are on humics. For the four successful macrofossil samples, we also obtained replicate dates on the humics. Samples were stored in glass vials and shipped to the Department of Anthropology radiocarbon prep lab at the University of California Santa Barbara. Here, samples were combusted for $^{14}C$ analysis, and then shipped to the Keck-Carbon Cycle AMS facility at the University of California, Irvine for dating. Age dates were then calibrated and worked into an age model using Bacon (Blauw and Christian, 2011) using Calib 8.2 with the IntCal20 calibration dataset.

*Palynology*

I followed the Faegri and Iversen (1989) methodology, which entails chemical digestion of sediment through a series of acids and bases (HCL, KOH, HF, Acetolysis) to isolate pollen for identification. The exine, or exterior shell of a pollen grain, is highly resistant to biological decay and non-oxidative attack allowing it to survive rigorous chemical treatment while other organic, carbonate and silicate material is removed. All samples were sieved at 150 microns following the KOH treatment to remove large fraction sediments and root material and after acetolysis with 7-micron mesh fabric to remove the small fraction material, further concentrating the material and making slides easier to count. Non-native *Lycopodium* spores were added as a tracer to calculate pollen concentration (Stockmarr, 1971). Each sample was stained with safranin and mounted with silicon oil. Pollen was identified to the lowest taxonomic level possible using the UNR reference collection and the Kapp et al. (2000) published pollen key. The pollen was counted at 400X magnification. A total of 63 pollen samples were counted through the first 2.2 meters of the core. Terrestrial pollen was expressed as a percentage. Aquatic pollen counts were divided by total terrestrial pollen to calculate aquatic pollen percentages. In samples where the aquatic pollen type is more abundant than the total terrestrial pollen count, this results in percentages greater than 100%. Pollen accumulation rate was calculated by dividing total concentration by years in the sample to produce grains$^{-1}$ cm$^{-2}$ yr$^{-1}$. The quantity of grass versus sedge (grass sedge index) was calculated using the formula [(grass-sedge)/(grass+sedge)] with numbers between -1 and 0 representing predominance of grass and numbers between 0 and +1 representing predominance of sedge pollen. In Great Basin wet meadows, when the water table drops 1 m below the surface, wet sedge meadows are replaced with dry grass meadows (Castelli, et al., 2000), and this index is used to help interpret the presence of dry phases (predominance of grass in the index).

*Sediment analysis*

The cores were split and imaged using an I-phone in panoramic mode run along a horizontal track at constant speed. Following imaging, cores were stored in the UNR Palynological walk-in refrigerator at 4 $^{o}$C. Loss on Ignition (LOI) (Dean 1974) was employed to calculate the organic, and carbonate percentages of the core. The process of LOI includes evaporating water from a given sample at 100 $^{o}$C for 24 hours, then burning off all organic material (TOC%) at 550 $^{o}$C for one hour and finally burning off carbonates (TIC%) at 1000 $^{o}$C for one hour. Once the sediments have cooled the material is weighed before and after each step so percentages of water, organics, carbonate and clastic sedimentary material can be calculated. LOI was done every centimeter through the working portion of the core (220 cm). LOI can allow us to discern periods of high moisture and biological productivity (high percentages of organics) from periods of drought (low percentages of organics) as well as acting as a proxy for water level by focusing on the amount of carbonate (Shuman 2003). Depths containing a high carbonate fraction can be indicative of dry conditions while depths containing a high organic fraction can indicate a wetter, more biologically productive environment. LOI can also indicate depositional events (Nielsen et al. 2016).

## Results

*Chronology*

A total of 21 radiocarbon dates were obtained from seeds and bulk sediment throughout the core (Table 1). Ages shown are calibrated ages using the Calib8.2 radiocarbon program with the Intcal20 dataset, and also the median age given in the Bacon age model and used for plotting the pollen and sediment data (Fig. 3).

Table 1. Radiocarbon ages for the DUF20 core given in stratigraphic order. All dating done at the University of California, Irvine AMS laboratory. Cal yr BP median ages calculated using Calib 8.2 with the Intcal 20 dataset., shown with the 2-sigma errors. Bacon age model represents the median calibrated age produced using Bacon (Blauw and Christian, 2011), with the age given for that run depth. Bolded samples represent duplicate dates on macrofossils and humics at the same depth.

| Sample | UCIAMS # | Run Depth | 14C age (BP) | Error ± | Fraction Modern | 2 © min | Cal yr BP median | 2 © max | Bacon Age Model | Material |
|---|---|---|---|---|---|---|---|---|---|---|
| DUF20-AL1-22 | 249516 | 48 | 965 | 15 | 0.8866 | 800 | 850 | 920 | 870 | Humics <70µm fraction |
| DUF20-AL1-36 | 249519 | 62 | 2205* | 15 | 0.7598 | 2150 | 2240 | 2310 | | Humics <70µm Fraction |
| DUF20-AL1-55 | 249520 | 82 | 2650* | 20 | 0.7189 | 2750 | 2760 | 2840 | | Humics <70µm Fraction |
| **DUF20-AL1-58** | **249513** | **85** | **1590** | **20** | **0.8203** | **1410** | **1470** | **1530** | **1430** | **seeds (carex and/or scirpus)** |
| **DUF20-AL1-58** | **249518** | **85** | **1870*** | **20** | **0.7924** | **1720** | **1780** | **1830** | | **Humics <70µm Fraction** |
| DUF20-BL2-35 | 249521 | 106 | 1385* | 15 | 0.8414 | 1290 | 1300 | 1340 | | Humics <70µm Fraction |
| DUF20-BL2-38 | 249522 | 109 | 1345* | 15 | 0.8456 | 1180 | 1290 | 1300 | | Humics <70µm Fraction |
| DUF20-BL2-41 | 249523 | 112 | 1565 | 15 | 0.8229 | 1390 | 1460 | 1520 | 1530 | Humics <70µm Fraction |
| **DUF20-BL2-43** | **249514** | **114** | **1620** | **15** | **0.8171** | **1410** | **1480** | **1540** | **1550** | **seeds (carex and/or scirpus)** |
| **DUF20-BL2-43** | **249524** | **114** | **1710** | **20** | **0.8081** | **1540** | **1590** | **1690** | **1550** | **Humics <70µm Fraction** |
| DUF20-BL2-45 | 249515 | 116 | 1640 | 20 | 0.8156 | 1420 | 1530 | 1570 | 1600 | seeds (carex and/or scirpus) |
| DUF20-BL2-46 | 256324 | 118 | 1690 | 15 | 0.8101 | 1540 | 1570 | 1690 | 1630 | Humics <70µm Fraction |
| DUF20-BL2-47 | 256325 | 119 | 1750 | 15 | 0.8042 | 1590 | 1650 | 1710 | 1650 | Humics <70µm Fraction |
| DUF20-BL2-48 | 242872 | 120 | 2270 | 15 | 0.7539 | 2180 | 2320 | 2340 | 2270 | Humics <70µm Fraction |
| DUF20-BL2-53 | 256323 | 125 | 2285 | 15 | 0.7522 | 2180 | 2330 | 2350 | 2290 | Humics <70µm Fraction |
| DUF20-AL2-38 | 256326 | 141 | 2270 | 15 | 0.7540 | 2180 | 2320 | 2340 | 2390 | Humics <70µm Fraction |
| DUF20-AL2-58 | 256327 | 161 | 2740 | 15 | 0.7112 | 2780 | 2820 | 2870 | 2990 | Humics <70µm Fraction |
| **DUF20-BL3-26** | **256328** | **169** | **3100** | **15** | **0.6799** | **3250** | **3310** | **3370** | **3450** | **seeds (carex and/or scirpus)** |
| **DUF20-BL3-26** | **256322** | **169** | **3180** | **15** | **0.6730** | **3370** | **3400** | **3450** | **3450** | **Humics <70µm fraction** |
| DUF20-BL3-60 | 249525 | 201 | 3980 | 20 | 0.6092 | 4410 | 4480 | 4520 | 4490 | Humics <70µm Fraction |
| DUF20-BL3-79 | 249517 | 219 | 4345 | 20 | 0.5821 | 4850 | 4910 | 4960 | 4900 | Humics <70µm Fraction |

