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Understanding Nevada's Current Drought in Historical and Paleoclimatic Context

STEPHANIE A. MCAFEE, Department of Geography and Nevada State Climate Office, University of Nevada, Reno, 1664 North Virginia Street, Mail Stop 0154, Reno, NV 89557 (smcafee@unr.edu)

ADAM Z. CSANK, Department of Geography, University of Nevada, Reno, 1664 North Virginia Street, Mail Stop 0154, Reno, NV 89557 (acsank@unr.edu)

MATHEW LACHNIET, Department of Geoscience, University of Nevada Las Vegas, 4505 S. Maryland Pkwy, Las Vegas, NV 89154 (Matthew.Lachniet@unlv.edu)

SCOTT A. MENSING, Department of Geography, University of Nevada, Reno, 1664 North Virginia Street, Mail Stop 0154, Reno, NV 89557 (smensing@unr.edu)

CONSTANCE I. MILLAR, USDA Forest Service, Pacific Southwest Research Station, 800 Buchanan St., Albany, CA 94710 (constance.millar@usda.gov)

DAVID RHODE, Desert Research Institute, 2215 Raggio Pkwy, Reno, NV 89512 (dave.rhode@dri.edu)

DAVID HURST THOMAS, Division of Anthropology, American Museum of Natural History, Central Park West @ 79th Street, New York, NY 20024 (thomasd@amnh.org)

ABSTRACT

Nevada lies in one of the driest parts of North America. The region has long grappled with droughts and also with extended periods in which the already dry climate aridified for decades or centuries. Here we place Nevada's most recent statewide drought (2020 – present) in the context of historical, archaeological and paleoclimate records dating back through the Mid-Holocene. The current drought is distinct from historical droughts that impacted the state in the 1930s, 1950s, and 1970's and 1980s. It is notably warmer than droughts of the 20th century and more spatially extensive than any of these, although the 1930s drought also impacted much of the West. The early 2020s drought is also embedded within a two-decade long dry period, raising important questions about whether it is (1) drought, a relatively short period of abnormal dryness; (2) megadrought, a longer and typically more severe period of unusually dry conditions; (3) the manifestation of aridification, a shift toward a generally drier climate because of long-term precipitation declines

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and/or warming; or (4) some combination of the three. A broader view suggests that at least some aspects of drought since 2020 may not be unique. Paleoclimate evidence from cave deposits, lake and meadow sediments, animal middens, dead wood and tree rings indicate that Nevada and much of the western United States experienced decadal and centennial long dry periods in the Middle Holocene (5000 – 7000 years ago), the Late Holocene, (1800 – 3100 years ago), during the Medieval Climate Anomaly (1000 – 650 years ago) and again 600 – 500 years ago. The archaeological record shows that Indigenous Nevadans responded by repeatedly adapting to changing paleoenvironmental conditions. However, some key questions about fine-scale temporal and spatial variability in the experience of drought remain. Limitations in the spatial, seasonal and temporal resolutions of climate reconstructions—and in the observational record—may obscure the evidence for short or seasonally specific wet periods within longer dry periods or spatial variability in precipitation. Nonetheless, proxy and archaeological evidence from the last 10,000 years shows that understanding and responding to drought requires viewing drought on these time spans with an appreciation for the details that appear in modern observations.

Keywords: drought, paleoclimate, proxies, archaeology

1. INTRODUCTION

Drought is both a regular part of Nevada's climate and one of the state's most significant climatic challenges. The State's 2018 Enhanced Hazard Mitigation Plan lists it as the sixth highest risk to Nevada (Division of Emergency Management, 2018), and the State Climate Initiative identifies drought as one of the top five climate impacts to the state (Nevada Climate Initiative, 2020). Since 1980, the state has experienced thirteen drought and extreme heat events with damages of over $1 billion each, making drought the most frequent kind of high-impact weather (National Centers for Environmental Information, 2022). Studies have suggested that recent dry years may be part of an "emerging megadrought" (Williams et al., 2020). In 2021 Governor Sisolak acknowledged that aridification, the long-term shift to a drier climate, is likely to magnify drought impacts (Nevada, 2021). The current severe drought—which has occurred within a two-decade period of generally dry conditions and rising temperatures—has only added to the substantial, often under-appreciated, nuance in the development, expression, and impacts of drought. Understanding the broader context of the current drought in relation to the historical and paleoclimate record is critical for managing potential future impacts of drought in a changing climate.

The American Meteorological Society defines drought as "a period of abnormally dry weather sufficiently long enough to cause a serious hydrological imbalance" (American Meteorological Society, 2019). A definition posed by Redmond in 2002 (p. 1144) is "insufficient water to meet needs." Both definitions speak to a uniformly understood characteristic of drought, that is, negative consequences caused by a lack of moisture. But even between these two commonly referenced descriptions of drought, there is disagreement. The American Meteorological Society's definition implies that drought must be driven by climate variability and that a return to normal or wetter conditions is expected. Redmond's definition allows a broader range of drivers, including overuse of water by humans, and allows for the possibility that a place could be in drought all of the time. As Van Loon (2015) points out, these definitions raise additional questions, such as, "What are normal conditions?" (p. 361), a question that becomes even more challenging over longer periods of time when baseline climate varies. Further complications arise because the length of drought, seasonality and phase of precipitation can influence how and even if negative consequences are experienced.

Nevada's two largest water providers, the Southern Nevada Water Authority and the Truckee Meadows Water Authority, both store sufficient water to meet customer demand over droughts lasting longer than a year. In contrast, some kinds of vegetation may begin to suffer after a relatively short period of abnormally dry conditions, especially if temperatures are high. Because drought can develop in multiple ways and can have a variety of impacts, there has been a proliferation of more specific drought definitions, from snow drought which describes a drought that develops because the snowpack is lower than normal (Harpold et al., 2017) to megadroughts, which last for decades (see Meehl and Hu, 2006; Ault et al., 2016; Cook et al., 2016). The growing range of terms used to define drought speaks to the fact that drought has always been a nuanced climate hazard. Climate change and particularly aridification make evaluating drought and its impacts even more challenging. However, the historical, archaeological and paleoecological records provide valuable information about how drought can impact Nevada's hydrology, ecology, and human communities and activities. This paper provides historical, archaeological and palaeoclimatological context for the current drought and evaluates how these records can provide insight on current and future droughts.

2. HISTORICAL DROUGHTS

In the historical record, we consider droughts to be initiated by two years in which the September Palmer Drought Severity Index (PDSI) is ≤ -1 and to end with at least two years in which the PDSI exceeds 0. The PDSI integrates precipitation deficits and temperature and typically represents longer-term droughts (6 months or longer, although it does vary regionally and recent months are weighted) (McKee et al., 1993; Vicente-Serrano et al., 2010). We also use the average summer (June – September) PDSI as a secondary drought indicator. For simplicity, we use climate division average indices based on a 5km-resolution gridded product derived from weather station data (Vose et al., 2014). Over the most recent two decades, we also use a third tool to assess drought – the US Drought Monitor. The US Drought Monitor (USDM) is a weekly product that assesses multiple lines of drought information including precipitation, temperature, estimates of soil moisture, wildland vegetation and agricultural condition, and water resources (Svoboda et al., 2002). The El Niño-Southern Oscillation (ENSO) is commonly associated with precipitation variability across the western US. In far southern Nevada, El Niño winters are often wetter than normal and La Niña winters are often dry. Across the rest of the state, ENSO has little consistent influence on cool-season precipitation (Wise, 2010; Ormerod and McAfee, 2017). We use the Multivariate ENSO Index (MEI) provided by NOAA (https://psl.noaa.gov/enso/past_events.html) to define El Niño and La Niña years.

Nevada has four climate divisions—Northwestern, Northeastern, South-Central and Extreme Southern. Climate division averages may not accurately represent all parts of that division (Figure 1). This is due partly to real spatial variability across climate divisions and partly to the underlying station network which is sparse and often not representative of the landscape. Nevada covers a large, topographically and climatically diverse area, yet it has the lowest weather station density in the lower 48 US states (Brown et al., 2016). Existing weather stations were designed and sited for specific reasons largely focused on human activities (e.g., water resources management, irrigation planning). As a result, weather stations are commonly located in lower elevations or in specific settings in higher elevations (McAfee et al., 2020). These inadequacies in the representativeness of the network, as well as errors in the data (see Goodison et al., 1998; Oyler et al., 2015), and attempts to correct errors or consolidate data, can propagate into gridded products, obscuring spatial diversity in the actual weather (Strachan and Daly, 2017; McAfee et al., 2019; Pierce et al., 2021). Consequently, climate patterns (Strachan and Daly, 2017) and spatial differences in trends can be more challenging to characterize in the observational record (McAfee et al., 2019).

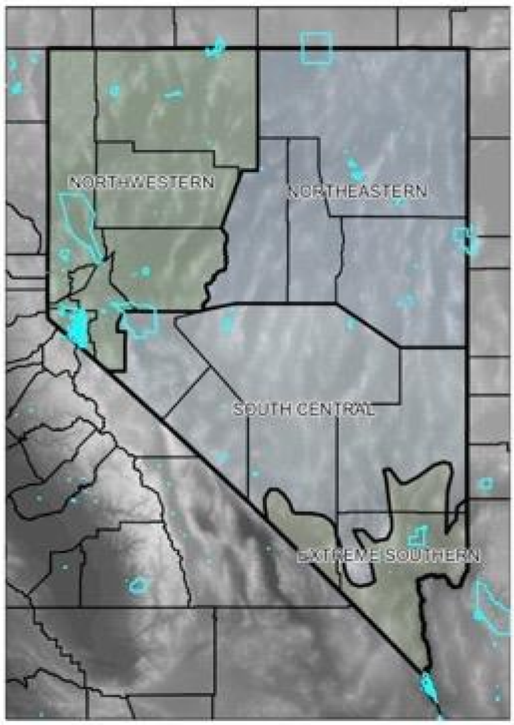

Figure 1 Map of Nevada outlining the four climate divisions (blue and green shading). Tribal Land (cyan) and county (black) boundaries are shown over the 800-m elevation map underlying PRISM climate data. Lighter colors indicate higher elevations.

Nevada has had multiple droughts since the late 19th century when weather station observations became widespread enough for reliable use. Although it is not unusual for most of the state to experience drought, there are typically regional differences. Parts of the state experienced droughts in the 1920s-1930s, the 1950s, the 1970s, the 1980s, the early 2000s, 2012-2015/16 and again beginning in 2020 (Figure 2). Recent droughts have been among the most severe in terms of magnitude. They have also been broken by shorter wet periods than earlier droughts, leading some to consider the entire two decades since the start of the 21st century the Millennium Drought (Wheeler et al., 2022).