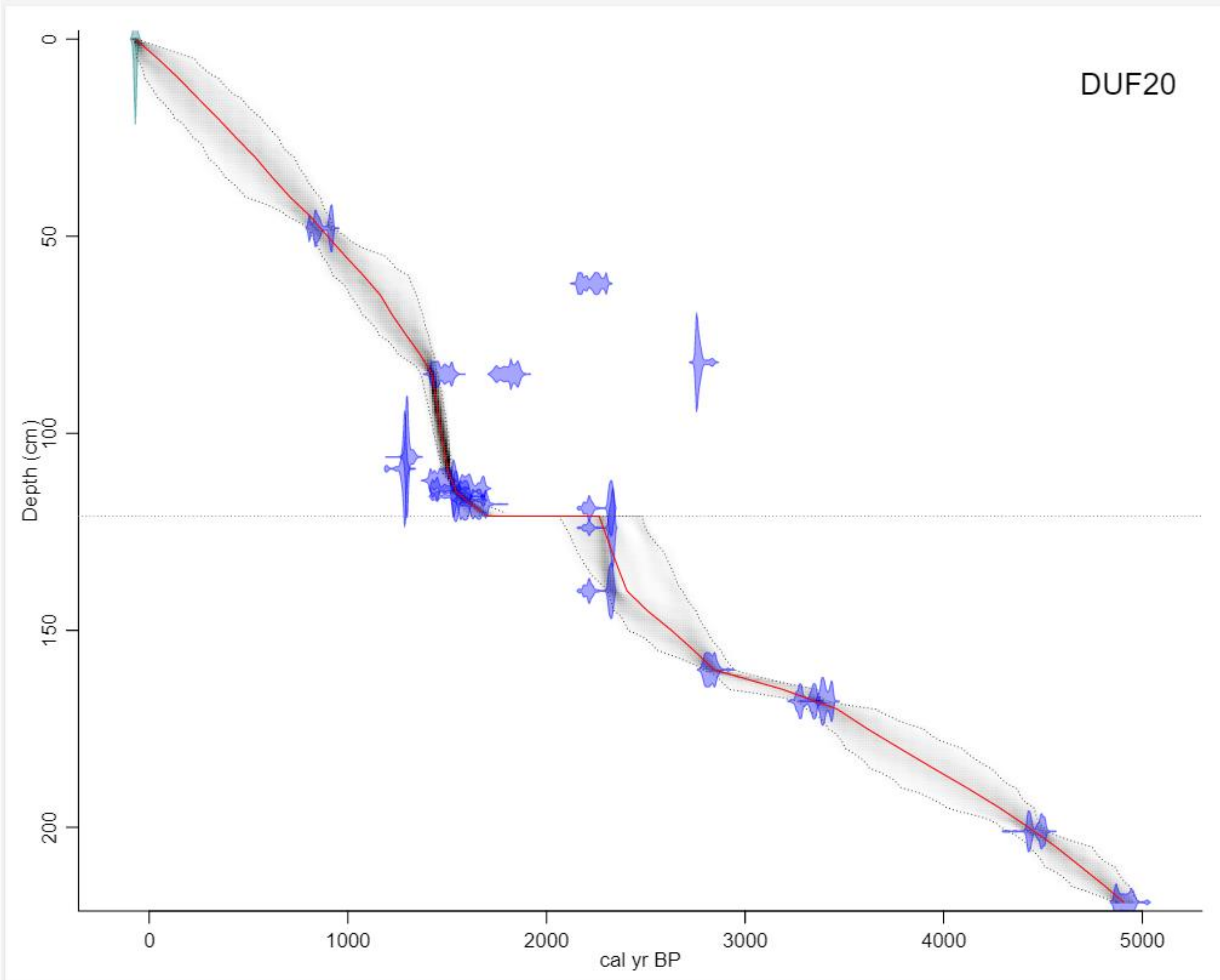


Fig 3. Bacon age model for the DUF20 composite sediment core. Red line represents the median calculated age used to associate with age/depths. Gray cloud represents the 95% confidence interval for median age at that depth. Purple symbols map the 2-sigma probability for each radiocarbon date (Blauw and Christian, 2011).

The youngest date at 48cm depth was 965 yr$^{14}$C ±15 and the oldest age at 219cm dated to 4345 yr $^{14}$C ±20. Four dates were on *Scirpus* and *Carex* seeds and the remainder were on humics from the <70μm size fraction. We obtained humic dates on three strata with macrofossils to test the potential error associated with the bulk humic dates. In two cases (run depth 114 cm and 169 cm) the humic dates are somewhat older than the macrofossil ages, however the dates overlap within the 2-sigma range, suggesting that there is no significant error in the age model from using the <70μm humic fraction from bulk sediments. In one case the age date is several hundred years older, and was rejected as an outlier by Bacon in making the age model. The surrounding environment is primarily basaltic so it is assumed there is little to no carbon reservoir affecting radiocarbon dating at this site. Mixing of older materials within the 1 cm samples used for dating humics likely has resulted in slightly older than expected ages, however as noted, within the range of dates obtained on macrofossils. The Bacon program rejected five dates as outliers in the chronology (Fig. 3).

In our effort to date as closely as possible the potential beginning and end dates for the LHDP we took the highly unusual approach of obtaining radiocarbon ages on continuous or nearly continuous samples across the depths of interest. Thus, we have eight radiocarbon ages across a 13 cm span of core between the depths of 112 and 125 cm. There are no significant age reversals across this span, however some contiguous samples returned essentially identical dates. Of note is the age gap of approximately 600 years between the 120 cm depth (2270 yr 14C) and the 119 cm depth (1750 yr $^{14}C$). We treated this as a sediment hiatus (Fig. 3) with essentially no sediment deposited during this period and potentially some sediment loss through deflation. There was no visual indication of a hiatus in the sediments at this depth (Fig. 4), however these results are consistent with the dating of sediments at three other sites across the Great Basin that are part of the larger project that also had a sediment hiatus across this time period (Mensing, unpublished data).

*Sediments*

A composite core was constructed from DUF20-A and DUF20-B by visually matching core sections in order to remove gaps and disturbance created through the coring process (Fig. 4). Due to the meadow being a relatively productive environment the first ~40 cm of the core are composed of actively growing roots that are difficult to sample, thus the top sample for this analysis was at 44 cm depth, near the first strata of well-humified peat. Below this depth the sediment was mainly organic rich, peat with occasional silt lenses.

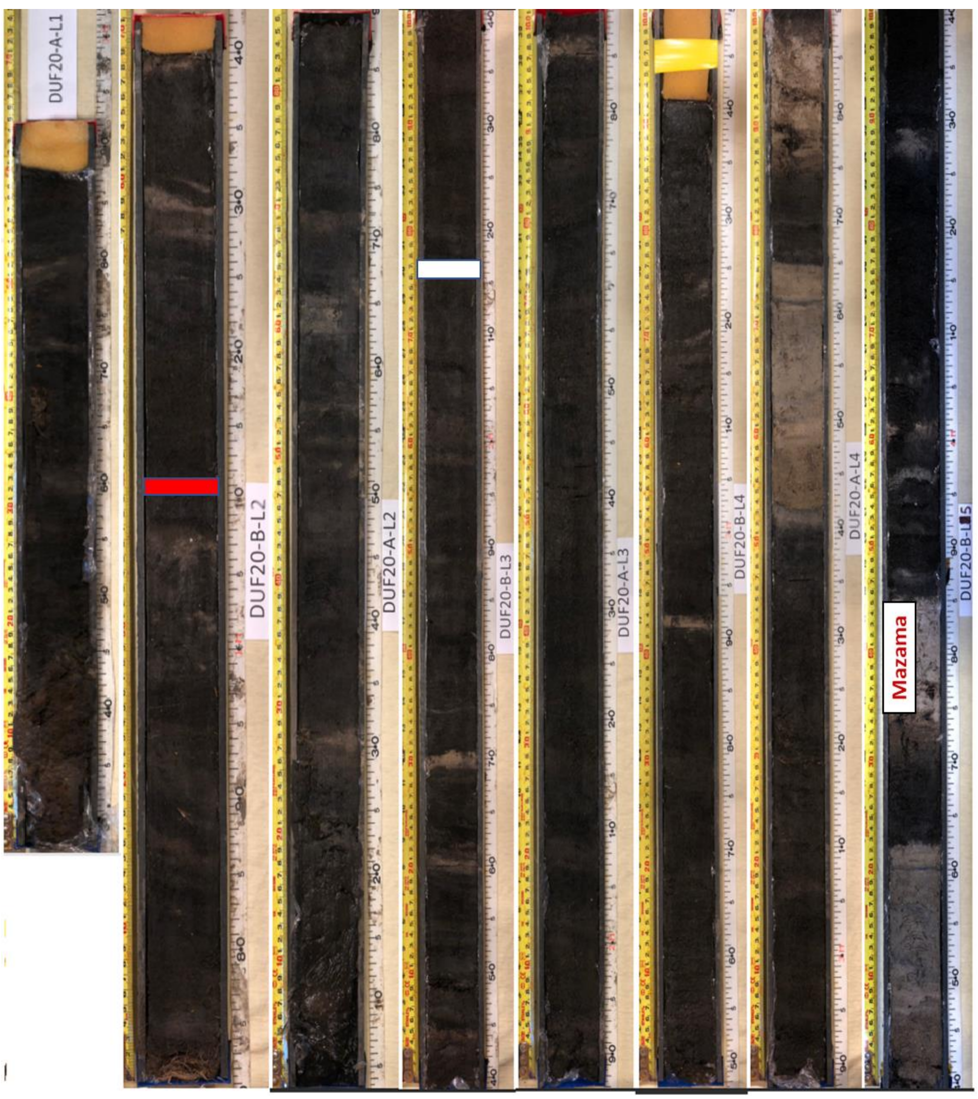

Fig 4. The upper image shows the composite core composed of sections of the two overlapping cores (DUF20-A and DUF20-B) collected at Dufurrena Ponds. Sediments show that there are few visual changes throughout the working portion of the core (top 220cm), stopping at the white bar. The red bar on section B-L2 represents the hiatus in sedimentation seen in Table 1 and Fig 3. The Mazama Ash can be seen in overlapping cores A-L4 and B-L5, spanning 35-45cm in B-L5 on the far right. The lower image shows the master core with core DUF20-A above and DUF209-B below. Red boxes indicate where the composite core moves from DUF20-A over to DUF20-B and then back again down core in order to construct a continuous core without breaks across coring gaps.

Loss on ignition analyses revealed the sedimentological history of the core, showing little organic or carbonate material through the core, especially during the LHDP. The TOC% loosely follows the grass/sedge index without contradicting periods of wet or dry. The little carbonate material that is present is likely a byproduct of the eroding basalt and is not in large enough percentages to indicate anything more about the environment.

*Pollen and non-pollen palynomorphs*

Briem and Mensing counted a total of 63 pollen samples to a minimum of 400 grains per depth apart from three samples counted to a minimum of 200 grains by Mensing due to low accumulation rates. Both researchers counted up to 200 pollen grains on separate pollen slides made from the same concentrate and then cross referenced each other's counts to verify that they were producing equivalent results. A total of 38 pollen and non-pollen palynomorphs (NPP) were identified (Appendix B). Through the portion of interest (the upper 220cm of the core) the terrestrial pollen consists of shrubs, grasses, cattail, and extralocal pine. Within this, nine taxa comprise on average 95% of the pollen sum. Indeterminate pollen was also counted within the terrestrial sum. Aquatic pollen including sedge (Cyperaceae), cattail (*Typha latifolia*) and pondweed (*Potomageton*) were counted and calculated separately from terrestrial pollen because they only grow in the wet meadow and being immediately adjacent to the core site their quantities fluctuate dramatically. Aquatic pollen identified were *Typha angustifolia*, *Typha latifolia*, Cyperaceae, and *Potamogeton.* NPP's included the algae *Botryococcus*, *Pediastrum boryanum*, *Pediastrum cornutum*, *Glomus* and non-pollen identified included trilete type spores.