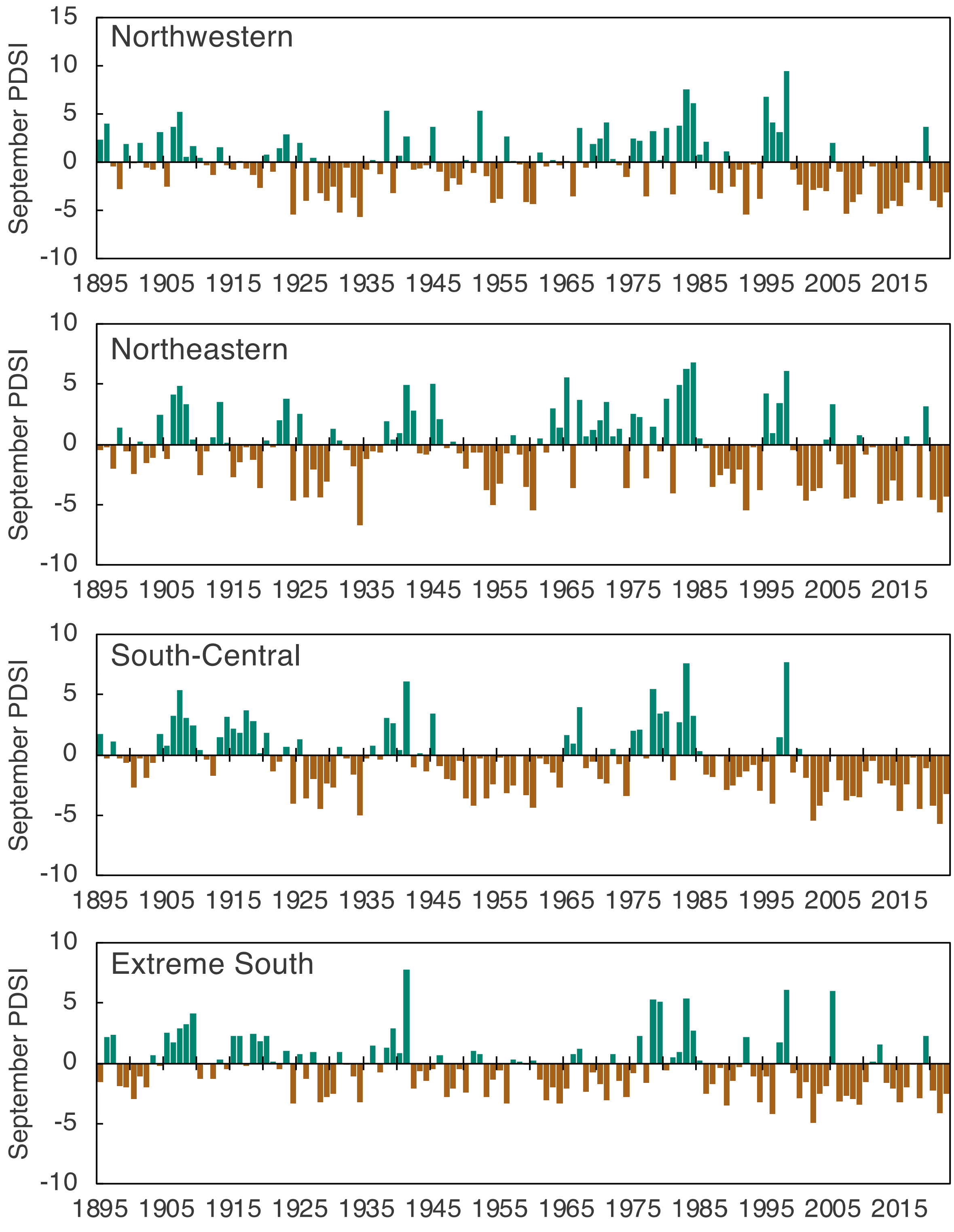

Figure 2 Time series (1895-2022) of the September Palmer Drought Severity Index (PDSI) provided by NOAA Climate at a Glance for each climate division. Positive values shown in green indicate wetter than normal conditions. Negative values shown in brown indicate drier than normal conditions. Comparison of September, June – September, and June PDSI values for each climate division are shown in Supplemental Figure1.

2.1 The 1920s and 1930s. The Dust Bowl in Nevada

Although the Dust Bowl or the 1930s is often thought of as impacting the Plains states, much of the western US was in drought between the 1920s and the late 1930s. In Nevada, this drought was most prominent in the northern part of the state. Northwestern Nevada met the criterion for drought in water-years 1918-1921 and again from 1926-1939. Northeastern Nevada was in drought from 1915-1921, 1926-1929 and 1933-1937, and South-Central Nevada from 1926-1937. Extreme southern Nevada was not as impacted during this window, with drought only from 1928-1934. These droughts were of great concern to local water and resource managers (Hardman, 1968). Because of this concern and the general lack of instrumental climate records available at the time, it drove one of the first studies to use paleoclimate data to contextualize drought (Hardman and Riel, 1936).

In general, the 1920 to 1930s drought was both dry and warm with average water-year (WY, October – September) temperatures above the 20th century mean (Figure 3). The drought started earlier, lasted longer, and was more severe in northern Nevada than elsewhere in the state. Schubert et al. (2004) and Cook et al. (2011) used modeling approaches to indicate that La Niña-like conditions and higher Atlantic sea-surface temperatures (SSTs) likely drove the 1930s drought. Neither analysis, however, shows a robust response in simulated precipitation over Nevada during the core drought years (1932-38 or 1929-40, depending on the study). Hoerling et al. (2009) concluded that SSTs had little influence on the development of the 1930s drought, and the MEI does not indicate persistent La Niña or El Niño events between 1926 and 1939. Moreover, drought in Nevada starts earlier, with the three northern climate divisions shifting into drought by WY 1926. It is notable that La Niña conditions did develop in WY 1934, still the warmest water year on record in Northwestern and Northeastern Nevada. Cook et al. (2009) determined that reduced vegetation and increased atmospheric dust flux as a result of soil degradation pushed the spatial pattern of the 1930s drought further north than a model forced by SSTs alone.

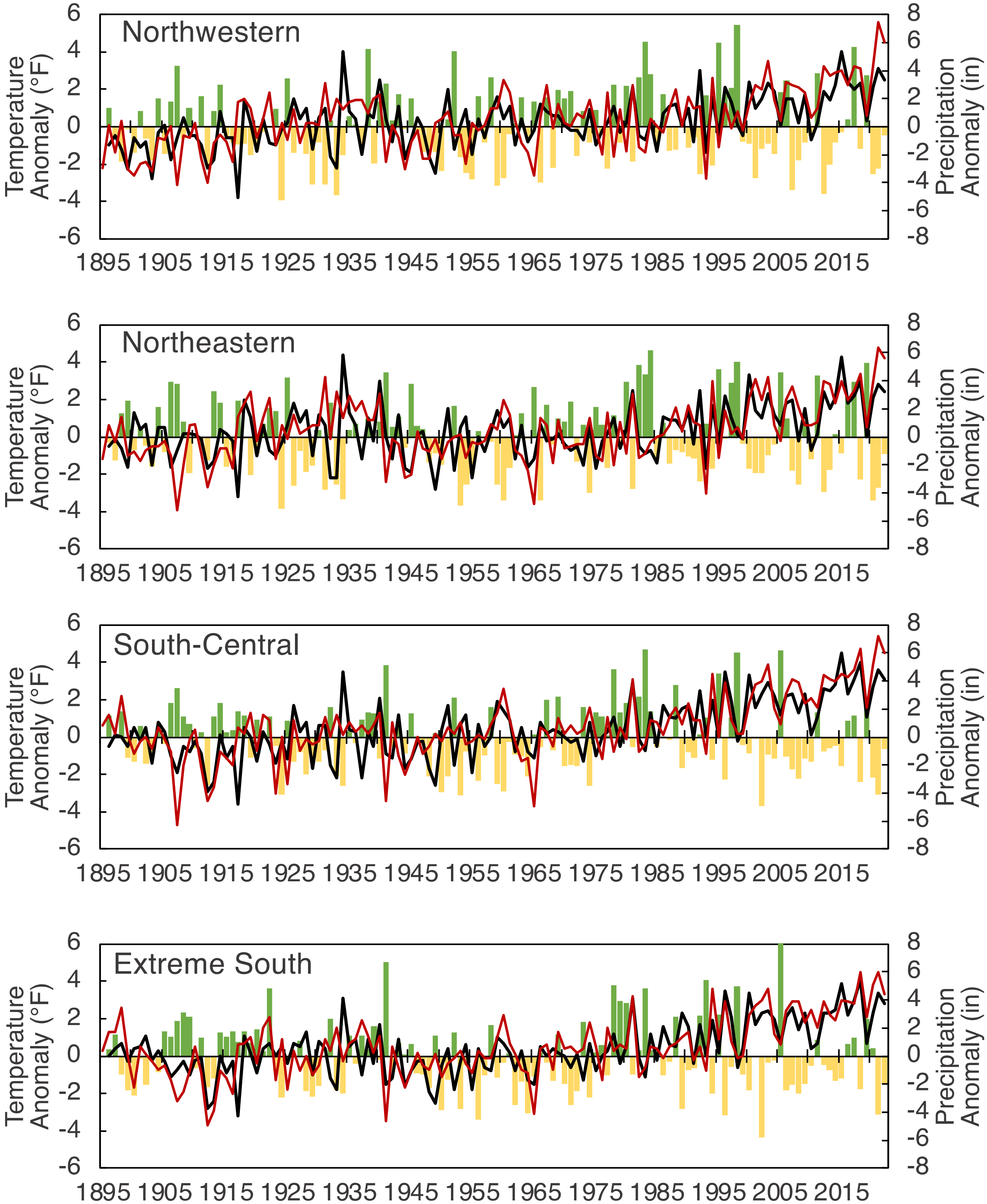

Figure 3 Time series of water-year (1896-2022) precipitation anomalies (green/yellow bars) and water-year (black lines) and summer (red lines, June – September, 1895-2022) temperature anomalies. Data provided for Nevada climate divisions by NOAA Climate at a Glance.

2.2 The 1950s

The 1950s drought is commonly referred to as the Southwest drought and is typically considered to span 1946-1956 (Hoerling et al., 2009). Although all of Nevada's climate divisions did experience some drought during this period, the onset and duration of drought differed across the state. Northwestern Nevada was consistently in drought from WY 1947-1955. In Northeastern Nevada, the PDSI did not meet the criterion for drought until 1953, but drought lingered until WY 1962. South-Central Nevada shifted into drought in WY 1947, and the PDSI remained negative through WY 1964. Extreme Southern Nevada was in drought from 1947-1950 and 1953-1956, but a relatively cool wet summer in 1951 and very wet conditions in March and April 1952 pushed the PDSI positive for September in 1951 and 1952. The 1950s brought a relatively cool drought with average WY temperatures somewhat below the 20^{th} century average. Hoerling et al. (2009) conclude that the 1950s drought can be explained by prevailing SSTs, and their model simulations produce drought over most of Nevada.

2. 3 The 1970s

In the 1970s, drought was severe across the Plains states and parts of the Upper Midwest (Wilhite et al., 1986), in the Colorado River Basin (Woodhouse et al., 2021), and in California (Scanlon et al., 2016). Nevada, however, did not experience widespread or protracted drought during the 1970s. In Northeastern and Northwestern Nevada, 1972, 1974, 1977 were quite dry, but intervening years had normal or even high precipitation. South-Central Nevada was in drought from 1970-74 and Extreme Southern Nevada from 1970 through 1977. As in the 1950s, drought in the 1970s appeared to be driven primarily by precipitation deficits rather than by temperature. Water-year average temperatures were near or below the long-term average in South-Central and Extreme Southern Nevada, while summer (June – September) temperatures were slightly warmer than average. The climatic drivers of the 1970s drought are not as clear. There were La Niña events in 1971, 1974 and 1976, and the tropical Pacific was relatively cool in 1975, as well. However, the Northern Hemisphere extratropical circulation was not conducive to a north-south precipitation dipole (Seager and Hoerling, 2014).

2. 4 The 1980s and 1990s

In both Northwestern and Northeastern Nevada, drought was present from 1987-1994. In the southern part of the state, drought developed in 1986 and extended through 1996, roughly consistent with the Colorado River Drought from 1988-1996 identified by Woodhouse et al. (2021). However, drought in South-Central and Southern Nevada was also punctuated by individual wet years: 1988 and 1995 in both climate divisions and 1992 and 1993 in Extreme Southern Nevada. As a result, drought was overall more severe in Northeastern and Northwestern Nevada. Water-year average temperatures were warmer than normal and warmer than during the 1920-30s drought, particularly in South-Central and Extreme Southern Nevada. There has been relatively little atmospheric diagnosis of the causes of the 1980s drought. There were four El Niño events during this period (1986-87, 1987-88, 1991-92 and 1994-95) and one La Niña (1989-90).

2. 5 The 2000s

All of Nevada has experienced some level of drought since 2000. Whether this constitutes a continuous drought containing a wet year or two or multiple droughts broken by wet years is somewhat subjective and depends strongly on the specific drought definition used. In Northwestern Nevada September PDSI was ≤ -1 in 18 of the last 23 years and, by the definition above has been continuously in drought. Using the average summer (JJAS), PDSI was ≤ -1 in 17 years. By that metric, the 2000s have had two droughts, 2000 – 2009 and 2012 to present. Over that same time in Northeastern Nevada, the September PDSI was ≤ -1 in 15 years, and that part of the state experienced two droughts, a short one from 2000-2003 and a longer one from 2006 to present. The average June-September PDSI was similarly low in 16 years. South-central Nevada experienced only four years when the September PDSI was > -1 and five years when the JJAS PDSI was ≥-1. Using September PDSI, the South-Central division has been in drought since 2001. In Extreme Southern Nevada, 18 of the past 23 years qualified as in drought based on September PDSI, whereas JJAS average PDSI was ≤ -1 in 16 years. The region has either been in drought continuously since 1999 (September PDSI) or from 2000-2010 and 2013-present (JJAS PDSI).

In Northwestern Nevada, summer average temperatures have been warmer than the 20th century average in every year since 2000. Water-year average temperatures were below normal in 2010. Temperatures were also warmer than normal in Northeastern Nevada, with below normal summer temperatures in 2005 and below normal water-year temperatures in 2008 and 2010. Both South-Central and Extreme Southern Nevada have had above normal summer and water-year temperatures every year since 1999.

Numerous proximate and more distant causes for recent drought have been suggested. Seager (2007) noted that drought early in the 2000s was associated with La Niña but did not find a satisfactory or persistent explanation for later years of the drought. There were higher than normal geopotential heights, indicating a ridge of high pressure, over the West Coast during January – March of 2002, 2003 and 2004, which would likely have blocked storms. Swain et al. (2014) demonstrated that there was a "ridiculously resilient ridge" of high pressure along the West Coast of North America in 2013. Williams et al. (2015) and Luo et al. (2017) identify precipitation shortfalls as the major cause of the drought, and both indicate that drought was exacerbated by high temperatures, although they differ somewhat in their assessment of how large a role temperature played. Seager et al. (2015) used modeling to demonstrate that La Niña and other aspects of SST forcing triggered precipitation shortfalls, although their analysis was focused on California, and ENSO forcing of precipitation is weak in northern Nevada (Wise, 2010). Since the beginning of the 21st century, all four Nevada climate divisions experienced drought in El Niño events during the 2003, 2007, 2010 and 2016 water years, as well as during recent La Niña events.

3. THE CURRENT DROUGHT

3.1 Drought development

According to the USDM, the most recent drought began in water-year 2020. October 2019 was unusually cold and dry statewide. Average monthly temperatures were almost 1.5°C to more than 3°C (3-6°F) below the 20th century mean (Figure 4). Of the 179 weather stations with complete records (i.e., no missing values) for October 2019, 88 reported no precipitation. Another 12 reported only trace precipitation – precipitation amounts too low to be accurately measured

(SC-ACIS, https://scacis.rcc-acis.org/). In northern Nevada, dry conditions continued through November, but November was notably wet in southern Nevada. December was wet statewide and many high-elevation weather stations received very heavy precipitation. January marked the start of a 12-month long period in which most of northern Nevada experienced below normal precipitation and above normal temperatures in every month. In southern Nevada, dry conditions in January and February were followed by wet conditions from March through mid-April. The spring and summer of 2020 were notably dry and warm across most of the state. The Harry Reid International Airport (formerly McCarran International) in Las Vegas recorded no measurable precipitation for 240 days between April 21 and December 16, 2020, breaking the previous dry-spell record of 150 days. The near complete lack of summer precipitation was so notable that it was dubbed the "nonsoon." August was particularly hot, with many locations in the state setting records for consistently high August temperatures.

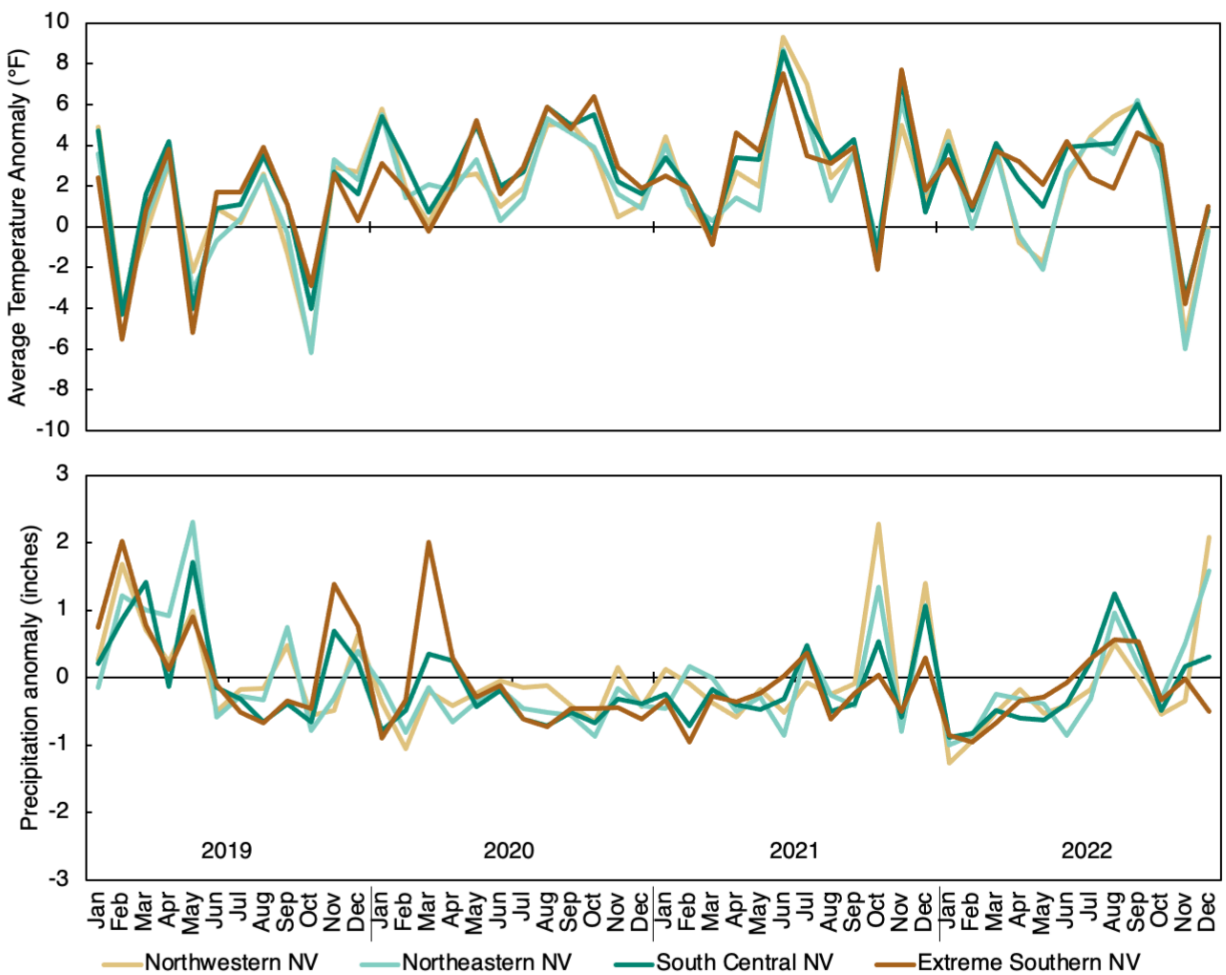

Figure 4 Monthly precipitation and temperature anomalies in each Nevada climate division, January 2019 – December 2022. Data provided for Nevada climate divisions by NOAA Climate at a Glance.