Three pollen zones were inferred from a dendrogram (Fig. 5) produced using The Past software. The boundary between zones 1 and 2 was inferred from distinct clusters in the dendrogram consistent with major changes in the pollen. We treated the sediment hiatus as the boundary between zones 2 and 3.

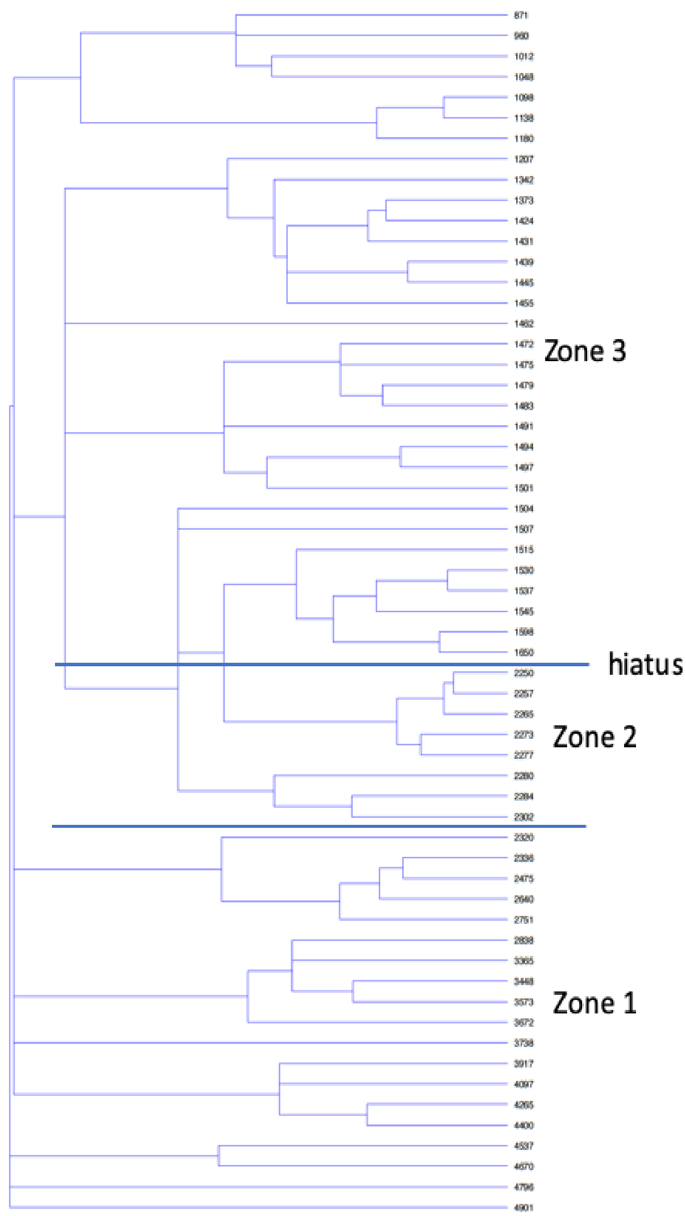


Fig 5. Dendrogram produced with the Past software, used to determine pollen zonation.

Zone 1, 4750-2750 cal yr BP, is constituted by high variability between aquatic and terrestrial pollen with relatively low accumulation rates. (Figs. 6 & 7). Pines, likely blowing in from the Warner Mountains and Pine Forest Mountains, vary from 15-40% during this period. *Artemisia Sarcobatus* and Amaranthaceae are fairly consistent among themselves throughout the entire record. Poaceae varies from 10-80% and Cyperaceae dips down below 100% and goes up to nearly 500% compared to terrestrial pollen.

Zone 2 (2750-2250 BP) represents the beginning of a high, persistent grass phase and a drop in Cyperaceae and *Potamogeton* pollen. The following four samples spanning the short period from 2320 to 2280 represent a brief period with high percentages of sedge and low percentages of grass. The following five samples spanning another short period from 2280 to the beginning of the hiatus at 2250, as indicated by the age model (fig. 3), return to high percentages of grass and low percentages of sedge. There is very little change in shrubs and herbs before the hiatus. The pollen accumulation rate data (fig 7) support the changes in the percentage data.

In Zone 3 as sediment deposition resumes after the hiatus, percentages of Cyperaceae are very high for the period from 1650 to 1500 cal yr BP, ranging from 65% up to 410%. Following this Cyperaceae remains fairly high averaging 85% through the upper section of the core. Percent grass pollen is highly variable, ranging between 6% and 55%, with short intervals of very high percentages at 1500 cal yr BP, 1460 cal yr BP, and 1200 to 1100 cal yr BP. Much of the literature for the Late Holocene suggests wetter conditions, (Grayson, 2011) however the resolution of many of the early studies is not comparable to the detail of this record. In addition, there is a large spike in the pollen accumulation rate that spikes and then falls immediately after the hiatus.