Generally dry and warm conditions continued through most of the first nine months of the 2021 water year. October 2020 was as dry or drier than October 2019; over 100 weather stations in Nevada reported no precipitation. Heavy monsoon storms in southern Nevada during June and

July of 2021 led to flooding but were not especially helpful in mitigating drought conditions. The 2022 water year started wet with much above normal precipitation in October and December, but the second half of the winter was notably dry. Precipitation was, overall, below normal in the 2022 water year, but some areas did receive heavier than normal spring rainfall or late season snow, and as a result, rangeland conditions in northern Nevada were in better condition than might have been expected (B. Schultz, pers. comm., 10/20/22). Somewhat unusually, drought conditions in the state began improving during the summer. Thunderstorms associated with a very wet and active monsoon spread north across the state. Although the precipitation was spotty, as is characteristic of summer storms, it was sufficient to raise surface soil moisture, as well as causing notable flooding in the Las Vegas Metro area.

3.2 Contribution of Temperature

In the context of the historical record, the most recent/current drought was unusual in several characteristics. First, it has been by far the warmest drought. When temperatures increase, the atmosphere's ability to hold moisture also increases. This increased atmospheric demand for moisture (enhanced evaporative demand) can enhance drought severity by increasing evapotranspiration from soils and plants and increasing evaporation of reservoirs. Temperature's influence on drought severity can be most simply evaluated by comparing the Standardized Precipitation Index (SPI, McKee et al., 1993; 1995) which normalizes precipitation deficits and surpluses to the Standardized Precipitation-Evapotranspiration Index (SPEI, Vicente-Serrano et al., 2010). The SPEI is a similar index based on the difference between precipitation and potential evapotranspiration. From 1896 through the 1990s, the 12-month SPEI minus the 12-month SPI (calculated using PRISM monthly data (Figure 5) is mostly positive, indicating that temperature is not exacerbating moisture deficits. Beginning in the 1990s, and particularly during the most recent three-year period, SPEI-SPI has trended negative, indicating that higher temperatures exacerbated drought because of enhanced evaporative demand.

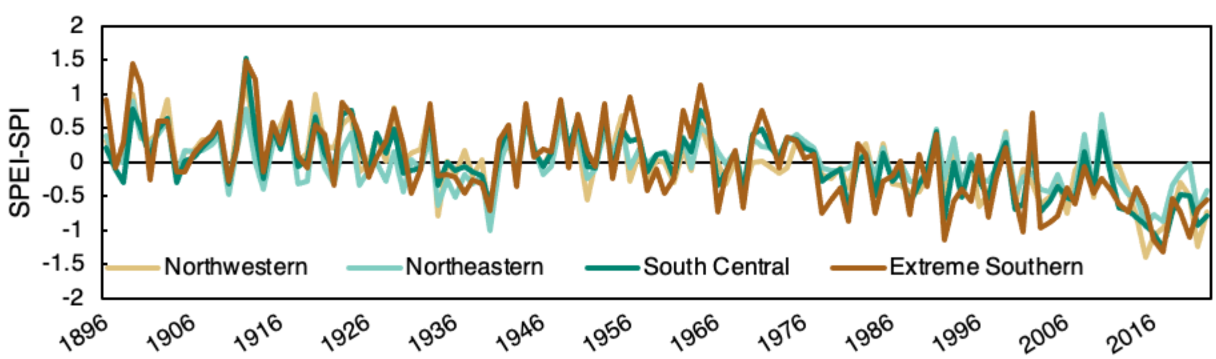

Figure 5 Difference between the September 12-month SPEI and SPI for each of Nevada's climate divisions. Data from PRISM and accessed through WestWide Drought Tracker.

Higher temperatures can also reduce the effectiveness of some drought-management strategies. In much of the western US, the seasonal snowpack is a key component of the water resources storage system, particularly in smaller basins with little or no reservoir storage like the Upper and Middle Carson River. During drought, snowfall is typically lower than normal simply because overall precipitation amounts are lower (i.e., dry snow drought Harpold et al., 2017).

During recent droughts, however, less precipitation than usual has been stored in the snowpack, even at high elevations where average temperatures are cooler. The SNOTEL (Snowpack Telemetry) station at the Mt. Rose Ski area is located at 8,801 feet elevation. The median April 1 SWE/P (snow water equivalent/precipitation) for the full period of record is 0.89, meaning that almost 90% of the cumulative precipitation between October 1 and April 1 remains in the snowpack. In recent drought years (2015 and 2022), the April 1 SWE/P were 0.59 and 0.61, respectively, indicating that about 40% of the accumulated winter precipitation was already lost from the snowpack.

Higher temperatures' exacerbation of drought is so widely acknowledged that the terms "hot drought" and "hotter drought" are frequently used to describe the most recent droughts (Breshears et al., 2005; Overpeck, 2013; Udall and Overpeck 2017). There are interesting and poorly explored aspects of hot drought, however. If enhanced evapotranspiration is a primary driver of hot drought, impacts from hot drought should be worse at lower elevations where temperatures are higher. Higher temperatures could also contribute to enhanced summer rainfall (Lundquist et al., 2019), which some Great Basin plant species can use to mitigate the effects of dry winters (Strachan, 2016).

3.3 Spatial Extent

The recent drought was spatially extensive within Nevada and across the western US more generally. The US Drought Monitor (USDM) was developed in the late 1990s (Svoboda et al., 2002) and has been operational since 2000. The most recent drought is only the second time in the over 20-year history of the USDM that the entire state has been characterized as at least D2-Severe Drought, and that severity of drought has lasted far longer. For about two months during the summer of 2007 all of the state was in D2-Severe or D3-Extreme Drought, after which drought conditions improved rapidly. This year, the entire state was in D2-Severe to D4-Exceptional drought from March 1 – May 24, after which a small area of D1- Moderate Drought was introduced. As of November 1, 2022, 99.5% of the state remained in at least D2-Severe Drought. The 2020s drought also marks the first time that more of 20% of Nevada was in D4-Exceptional Drought, the most serious drought characterization made. At the height of the drought from March through July 2021 just over 40% of the state was deemed to be in D4-Exceptional Drought.

The drought was also regionally extensive. In November of 2021, over 90% of the western US (Washington, Oregon, California, Idaho, Nevada, Montana, Utah, Arizona, New Mexico, Wyoming and Colorado) was experiencing D1-Moderate or more significant drought for the first time since the inception of the USDM. Over 20% of the western US was in D4-Exceptional Drought, another first. According to the National Centers for Environmental Information, almost 98% of the western US was in drought during June 2021, making drought more extensive than during the Dust Bowl (NCEI, 2021). In June 2021, drought was present across most of the western US, as well as the northern Plains. The sheer extent of the drought exacerbated the impacts, most notably in agriculture (see section 3.6).

3. 4 Hydrological Impacts

Hydrological drought is typically characterized by low streamflow and depleted lake and reservoir levels (van Loon, 2015). Groundwater is usually more resilient to drought than surface water supplies (Pohll et al., 2016). Water resources management can complicate the evaluation of hydrological impacts so that lake, stream and reservoir levels may not fully reflect drought conditions. Drought conditions can also cause temporarily counter-intuitive results, such as above normal streamflow early in the spring, if the snowpack begins melting earlier in the year than usual. Nonetheless, Nevada and the Great Basin had lower than normal streamflow in water-year 2020 (Jian et al., 2021) and significantly lower than normal streamflow in 2021 (Jian et al., 2022).

Many of the reservoirs in or serving Nevada have also been below normal during recent years. The Lahontan Reservoir in the Carson basin was at 4% and 5% of capacity in late October of 2021 and 2022, respectively. In the Lower Humboldt basin, Rye Patch Reservoir was at 4% of capacity in late October of both years. Lake Mead has been at less than 30% capacity at the end of each October since 2014.

3.5 Ecosystem impacts

Although the effects of the most recent drought (2020 – present) on Nevada's ecosystems are not yet well documented, the effects of other recent droughts on western ecosystems have been pervasive and point toward expected impacts. Increasing warmth intensifies drought impacts (Breshears et al., 2005; Millar and Stephenson, 2015). Direct effects of drought on tree death through carbon starvation and hydraulic failure (McDowell et al., 2008) have occurred at large scales across California and the Great Basin in the late 20th and early 21st century. The 2012-2015 drought, for instance, resulted in up to 80% stand mortality of montane Sierra Nevada forests (Goulden and Bales, 2019). Drought effects combined with increasing temperatures have also directly induced massive die-offs of pinyon woodlands in the Great Basin, with the highest mortality in low, warm sites and high density stands (Flake and Weisburg, 2019; Shriver et al. 2022).

The interaction of drought with other stressors, such as bark beetles and pathogens, has led to even greater forest and woodland mortality (Greenwood and Weisberg, 2008; Hicke et al., 2020). Bark beetle outbreaks especially have been accelerated by recent hot droughts in the Great Basin, causing not only extensive mortality, but increasing the range of species affected by beetles, and triggering the beetles to expand their own distributions as well (Howe et al., 2021). Most pine species in Nevada have been severely negatively affected by bark beetles. Warming temperatures enable native bark beetles to move upslope into montane zones where they previously have not caused outbreaks and where the high elevation species are more vulnerable (Howe et al., 2021). For example, limber pine (*Pinus flexilis*) experienced widespread bark-beetle-caused mortality linked to hot droughts and bark beetles starting with the 1988-1992 drought (Millar et al., 2007) and stand mortality up to 70% was documented in whitebark pine (*P. albicaulis*) in 2007-2010 (Millar et al., 2012). Most concerning has been the recent and extensive mortality in high-elevation Great Basin bristlecone pine (*P. longaeva*) due to drought stress and bark-beetle outbreaks (Figure 6; Bentz et al., 2022). Great Basin bristlecone pine previously had been documented to be resistant to bark beetles (Bentz et al., 2017), but in warm locations during recent severe droughts resistance has broken down, apparently a result of build-up of massive pools of bark beetles hosted by singleleaf pinyon pine (*P. monophylla*) and limber pine that overwhelm bristlecone pine defenses (Bentz et al., 2022).

Figure 6 Bark-beetle and drought-induced mortality in Great Basin bristlecone pine. C. Millar.