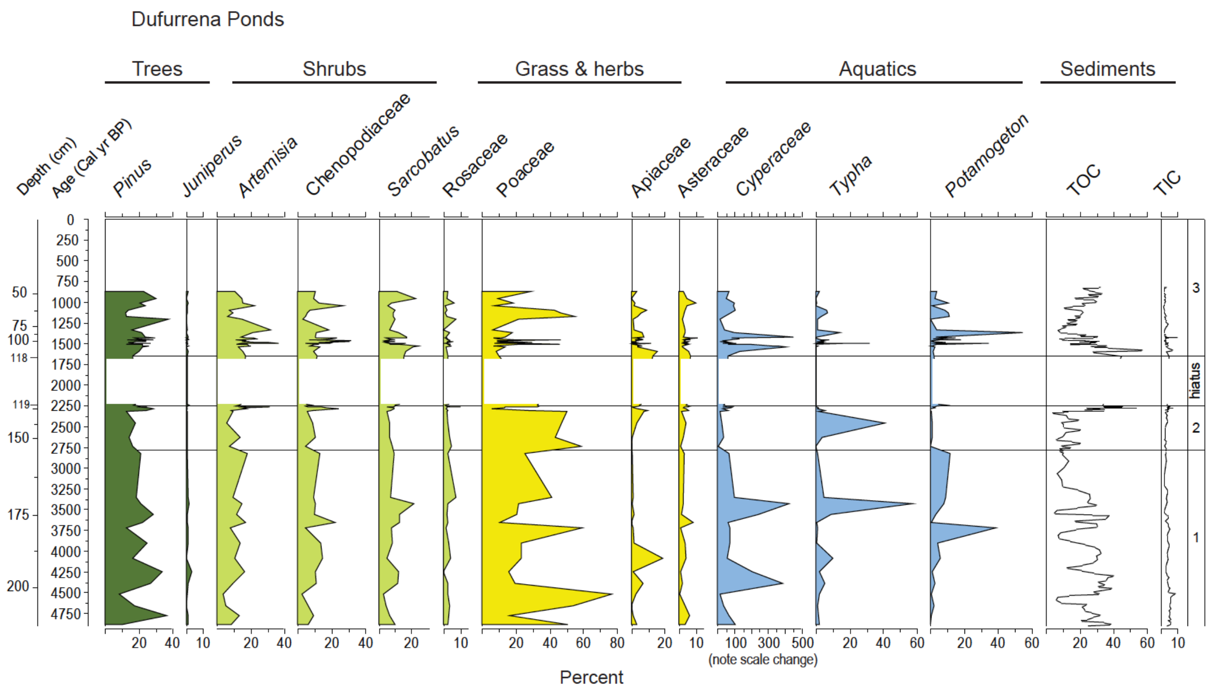


Fig 6. Pollen percentages for the most abundant terrestrial pollen types, aquatics and algae. TOC%'s and TIC% can be seen at the right of the figure.

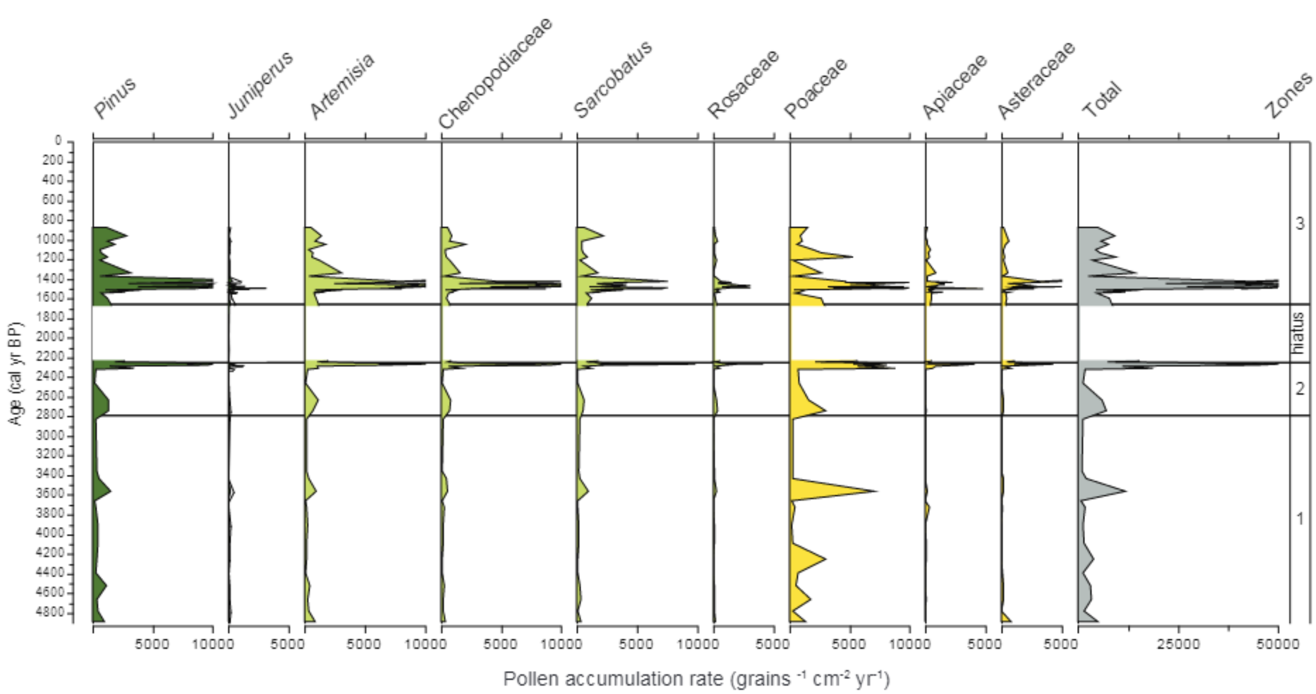

Fig 7. Pollen accumulation rates for the pollen types shown in Fig. 6 as well as total accumulation rate for all terrestrial pollen.

## Discussion

### *Evidence for the LHDP*

The Late Holocene Dry Period (LHDP) was proposed as a ~1000-year period of below average rainfall from ~2800 to 1850 cal yr BP spanning much of north-central Nevada from the eastern Sierra Nevada across the state and into the Bonneville Basin (Mensing et al., 2013). They referred to this as the longest persistent dry period within the Late Holocene, however the exact timing and geographic extent still remained uncertain. The pattern of dry sites appeared to conform to the dipole pattern of ENSO-related precipitation variability across the west (Redmond and Koch, 1991; Cayan and Redmond, 1994; Dettinger et al., 1998; McCabe et al. , 2008; Wise 2010), with sites to the south of the dipole recording dry climate during the LHDP, but sites to the north recording wet climate across the same period (Fig 8.) This pattern represents the northern position of the jetstream.