Drought effects are not limited to forests and woodlands but affect Nevada's shrublands and rangelands as well. Flake and Weisberg (2021) documented decreases in perennial grasses and forbs across multiple plots in central Nevada from 2005 to 2015. Generally positive, though complicated, relationships between precipitation and sagebrush (*Artemisia* spp.) recruitment in Nevada (Hourihan et al., 2018) suggest that prolonged or significant drought could negatively impact sagebrush. Cascading effects from drought-induced mortalities affect spread of invasive species such as cheat grass. Drought has been known to trigger expansion events of cheat grass (*Bromus tectorum*) since the 1930s (Young et al., 1987; Young and Allen, 1997), but recent work has shown more nuanced relationships between cheatgrass expansion and drought (Flake and Weisberg, 2021).

Beyond plants, recent droughts have affected many species of terrestrial wildlife and aquatic biota. For instance, winter drought characterized by lack of snow, appears to cause acute thermal stress on Great Basin populations of the small montane mammal, American pika (*Ochotona princeps*; Wilkening et al., 2011; but see Smith and Millar, 2018). A relative of rabbits and hares, pikas do not hibernate and rely on snowpack to insulate their talus habitats in winter. With low or no snowpack, pikas are exposed to subfreezing temperatures and experience demographic reductions that may lead to population extirpation. Similarly large mammals such as bighorn sheep have suffered population declines as a direct effect of drought. In the endangered

Sierra Nevada bighorn sheep (*Ovis canadensis sierrae*), drought since the late 20th century has had highly detrimental effects on sheep population sizes, especially through effects on reproduction and juvenile survival, where water availability is essential (Connor et al., 2018). Similarly, extreme drought has significantly decreased juvenile survival in desert bighorn sheep (*Ovis canadensis 24elson*). For example, droughts of the early 2000s severely reduced lamb numbers of desert bighorn sheep across Nevada to levels below that required for population maintenance (Cox and Cummings, 2005).

Aquatic ecosystems have been severely impacted by contemporary droughts. Terminal lakes of the Great Basin are notoriously subject to species declines and ecosystem collapse as a result of lower water levels. Declining water volume results directly from reduced precipitation and inflow, but in recent decades has been amplified by rising temperatures that increase evaporation as well as agricultural and domestic demands. Many of the large lakes in the western Great Basin, such as Pyramid Lake (Melack et al., 1997; Guatam et al., 2013), Walker Lake (Beutel et al., 2001), and Mono Lake (Wiens et al., 1993; Melack et al., 1997), have experienced these impacts. Native biota, complex trophic relationships, and affiliated Tribal socioeconomic bases have been directly affected by increases in salinity, changes in seasonal cycles of lake stratification and mixing, and increases in abundance and diversity of invasive aquatic species, as well as indirectly affected by lower lake levels, as in the case of Mono Lake. At Mono Lake, lower lake levels resulting from cumulative and acute drought, caused exposure of a land bridge linking the mainland to the large islands. The land bridge allows coyotes (*Canis latrans*) to reach the islands and prey on California gulls and their eggs (*Larus californicus*), which formerly depended on the island as predator-free habitat for breeding (Winkler and Shuford, 1988; Wiens et al., 1993).

3.6 Agricultural Impacts

Nevada's farmers and ranchers were impacted both directly and indirectly by the recent drought. Direct impacts include reduced forage productivity, hauling water and/or feed to grazing livestock, reducing herd size, reduced water allocations for irrigation and subsequent low production, and hay purchasing. The widespread extent of the drought increased hay demand and prices (Arden, 2021; Haynes and Schumacher, 2021). As a result, there were significant economic losses in the state. In 2020, the Farm Service Agency's Nevada offices report paying out over $7 million in disaster assistance for 2020 losses through the Livestock Forage Program (LFP). In 2021, they reported additional LFP payments of $4.4 million related to 2020 losses and over $10 million in LFP payments related to 2021 losses (USDA, 2022).

4. TRACKING PAST DROUGHT AND ITS IMPACTS

Understanding contemporary droughts provides important perspectives on the future. Time is arguably even more relevant for scaling current events and preparing for future conditions than consideration of drought manifestation over space. Yet many modern people suffer from "time-blindedness" (Bjornerud, 2018). Whereas we can readily imagine 3000 miles as a flight across the United States, modern humans tend to think in recent-generation intervals: back in time to their grandparents; forward to their grandchildren, considering maybe 200 years as relevant for decision-making. In contrast, one of Nevada's state trees—Great Basin bristlecone pine—can live to 5000 years old, and thus a parent-offspring pair can span 10,000 years. Understanding, conserving and managing Nevada's ecosystems in the face of increasing drought requires thinking on these time spans. Trees and other natural indicators ("proxies") of past climate provide important insights into relevant deep time. Further, the deep-time narratives of Great Basin's Indigenous peoples reveal compelling insights into how people navigated and adapted to past droughts.

Observational records, archaeological records and paleoclimate proxies all provide valuable information about drought and, where they overlap in space and time, they provide complementary but not identical information. The primary difference between observational and other records is in the level of spatial and temporal detail that can be provided. Even in dry years, there can be areas or seasons with wetter than normal conditions. Spatial and temporal variability in precipitation is especially prominent in Nevada because of the complex basin and range topography. It seems likely that archaeological or paleoclimatic records will not fully capture the detailed spatial experience and expression of drought on the landscape. Most archaeological and paleoclimatological records represent climate over a relatively small area. Depending on the location of these records relative to locally wet or dry spots, they could also capture conditions that are not broadly representative of the landscape in a given year. Similar problems can arise with current observations because of the large distances between weather stations in much of Nevada. Another key disparity is in temporal resolution. Most weather and climate observations provide information at monthly if not daily (or even finer) time steps throughout the entire year. However, archaeological information and paleoclimatic proxies typically have a lower temporal resolution – annual or sub annual at best and often decadal or coarser. Finally, most proxies record climate from a specific season because of the physical or biological mechanisms driving the climate response. Despite the uncertainties, paleoclimate proxies provide information on time scales of hundreds to thousands of years prior to the beginning of instrumental records, thus broadening our understanding of the natural limits of climate variability on timescales relevant to the future. Many commonly used climate proxies in Nevada and the West reflect primarily winter or cool-season precipitation (see section 4.2). This is beneficial for understanding drought as it relates to water resources and to some ecosystem processes, but many plant species respond differently depending on the seasonality of precipitation and drought (e.g., Strachan, 2016; Pyle et al., 2021; Bishop et al., 2022), leading to a mismatch between the information that is recorded and the information that is needed.

4.1 Archaeological record: Indigenous evidence for and adaptation to droughts

4.1.1 Materials and methods for understanding native lifeways

The contents and distribution of archaeological sites provide valuable clues about droughts in Nevada. Archaeologists have used three primary proxies to date periods of occupation and abandonments: radiocarbon dating, index fossil frequencies and obsidian hydration rim thickness. Kelly and Thomas (2017 pp. 117-141) review the theory and practice of each technique, and the sections below define their relevance to Nevada climate studies.

Radiocarbon (^{14}C) dating is today's most important method for dating archaeological sites in Nevada, providing estimates of the age of materials made of organic carbon. The age of an archaeological sample is estimated by measuring the amount of carbon-14 present in the sample and comparing it against an internationally used reference standard. Modern radiocarbon labs use Accelerator Mass Spectrometry ^{14}C dating, which allows dating of very small samples and provides decadal accuracy. Because of variability in ^{14}C production in the atmosphere through time, radiocarbon ages must be "calibrated" to calendar ages through a conversion derived from known-age dendrochronological samples. Because radiocarbon dating potentially provides results accurate to a human lifespan, archaeologists rely heavily on radiocarbon dating to document abrupt climate changes and human responses. Several potential biases in radiocarbon dating must be considered, including 'old wood effects', contribution of ancient carbonates lacking ^{14}C to younger materials in lacustrine samples and biases in collection strategies.

Great Basin archaeologists have refined projectile point chronologies for the past half-century (Thomas, 2013). Although operating at a millennial scale, these time sensitive artifacts provide age estimates that help correlate buried and surface assemblages. Beginning ~14,000 years ago, dart and spear point forms evolved through a series of "types" and after ~1500 years ago, were replaced by two sequential types of arrowheads. Thomas (2020 Tables 2.1 and 2.2) summarizes a database of nearly 48,000 typable Great Basin projectile points. Although index fossil and radiocarbon dating operate on vastly different scales, a recent Basin-wide synthesis demonstrates that pooled projectile and radiocarbon trajectories are highly correlated, with a statistically highly significant correlation coefficient of $r_{i,c} = 0.988$ (Thomas, 2023 Fig. 2.13).

Obsidian hydration dating (OHD) is a way of dating materials based on measuring how much water was absorbed by obsidian (Rogers, 2023), which accumulates over time due to environmental exposure. Recent advances in understanding the physics and chemistry of obsidian hydration have led to development of mathematical models for OHD and revised interest in the method (Rogers, 2007; 2010). OHD dates are not as accurate as radiocarbon but are more accurate and precise than using methods like projectile point typology. The utility of OHD for archaeological dating is limited in Nevada by the local lithic landscape, which is starkly divided between a centralized "chert core" (where obsidian sources are almost non-existent) and an encircling "obsidian rim" with multiple sources (Thomas, 2012; 2020 pp. 609–635). This bedrock reality means that obsidian tools and debitage are relatively common around the state margins and virtually absent in central Nevada.

4.2 Proxy records of drought

A climate proxy is a physical system or biological organism that responds reliably to and records temporal climate variability and can be used to reconstruct climate in times or places without reliable observational data. For example, many trees grow annual rings and the width of these rings is largely controlled by available moisture and/or temperature. We can then compare the ring widths of living trees with long-term instrumental records of precipitation and temperature, to calibrate the sensitivity of changes in tree-ring width to precipitation. Using this calibration dataset, we can then extract tree cores from long-lived trees to reconstruct drought, going back hundreds to thousands of years. While climate and physical environment have changed substantially through time, the use of proxies assumes that the natural processes that control a particular physical activity have remained essentially unchanged through time.

A wide range of physical proxies have been used reconstruct the timing, duration, and geographic extent of past droughts impacting Nevada, although proxies themselves do not necessarily reveal the climate mechanism causing drought. Each proxy has advantages as well as limitations, and by combining a variety of different proxy methods (multi-proxy analysis) we have been able to put together a remarkably complete picture of drought in Nevada during the pre-instrumental period. This review will specifically review drought reconstructions in Nevada using tree-rings, sedimentary cores, woodrat middens, geological records and archaeology.