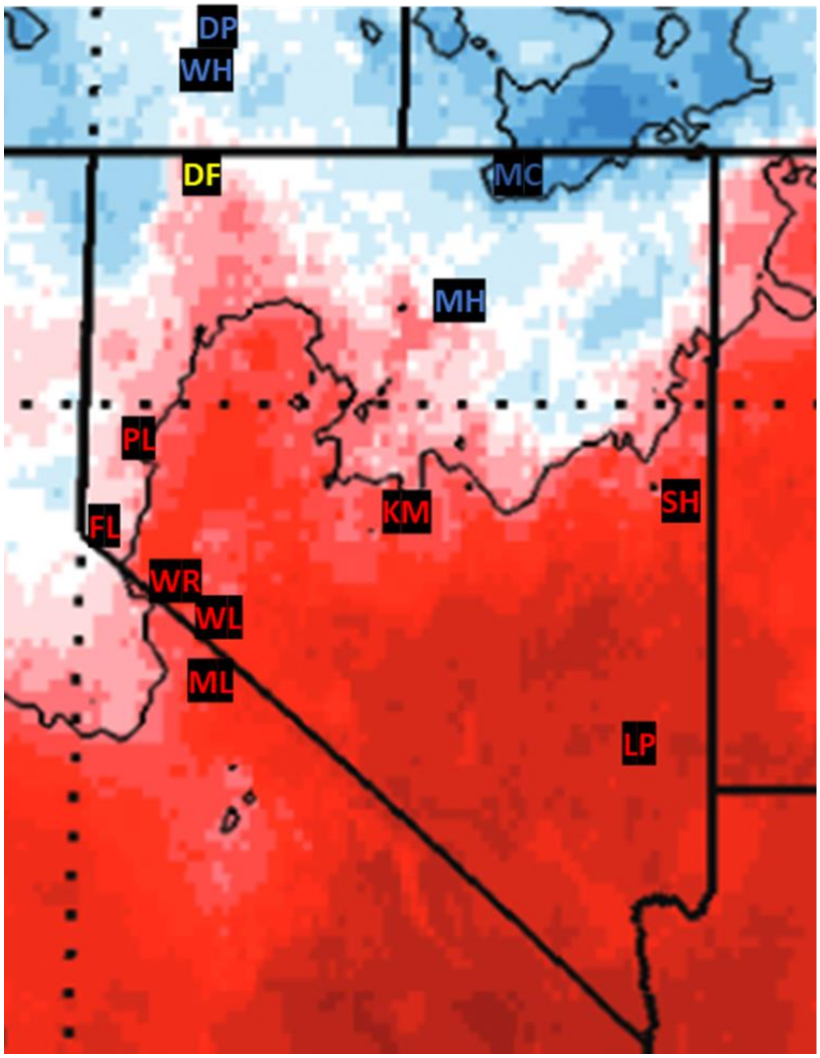


Fig 8. Sites discussed and presented in Fig. 9. Red letters indicate previous studies with evidence for dry climate during the LHDP. Blue lettering represent studies with evidence for wet climate during the LHDP, and yellow lettering represents the site for this study.

Recent research supports the presence of the LHDP in Nevada. In the Wassuk Range just west of Walker Lake, low-radial growth and recruitment rate of limber pine (*P. flexilis*) is recorded between 3050 and 1800 cal yr BP (Millar et al. 2019). The period from 1950 to 1800 cal yr BP experienced the lowest growth rates for the 4,000-year record and represents ~150 years of extreme drought (Fig. 9). This was followed by a distinct cool period with several centuries of high growth rates lasting until about 1550 cal yr BP, which is also documented by rising lake levels seen in the lake transgression from the Marina Low Stand at Mono Lake (Stine 1990) and rising lake levels at Walker Lake (Adams, 2007). The growth rates in the Wassuk Range limber pine at the end of the LHDP (1950 to 1800 cal yr BP) are less than those of those recorded in the much more widely cited Medieval Climate Anomaly (MCA) between 1050 and 850 cal yr BP, and 750 to 600 cal yr BP, suggesting that the most extreme drought of the LHDP likely exceeded that of the MCA.

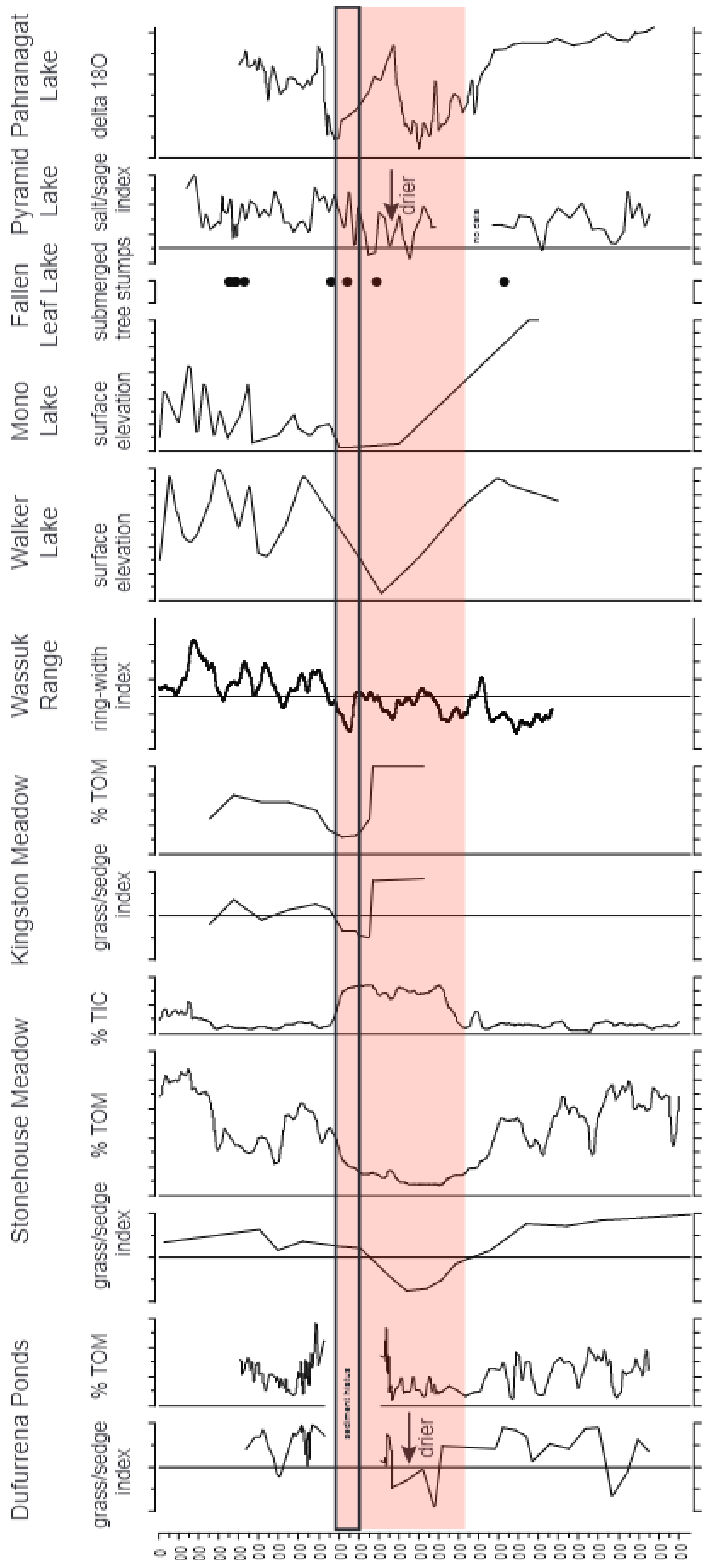
Pahranagat Lake
delta 18O
Pyramid Lake
salt/sage index
drier
no data
Fallen Leaf Lake
submerged tree stumps
Mono Lake
surface elevation
Walker Lake
surface elevation
Wassuk Range
ring-width index
Kingston Meadow
% TOM
grass/sedge index
Stonehouse Meadow
% TIC
% TOM
grass/sedge index
Dufurrena Ponds
% TOM
sediment hiatus
grass/sedge index
drier