4.2.1 Living trees and dead wood

Living trees and dead wood are excellent time keepers and provide important evidence about past climates. Their value derives from the ability to accurately date annual growth rings far into the past, and to interpret climate information based on the width of the growth rings (Speer, 2010). In temperate latitudes with dominant winter and summer seasons such as Nevada, tree stems grow in diameter during the warm season and do not grow in winter. In spring, cells around the outer edge of the tree's stem start to expand and multiply forming large cells through midsummer. As temperature declines and moisture becomes increasingly limited in late summer, stem growth slows, producing smaller and smaller cells that are densely packed, and finally stops altogether in late fall. This sequence of no growth (winter), large-cell growth (spring and summer) and small-cell growth (fall) creates the familiar circular pattern seen in cut stumps. The outer most ring is most current and the innermost ring (pith) the oldest.

Although the sequence of ring widths correlates generally to climate within a geographic region, species respond to elements of weather, such as precipitation or temperature, in varying ways. Once these relationships have been determined, the annually dated ring widths can be used to interpret climate as far into the past as the master chronology extends. In the arid Great Basin, precipitation is a strong determinant of growth for many native trees, and, thus, periods of historic drought (narrow rings) can be more readily evaluated than in regions where trees respond to other climate factors (Millar et al., 2021). Dead wood, which can be remarkably well preserved in the arid climates of the Great Basin, can also be sampled and ring widths measured. If the dead tree's age overlaps a live tree that has been dated and ring widths measured, it is possible to align the overlapping sequences (being unique like barcodes), and, by comparison to the age/dates of the live tree, the dead tree also can be dated (Stokes, 1996). In this way, and using many stems of dead trees, a "master chronology" of ring widths can be developed that extends from present to as old in time as one can find and date overlapping old dead wood. Master chronologies of Great Basin bristlecone pine extending over 9000 years have been constructed (Salzer et al., 2019). Since moisture availability is a common limit to growth in arid regions, these long bristlecone pine chronologies can be used to date trees at locations throughout the Great Basin, even for different tree species. Dead trees occurring in places where live trees are not currently found (e.g., stumps in lake basins and rivers), indicate past climate variations, including drought. In Nevada, arid, cold climates at high elevations, combined with tree species that have very resistant wood, yield many situations where long-preserved dead wood give clues to past climates.

Although the basic concepts hold in general, there are many situations where tree-ring dating and climate inference is not so easy. During years of unfavorable conditions, a tree may only produce a partial ring (Fritts et al., 1976) or, under conditions such as hot droughts, not put on an annual growth ring at all (Novak et al., 2016). St. George et al. (2013) found that in 1580, several tree ring chronologies developed in US Southwest have 80-100% of trees that did not put on an annual growth ring. Such "missing rings" challenge accurate dating. In contrast, late summer or autumn warm spells can cause trees to start growing again, adding "false rings" that similarly confound dating. Accuracy of ring widths for inferring climate is particularly challenging because most species respond to some combination of temperature, precipitation, soil moisture, frosts and freezing, etc., meaning the measure of a ring gives a mix of information that can be difficult to tease out. Further, since climates differed in the past from the present, the climatic factors that affect tree growth might have (or not) been different. For instance, during past cold glacial intervals, Great Basin bristlecone pine growth may have been more sensitive to temperature throughout its distribution than during warm periods such as the present (Salzer et al., 2014). Moreover, not all trees record temperature or precipitation extremes faithfully (Wise and Dannenberg, 2019), so it may not be possible to ensure that true drought severity is captured. Trees may not fully "reset" during dormancy, and accumulated drought stress may limit growth in subsequent wet years (Kannenberg et al., 2019), potentially limiting tree-ring based reconstruction's ability to identify wet years during a protracted drought. There is some evidence that the length of drought and the impacts of temperature can lead to non-linearities in the impact of these drought legacies, suggesting further study is needed (e.g., Ovenden et al., 2021).

4.2.2 Soft sedimentary records

Natural wet depressions, like lakes, bogs, fens and wet meadows, accumulate soft, permanently moist sediments that can be extracted in cores by hand or with mechanical assistance. Since many different types of material accumulate in sediments, cores have been used to analyze a wide array of climate proxies in Nevada and the Sierra Nevada including stable oxygen isotopes, denoted $\delta^{18}O$ (Benson et al., 2002; Yuan et al., 2004), magnetic susceptibility and scanning X-ray fluorescence (Noble et al., 2016), pollen (Wigand and Rhode, 2002; Mensing et al., 2004), charcoal (Beaty and Taylor, 2009), chironomids (Porinchu et al., 2003), diatoms (Johnson et al., 2017; Ball et al., 2018) and organic geochemistry in the form of $\delta^{13}C$, C:N, and lignin phenols (Ball et al., 2018). Each of these proxies measures different environmental conditions, but all sedimentary core studies have similar advantages and limitations associated with sedimentation processes. One advantage of sediment cores is that they often span multiple thousands of years. The main limitations on record length are how long the depository has existed and whether there are periods of missing sediments called hiatuses possibly resulting from drought conditions, non-deposition or erosion. Another advantage is that a single core can produce multiple lines of supporting evidence that can create a more complete record of past climate. The most serious limitations are in age control and resolution. As with archaeological materials, age control is typically based on radiocarbon dates of organic material found in the core, and dates typically have an uncertainty of 30-50 years or more. In addition, how quickly sediment accumulates (the sedimentation rate) and the degree of sediment mixing control the minimum temporal resolution possible. As a result, sediment proxies typically reflect decade to century-scale climate variability and are far less likely to resolve shorter duration droughts. Sediment cores are collected from one location but can accumulate material from many kilometers away. Thus, cores are generally considered to represent the predominant conditions across a landscape extending tens of kilometers or more from the core site.

4.2.3 Cave deposits

Despite its largely dry climate, the Great Basin contains numerous caves that formed from dissolution of limestone bedrock. Some Great Basin caves initially formed beneath the water table and were later uplifted due to tectonic forces or erosion related to base level lowering to altitudes far above the modern water table. Within these caves, some contain calcite deposits called speleothems, which are accumulations of calcium carbonate from the gradual accretion from drip waters entering through the cave roof (Fairchild and Baker, 2012). The presence of speleothems in Nevada caves indicate that a positive moisture balance is at least seasonally present to allow snowmelt or precipitation to infiltrate the soil and epikarst (the layer of limestone beneath the soil and above the cave) to form speleothems. Today, stable oxygen and hydrogen isotopic evidence of cave waters shows that most caves receive infiltration from winter precipitation and snowmelt, with only minor contributions from summer infiltration evident because of high evaporation rates (Winograd et al., 1998; Lachniet et al., 2014; Lachniet et al., 2020). Because cave speleothems (primarily stalagmites) can be dated radiometrically with uranium-series geochemistry, and because the stable oxygen isotopic composition of the calcite ($\delta^{18}O_c$) tracks variations in precipitation oxygen isotope values ($\delta^{18}O_p$), stalagmites can provide continuous long-term paleoclimate records. Stable carbon isotopic value in calcite ($\delta^{13}C_c$), in well-behaved stalagmites, may record variations in soil carbon $\delta^{13}C$ values, which itself may be related to local hydroclimate (Fohlmeister et al., 2020). Similarly, trace metal concentrations in speleothem calcite may record effective moisture variations, or in-cave processes that are linked to past climate (Fairchild and Baker, 2012). Finally, water-table speleothems such as folia and mammillary deposits can record variations in the altitude of the water table over time in phreatic systems (like Devils Hole), providing long-term and regionally-integrated records of past hydroclimate (Szabo et al., 1994; Wendt et al., 2019). The longest accurately-dated speleothem records come from Devils Hole (Moseley et al., 2016) and Leviathan Cave (Lachniet et al., 2014; Lachniet et al., 2017), the latter site which showed a strong Milankovitch (orbital) forcing of Great Basin paleoclimate – as expressed in $\delta^{18}O_c$ variations – over the last 175,000 years.

4.2.4 Woodrat middens and other biogenic accumulations

Many animal species accumulate substantial quantities of biological materials in and around their dens or perches. Owls may regurgitate pellets of undigested bones, feathers and exoskeletons from a favorite cave ledge, eventually leaving a massive pile beneath it. Woodrats habitually collect a wide array of objects including plant fragments, seeds, bones, feathers, stones etc., from within their foraging range to bring back to their dens, forming so-called 'packrat middens.' Among these accumulations, packrat middens are the best-studied for paleoecological information, with thousands of midden samples collected throughout arid western North America. Under proper conditions middens may persist for tens of thousands of years and are datable using radiocarbon. Their contents can yield multiple independent proxy records of regional climate, proxies such as the occurrence or abundance of specific plant or animal taxa having specific climatic tolerances (e.g., Sharpe, 2002; Madsen et al., 2001; Thompson et al., 2012), or the changing diversity of species in a particular point in the regional landscape (e.g., Tausch et al., 2004; Grayson, 2011), or variations in stable isotopic values of biotic remains, that may correlate with local moisture or temperature fluctuations (e.g., Long et al., 1990; Tomé et al., 2022).

5. DROUGHTS PRIOR TO THE OBSERVATIONAL RECORD

The archaeological record and the proxies described above have been used to develop a detailed record of drought and aridity in Nevada stretching back almost 10,000 years. Three notably arid periods with impacts on ecosystems and Indigenous Nevadans stand out: the Middle Holocene (7000 – 5000 years ago), the Late Holocene (3000 – 1800 years ago), and the Medieval Climate Anomaly (1000 – 650 years ago), which was closely followed by another dry period from about 600 to 500 years ago.

5.1 Middle Holocene

5.1.1 Evidence for aridity and drought

The Middle Holocene, roughly 7000 to 5000 years ago, was a generally warm, droughty period in many parts of the Northern Hemisphere including the Great Basin (Hughes and Diaz, 1994). Holocene paleoclimate variations are linked to variations in Northern Hemisphere summer insolation (NHSI), which reflects the intensity of solar radiation received by the Great Basin over time. Variations in NHSI have set the pacing for Great Basin temperature variations for at least the last 175,000 years (Lachniet et al., 2014; Moseley et al., 2016). During the Middle Holocene, NHSI peaked between ca. 10,000 to 11,000 years ago, though the region experienced its driest conditions a few thousand years later. Direct evidence from Lake Tahoe indicates that 6300 years ago, Nevada and the West experienced a significant warming and drying trend. Stumps of submerged trees dating from that time and that were at least a century old were found rooted more than 3.5 m (11 ft) below the natural rim at the southern end of Lake Tahoe (Harding, 1965; Lindström, 1990), indicating that lake level must have remained very low for more than 100 years. Lake Tahoe contributes at least 30% of the flow to the Truckee River (Benson et al., 2002), so when water levels in Tahoe remain below the rim for any reasonable period or time, water levels also fall in Pyramid Lake. During the Middle Holocene, sedimentary $\delta^{18}O$ indicates low water levels in Pyramid Lake (Benson et al., 2002), and pollen data from the area dating to about 7500 years ago shows an increase in desert plant species like *Atriplex* (Mensing et al., 2004). At roughly the same time (ca. 6500 years ago), Lily Pond near Lake Tahoe shows an uptick in fire activity, recorded by sedimentary charcoal (Beaty and Taylor, 2009).