Fig 9. Summary figure showing Dufurrena Ponds (DP) in relation to previous studies in the Great Basin. The pink band spans the full duration of the LHDP from 3100 to 1800 cal yr BP following Millar et al., 2019. The open black box represents the driest time during the LHDP, defined by extreme low tree growth (Millar et al. 2019). The grass/sedge index shown for all pollen studies represents [(%grass-%sedge pollen)/(%grass+%sedge pollen)]. Negative values represent dry conditions. %TOM (total organic matter) is a general measure of productivity, with lower percentages typically representing lower meadow productivity. High %TIC (total inorganic carbon) at Stonehouse Meadow (Mensing et al., 2013) is a result of preservation of shelly material due to dry conditions.  Kingston Meadow (Mensing et al., 2008) has negative grass/sedge index values during the driest period of the LHDP. Radial growth (ring-width index) is at its lowest for the last 4000 years during the LHDP at the Wassuk Range (Millar et al., 2019). Mono Lake (Stine 1990) and Walker Lake (Adams 2007; Puckett, 2021) are both at extreme low stands during this time.  Submerged tree stumps at Fallen Leaf Lake (FL) (Kleppe et al., 2011) coincide with the hiatus of the LHDP, The saltbush/sage index at Pyramid Lake (PL) demonstrates drying at the same time as DP (Mensing et al., 2013), (Mensing et al., 2004).. $^{18}$O levels at Pahranagat Lake (PL) (Theissen et al., 2019) show bimodal drying during the LHDP.

In the Dufurrena Pond record, between 2250 and 1650 cal yr BP, there is a clear hiatus in sedimentation. Continuous dating of sediments found that from the 119 cm depth to the 120 cm depth, there is a 600-year gap in age dates. This is longer than the period identified by Millar, 2019 but is concurrent with the timing of the most severe drought identified in the Wassuk Range limber pine record as well as the lowest known surface elevations for Mono Lake and

Walker Lake (fig 9). The commonly accepted lake level curve for Walker Lake (Adams 2007, Adams and Rhodes 2019) constructed primarily from above water lakeshore features shows a lowered lake at 2000 cal yr BP, but age and depth are unknown. Recent underwater archaeology at Walker Lake using a combination of investigation by scuba divers as well as sub-bottom profiling using ground penetrating radar found submerged lakeshore features at 1180m (Puckett, 2021). Radiocarbon dating of fish bones at this depth returned an age of 2290-2160 cal yr BP (2-sigma range). Following decades of water extraction, the modern surface elevation is ~1190 m. The date on the submerged shoreline recorded by Puckett (2021) suggests that during the LHDP, Walker Lake may have been 10m below the modern level and as much as 20 m lower than the lowest surface elevation proposed during the MCA droughts.

Although less well dated, the pollen and percent organic material at Kingston Meadow in the Toiyabe Range of central Nevada (Mensing et al, 2008) show a distinct dry period between 2000 and 1800 cal yr BP (fig 9). Woodrat midden data from the site show low species diversity at this time, potentially from drying of riparian habitats (Tausch, unpublished data). A new $^{18}$O record from Lower Pahranagat Lake in south central Nevada also suggests dry climate between 2000 and 1800 cal yr BP (Theissen et al. 2019) suggesting that the geographic range of this dry period was extensive.

The hiatus in sedimentation at Dufurrena Ponds between 2250 and 1650 cal yr BP most likely resulted from the absence of deposition of new sediments, and likely deflation of some existing sediments associated with a drying of the meadow due to prolonged dry climate. This period is inferred as the driest time of the LHDP.

Dufurrena Ponds also has evidence for drought during the first part of the LHDP. The earlier drought of the LHDP does not appear to have been as severe, but was more prolonged. As previously noted, the Wassuk Range tree ring record has below average growth rates for much of the period between 3050 and 1950 cal yr BP during the earlier part of the LHDP. The grass-sedge index is used as a proxy for drought based on the principle that sedge (particularly *Carex nebrascensis*, one of the most common sedges in wet-meadows in the Great Basin) disappear when water tables fall below 30 cm depth, and as water table continue to decline, they are replaced by dry grass dominated meadows (Castelli et al., 2000). The grass-sedge index at Dufurrena Ponds is negative (predominated by grass pollen) between 2750 and 2330 cal yr BP. This is inferred as a multi-century dry period, although given that sediments were preserved, not as extreme as the late LHDP. Percent organic matter is also low at this time, supporting the interpretation of drier climate and reduced production as well as potential oxidation of organic matter. The timing and magnitude of this dry phase is consistent with the record at Stonehouse Meadow (fig 8) in eastern Nevada, used by Mensing et al. (2013) to originally infer a widespread LHDP.

*Wet phases during the LHPD*

Contrary to what Mensing et al. (2013) hypothesized based on the Stonehouse Meadow record, the entire milennia between ~2800 and 1800 cal yr BP does not appear to have remained universally dry. The Wassuk Range limber pine record shows periods of average tree growth between ~2750 and 2600 cal yr BP and again between ~2150 and 1950 cal yr BP. The Lower Pahranagat Lake record has what appears to be a wet phase between 2400 and 2000 cal yr BP. The Dufurrena Pond pollen record also shows a period of return to sedge dominated wetland between 2320 and 2280 cal yr BP before grass once again begins to predominate the record. The evidence suggests that similar to the MCA, the LHDP has two dry phases with a wet phase in the middle. These could be distinct and separate dry phases with potentially different causes, or one prolonged dry phase with a weakening of drought conditions in the middle. Regardless of the cause, all of the sites mentioned above demonstrate periods during the LHDP where drying was not as severe.

*Dipole and Geographic Extent/Potential Climate Drivers*

In the Northern Great Basin virtually all precipitation is received via the jet stream during the winter months (Dec-Feb). The sites in this study are too far North to be impacted by the North American Monsoon. Depending on the position of the jet stream the Pacific northwest will be wet while the American southwest will be dry and vice versa. LHDP site selection is largely based on this dipole figure (Wise, 2010) (Fig. 8) indicating that when the southern Great Basin is dry the northern portion is wet, with a narrow zone of ambiguity running through north/central Nevada. The figure from Wise (2010) shows correlation coefficients between Jun-Nov SOI and Oct-Mar precipitation for the period 1926-2007. Negative correlations are shown in red and positive correlations in blue. Depending on whether ENSO is in the El Nino or La Nina phase one of the regions will be wetter than normal while the other is dryer than normal. Positive Southern Oscillation Index (SOI) conditions (La Nina) facilitate a more northerly storm track, because the Aleutian low is weakened, resulting in dryer conditions in the US Southwest and wetter conditions in the Pacific Northwest. Although the spatial pattern of precipitation response during the LHDP, with dryer sites located in areas that are normally dry during La Nina and wetter conditions in areas that are wet during La Nina. This is not to say that ENSO was the mechamism responsible for the LHDP, however any mechansim that can result in a long-term weakening of the Aleutian low that persists for long periods of time could be a possible explanation for the LHDP. The results of this study lend further support for a strong N-S dipole relationship in western North America related to the strength of the Aleutian low and the position of the storm track. This further supports earlier work by Cook et al. (2018) that colder temperatures in the tropical Pacific, similar to those that exist during La Nina conditions, could be a potential explaination for large-scale megadroughts, like the LHDP, in the geologic past.

*1200 BP drying*

~1200 BP the DP site shows drying in the grass/sedge index that is consistent with low tree count and radial growth shown at WR (Millar et al., 2019). This drying is not observed at other sites but as more study is done, could be proven to be a discrete drying period from the MCA and the LHDP.

## Conclusions

Evidence for Late Holocene drying can be found in certain areas within the Great Basin, with the strongest signal found at the southern sites discussed in fig 9. Apart from Dufurrena Ponds, sites in the northern Great Basin (fig 8) do not demonstrate this, and some even show a wetter signal during this time. Though Dufurrena Ponds are in the northern Great Basin, they follow the drying that is seen in the south which is consistent with modeling done by Wise (2010), suggesting that this ‘see-saw’ type dipole could have stayed in a semi-permanent position in the past. The potential for such a persistent precipitation pattern in the future could have significant impacts on populations within the southwestern United States through multi-centennial dry periods.

Our effort to generate new palynological records in north-central Nevada, an area of predominantly basaltic bedrock, was frustrated by low sedimentation rates and poor pollen preservation (fig 2) (Appendix A). Whether this is a result of the weathering process of the rock, or simply a region of very low productivity is unclear, however this is still an important region to try to obtain paleoecological records to determine the full geographic extent of the northern limits of the LHDP. New records in this region could potentially help clarify the conclusions of this study.

The results from this study further strengthen the dipole hypothesis for the LHDP in the Great Basin. We suggest that the main driver is reduced precipitation associated with a shift in the jet stream storm track, similar to what Cook et al. (2018) suggested as a potential mechanism to explain the Medieval Climate Anomaly. However further studies that help understand causal mechanisms for such a prolonged dry period are still needed.

*Acknowledgements*

This project would not be possible without funding through the National Science Foundation (NSF GSS award 1636519). Permission was granted to core various sites through Owyhee Indian Reservation and Barrick Gold and Sheldon Hart Mountain National Wildlife Refuge. Undergraduate students Karl Oldperson, Destiny Pete, Destiny, and Jordan Palli all contributed to recovering various cores. Data and analyses from Scott Mensing, Adam Csank and Theo Dingemans were critical to this study.

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**Appendix A**

*Additional coring sites*

Tomera Ranch is located at 40 30’ 00” N 116 07’ 53” W at an elevation of 5084’. This is a wet meadow complex in a shallow basin/valley. The core has an interesting potential dry period but needs to be studied further. Another working site is at Gund Ranch located at 39 54’ 12” N 116 35’ 27” W at an elevation of 5676’. This core was taken from a large meadow complex in Grass Valley. This is a wide valley with inflow through the alluvial fans. The meadow is at the edge of an extensive playa. Two sections of the core could be representing dry periods of interest within the LHDP. The final working site is at Potts Ranch located at 39 04’ 57” N 116 38’ 37” W at an elevation of 6653’. This is a wet meadow complex in the very large and wide Monitor Valley.

*Owyhee Reservoir (42°02'46.3"N 116°09'39.0"W)*

Owyhee Reservoir is located on the Idaho/Nevada border on the Duck Valley Reservation. Two coring expeditions were taken in July 2018 and December 2018. The region is located on the massive Steen Mountain Basalt Flows (Jarboe et al. 2008) that erode very slowly, resulting in extremely slow sediment rates in the basin. On the first expedition we cored using the conventional Livingston method on a barge in the middle of the reservoir with minimal recovery due to dense, clay rich sediments. The second expedition we used a modified Livingston (see *coring equipment*) on the margin of the reservoir with the same lack of success. The sediments in the region are clay rich, but poor in pollen concentration and preservation. Additionally, the sedimentation rates are too slow to capture the resolution of this study. The dates are ....

*Hot Lake*

Located near Willow Creek, geothermal activity and sedimentary mixing made this site unviable. The site itself is an extensive marsh area with a lake in one of the valleys north of Interstate-80 near the Snowstorm Mountains. The water that flows in is presumably from a combination of springs and runoff through the large alluvial fans to the north and west. The core taken from the lake looked massively re-worked and was rejected based on appearance alone. Another core was taken from the meadow, but pollen preservation was only good down to about 40 cm. Below that it was intermittent, with some samples being countable and others not. Age control suggested that 40 cm depth was only about 500 cal yr BP, so that the site didn't capture the LHDP. In places there was no sediment in the lake likely because the spring flow kept it all suspended and then it would flow towards the edges where it settled. We took a sediment core from the edge of the lake where the sediments were considerably thick, but as noted, likely all simply resuspended from the central deeper water.

*Willow Creek*

Willow Creek meadow is a tributary of the Humboldt River, running through the Upper Humboldt Plains north of Elko, NV. None of the high elevation mountain ranges in the region feed Willow Creek as it is fed by the Tuscarora Mountains which are less than 2500 m, which should make the site relatively sensitive to an extended dry period. This mountain range has an influence on the pollen assemblages found in the sediment core. The core was recovered from a meadow immediately south of Willow Creek Reservoir, west of Tuscarora, NV. The meadow is watered by a seep in the basalt that has caused minimal channelization. The elevation of the site is approximately 1600 meters. The area has been grazed by cattle and the soft surface sediments have been disturbed. The sediments of interest are a minimum of 20cm below the surface and safe from cattle grazing. This core was rejected due to poor age constraints and low pollen concentrations. After 20cm the pollen concentration got progressively worse until there was nothing to count.