Additional stumps rooted between 0 and 1.3 m (0-4.2 ft) below Lake Tahoe's natural spill point suggest another period of persistent dry conditions or multiple droughts between 5600 and 5000 years ago (Lindström, 1990). The Pyramid Lake data suggest that the most arid conditions occurred about 5000 and 5200 years ago. Modern Pyramid Lake is about 107 m (351 ft) deep, but hydrologic modelling (Benson et al., 2002) suggests that severe extended droughts could possibly reduce the lake depth to 88 m (289 ft, a surface elevation of ~ 1140 m, 3740 ft), 20 m (66 ft) below the surface elevation today of 1160 m (3806 ft) and nearly 40 m (131 ft) below the surface elevation prior to the Newlands Irrigation Project water diversions.

During the Middle Holocene, dry conditions were widespread. In eastern Nevada, Thompson (1992) reported reductions in groundwater and marsh contraction. More arid than present conditions were also noted in southeastern Oregon (Wigand, 1987) and north-central Utah (Grayson, 2011). The largest observed Holocene increase in Great Basin bristlecone pine's upper treeline in the White Mountains of eastern California also occurred at this time (LaMarche, 1973 Figure 7). Bristlecone pine tree rings also record the highest temperatures of the Holocene about 6800 years ago during an extensive period of extreme drought that persisted throughout the Middle Holocene (Feng and Epstein, 1994). A compilation of 98 moisture-sensitive Holocene paleoclimate records demonstrates that most Great Basin hydroclimate records exhibited dry conditions during the Middle Holocene (see Lachniet et al., 2020 Figure 7). Lachniet et al. (2020 p. 11) noted a strong inverse correlation of the Middle Holocene aridity index with the abundance of dated woodrat middens in the American Southwest, suggesting that the number of middens (and presumably the number of rodents producing them) is significantly reduced under major drought conditions. The Middle Holocene aridity is also captured in trace element concentrations in a Lehman Cave stalagmite (Steponaitis et al., 2015). Temperature-sensitive speleothem $\delta^{18}O_c$ peaked with highest values between 9000 and 5000 years ago indicating warmer winter temperatures, and the combined data suggest that the Middle Holocene was both warmer and drier than later periods.

Figure 7 Mid-Holocene treeline advance of bristlecone pine on Campito Mountain in the White Mountains. C. Millar.

It has been suggested that greater summer insolation during the Middle Holocene led to expansion of the east Pacific subtropical high-pressure system, leading to diminished precipitation (Whitlock et al., 1995, Whitlock and Bartlein, 1997). Middle Holocene aridity may have been related to a prolonged La Niña-like climate state in the tropical Pacific Ocean (Barron et al., 2003), which was characterized by large sea surface temperature gradients between the western Pacific warm pool and the eastern Pacific cold tongue (Lachniet et al., 2020). The period of maximum

Great Basin aridity also coincided with widespread warm conditions in the Arctic, suggestive of low- to high-latitude climate teleconnections to Nevada.

5.1.2 Human Responses to the Middle Holocene

The first Nevadans (Paleoindians) lived at least 12,000-9000 years ago alongside Late Pleistocene and Early Holocene pluvial lakes and marshlands. Unlike their contemporaries on the Great Plains, the early Nevadans were not big-game hunters of mammoths and now-extinct bison. Instead, these broad-spectrum foragers ate what their descendants would eat for millennia—bighorn, pronghorn and some mule deer when they could get them, but also small-bodied birds and mammals such as sage grouse and jackrabbits, insects such as grasshoppers, and plant foods, including geophytes, cactus pads, and small-seed plants like ricegrass, dropseed and goosefoot (Rhode and Louderback, 2007; Grayson, 2011; Madsen et al., 2015 p. 17).

The Middle Holocene drought impacted native Nevadans in multiple ways. Because they were largely tethered to the lowlands, Paleoindians largely bypassed central Nevada. But as the Middle Holocene became hotter and drier (9000 years ago), Pleistocene remnant lakes dried up and Nevadans moved away from the playas and deltas to these tall mountains and upland valleys. Intensive processing and milling of small seeds and pinyon pine nuts resulted in a dramatic new settlement pattern, and a striking number of upland caves and rockshelters (the "man caves") were occupied for the first time, likely reflecting gender-specific foraging strategies (Louderback, 2022). The flexible foragers crafted strategies appropriate to upland resources patchy in both time and space, by moving themselves to the resources in a desert-mountain pattern (Simms, 2008 pp. 32–37).

In response to Middle Holocene aridity, Indigenous Nevadans developed strategies appropriate to the evolving desert-mountain mosaic and this overall lifeway would persist, reflecting significant challenges and transformations during the Late Holocene Dry Period. Madsen (2007 p. 15) characterized the shift from Paleoindian to Middle Holocene adaptations as essentially a shift "from broad-spectrum foraging to very broad-spectrum foraging." Generations of archaeologists speculated a near-complete Great Basin "Altithermal" (Middle Holocene) abandonment due to severe drought. But we now know that human population growth rates met or exceeded exponential expectations throughout the entire Middle Holocene drought (Robinson and Thomas, 2023). Clearly, these were resilient Nevadans actively engaging in generational-scale shifts in response to aridification.

5.2 Late Holocene

5.2.1 Evidence for a Late Holocene Dry Period

The Late Holocene Dry Period is (LHDP) contained two long, dry intervals, from about 3100 to 2200 years ago and about 2000 to 1800 years ago with dry conditions extending to about 40°N across most of the basin and slightly further north in northwestern Nevada. These dry periods are recorded by limber pine ring-widths and very low tree recruitment in the Wassuk Range (Figure 8, Millar et al., 2018), reduced growth in other limber pine chronologies located in the eastern Sierran Nevada (Millar et al., 2021), and in pollen records collected at multiple wet meadows from central to northwestern Nevada (Mensing et al., 2007; 2013; 2023). Mono Lake shorelines (Stine, 1990), pollen (Benson et al., 1991), and changes in sediments (Yuan et al., 2006) and microfossils in Walker Lake (Bradbury, 1987; Bradbury et al., 1988), indicate low water levels and, during the driest decades, potentially saline lake waters consistent with very dry conditions. Similar evidence was found at Mono Lake (Stine, 1990; Zimmerman et al., 2012). Tree stumps below the current water level of Fallen Leaf Lake near Lake Tahoe indicate extreme aridity around 1800 years ago (Kleppe et al., 2011). Tree-ring, pollen and other lake records are consistent with changes in the diversity of plants and the number of woodrat middens at the same time (Tausch et al., 2004 p. 34).

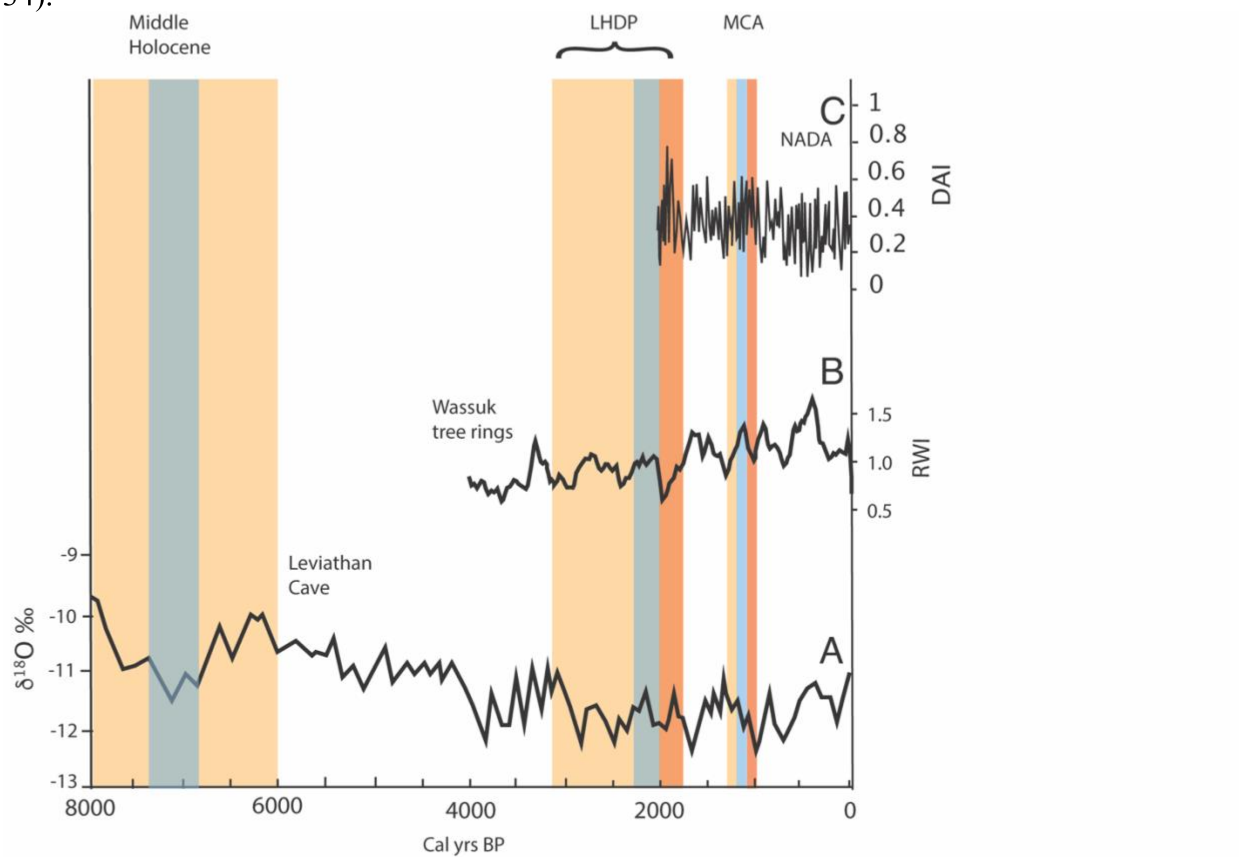

Figure 8 Time series of the past 8000 years of drought in Nevada. Figure shows A) the Leviathan Cave record (Lachniet et al., 2020); B) Wassuk limber pine chronology 20-year spline; Millar et al., 2021); C) Drought Area Index (DAI) from the North American Drought Atlas (NADA) for Nevada (Cook et al., 2004). Tan colors indicate the span of the arid intervals discussed with blue colors indicating wetter intervals within the overall drier period. Orange colors indicate the driest part of the arid interval. We show the Middle Holocene, Late Holocene Dry Period (LHDP) and the Medieval Climate Anomaly (MCA).

5.2.2 Human Responses to the LHDP

Population densities plummeted in Nevada during the LHDP with a human toll that is impossible to calculate. Almost every major archaeological site in central and southern Nevada was abandoned (Thomas, 2020; 2023; Mensing et al., 2023). But at the same time, Monitor Valley foragers established a pithouse village at 11,000 feet elevation on Mt. Jefferson in central Nevada.

Although the LHDP severely degraded most of the highest-ranking habitats south of about 40° N latitude, landscapes immediately to the north persisted largely unchanged or maybe even improved somewhat. The geographically and temporally variable LHDP closed some options and opened up others that would condition Indigenous Nevadans lifeways forever. As the LHDP drought unfolded and worsened through time, Indigenous Nevadans faced life-changing decisions (Freeman et al., 2019): Should we stay or flee to wetter territory a few days walk to the north?

Shared interests in their sacred mountain landscapes must have made it painful to walk away, but some did. With the onset of LHDP aridity, people abandoned dozens of significant Nevada places including well known sites like Gatecliff Shelter (Thomas, 1983), Triple T Shelter (Thomas and Kelly, 1988), Ruby Cave (Garcia, 2006), O'Malley Rockshelter (Fowler et al., 1973), James Creek Shelter (Elston and Budy, 1991), Pie Creek Shelter (McGuire, et al., 2004), the Falcon Hill caves (Hattori, 1982), Firebrand Cave (Blair and Winslow, 2006), Gypsum Cave (Gilreath, 2009), Hidden Cave (Thomas, 1985) and Lovelock Cave (Loud and Harrington, 1929).

In western Nevada, Lovelock communities reacted to LHDP stresses by moving *en masse* to escape the persistent aridity, becoming upland refugees for a millennium. Knowing that some previously marginal habitats in northern Nevada continued the wetter climates from before, those moving northward found better conditions than they left behind. However, because pinyon did not (and does not now) grow north of the Humboldt River, they forfeited the fall pinyon harvests that for millennia had supported supercamps where multiple extended families joined together for communal hunts. The Ideal Despotic Distribution also suggests that refugee communities transplanting northward to escape LHDP aridity may have been unwelcome intruders facing stiff competition because others were already living in or using the area (Kennett et al., 2009; Winterhalder et al., 2010; Giovas and Fitzpatrick, 2014; Codding and Bird, 2015; Codding et al., 2019).

For more than 150 generations, the highest peaks and passes had become origin places for central Nevadans, their birthright connections linking them to specific landscapes in a mosaic of ritualized cartographies (Stoffle et al., 2004). Despite the dozens of abandoned homesites all around them, some refused to abandon their drought-stressed ancestral homelands south of the Humboldt River. Those who stayed were doubtless swayed by "sunk-cost effects" in which suites of beliefs, rituals and social practices discouraged people from abandoning their established way of doing things (Arkes and Ayton, 1999; Janssen et al., 2003 p. 723). Indigenous sunk-costs were tied to specific places where people created their own lived histories—not merely through labor investments in hunting blinds and pronghorn drive corrals, but places where their social and cosmological actions created ritualized landscapes on a regional scale (Thomas, 2019; 2023). Rituals and ceremonies reinforced relationships between communities and their landscapes helped to mediate effects of abrupt environmental fluctuations, potentially leading to a sustainability and resilience in the continued maintenance and modification of such traditions over protracted periods of time.

Despite worsening LHDP conditions, some central Nevada communities refused to move even a short distance northward into more mesic territory because of the deep historical memories anchoring them to their vertical mountain landscape. These resilient communities downsized into smaller households better equipped to survive the drought, moving their extended families among multiple shorter-term, water-tethered encampments. They stopped the millennial-long practice of upland bighorn hunting in favor of more intensive family foraging in the alpine reaches and pinyon-juniper woodland. They broadened their diets to include plants and animals considered too costly during wetter times, spending less time searching for things and more effort processing what they found (Carpenter et al., 2019; Scheffer et al., 2021).

Just a few miles from the then-abandoned man cave at Gatecliff Shelter, Monitor Valley foragers pioneered new ways to make the most of their drought-degrading homeland and moved seasonally to the mountain tops. Located 3353 m (11,000 ft) above sea level, Alta Toquima was the highest known village site in North America when first recorded, and the 31 domestic structures preserved there remain the most dramatic example of Late Holocene Dry Period resilience (Thomas, 2020). Occupied almost exclusively during the most arid intervals of the LHDP, Alta Toquima was abandoned during wetter times. Gatecliff Shelter and James Creek Shelter were reoccupied during the brief wet phase (2200-2000 years ago) when the landscape became sufficiently well-watered to once again support patches of summertime seeds and geophytes. Both sites were abandoned again when the extreme aridity returned (2000 – 1800 years ago).

5.3 The Medieval Climate Anomaly

5.3.1 Evidence for the Medieval Climate Anomaly

The Medieval Climate Anomaly (MCA), which occurred between 1000 and 650 years ago, was a period of anomalous warmth throughout much of the Northern Hemisphere with particularly long and significant droughts (megadroughts) occurring in the North American Southwest (Coats et al., 2016l Cook et al., 2016; Anchukaitis et al., 2017). Tree-ring reconstructions, dead wood, lake sediment, paleo-shoreline data and archaeological evidence all point to frequent, impactful droughts lasting multiple decades in Nevada, the Sierra Nevada and across the Great Basin at this time. These droughts were separated by a relatively short wet period ("pluvial") lasting for decades (Stine, 1994; Cook et al. 2004; Hatchett et al., 2015).

Periods of consistently narrow rings, indicating growth limitations related to drought, have been reported in several species of high-elevation pines in the Sierra Nevada as well as Basin and Range mountains in Nevada and eastern California (LaMarche, 1974; Graumlich, 1993; Scuderi, 1993; Millar et al., 2021). Stumps dating to this period have been found in Fallen Leaf Lake (Biondi et al., 2006; Kleppe et al., 2011) and in Mono Lake, Lake Tenaya, Osgood Swamp and the West Walker River (Figure 9, Stine, 1990; 1994), indicating substantially lower water levels. Isotopic evidence from Pyramid and Walker Lake sediments confirm drought at the time (Benson et al., 2002; Yuan et al., 2004).

Figure 9 Stumps in the Walker River dating to the Medieval Climate Anomaly ("Stine stumps"). C. Millar.

Deadwood dating to this period and located above the modern treeline indicates that temperatures were likely also quite warm (La Marche, 1973). Some of the remnant wood dating to the MCA was identified as belonging to primarily mid-elevation tree species that are not found at such high elevation (> 3000 m) today (Millar et al., 2006). On Mt. Grant in the Wassuk Range, limber pines that had been growing widely across southern and western slopes for at least the prior 1500 to 2000 years were extirpated by extreme drought of the MCA, and have not recolonized since (Millar et al., 2018). East slopes of Mt. Grant suffered reductions in stand density during this interval.

Tree-ring, remnant wood and lake sediment records also indicate a 50 to 100 year-long dry period in and around the 1400s. Tree-ring chronologies contributing to a Sacramento River reconstruction (Meko et al., 2001) and limber pine chronologies in eastern California and Nevada (Millar et al., 2021) indicate dry or very dry periods during this time. Lake levels in the region dropped as indicated by pollen and $\delta^{18}O$ in Pyramid Lake (Benson et al., 2002), submerged stumps in Mono Lake (Stine, 1990) and isotopic evidence from Walker Lake (Yuan et al., 2004).

5.3.2 Human Responses to the MCA

After the arid LHDP, exponential population growth returned until the megadroughts of the MCA once again challenged Indigenous Nevadans, who responded in three very different ways. Central Nevadans continued to rely on survival strategies honed during the LHDP (Thomas, 2020). They temporarily set aside some seasonal settlements when short climatic shifts impacted search times and encounter rates of critical resources, briefly abandoning alpine Alta Toquima in favor of subalpine basecamps to harvest seeds and geophytes. They repurposed Gatecliff Shelter from an abandoned man cave into a family friendly campground. Such abrupt environmental impacts played out differentially by elevation, and these alternating settlement strategies reflect a flexibility that helped ensure regional community sustainability without requiring internal structural changes.

Lovelock culture communities returned to the Lahontan Basin when the wetlands refilled after the LHPD, refurbishing previously abandoned settlements in the Black Rock Desert, Pyramid Lake, the Humboldt sink and Stillwater Marsh. Despite a millennium-plus absence from the marshlands, resilient Lovelock communities returned from their LHDP hiatus with the same baseline material culture intact. As their ancestral homeland once again abruptly turned inhospitable toward the end of the MCA, most of the Lovelock culture population moved westward over the Sierra Nevada and became ancestral to ethnohistoric Penutian-speaking groups such as the Maidu, Klamath and Modoc (Hattori, 1982; Camp, 2017). Although Northern Paiute people moved in to fill the void following the MCA, genetic evidence demonstrates that some Lovelock foragers decided to stay in the Lahontan Basin (Moreno-Mayar et al., 2018).

During the wetter intervals of the MCA, parts of Nevada could support the corn agriculture that spread into the Great Basin. Developing ties to the Puebloan cultures of the greater American Southwest, the Fremont (of eastern Nevada and Utah) and the Virgin Branch Puebloans (near Las Vegas) engaged in maize farming. Some Fremont became full-time farmers, some remained full-time foragers, and some practiced a mixture of farming and foraging interdependently (Upham, 1994 p. 118; Madsen and Simms, 1998; Roberts et al., 2022). Although temperatures during the MCA remained warm enough to grow maize, drought about 800 years ago led to the collapse of Fremont agriculture.

Virgin Branch communities in southern Nevada also adopted Ancestral Puebloan practices including maize dependence, ceramic production, and the construction of pit houses and pueblo architecture (Lyneis, 1995; Willis and Harry, 2019). At the same time, Virgin Branch populations also maintained deliberate ties to their Nevada roots and rejected the social hierarchies that characterized their Pueblo neighbors to the southeast. Despite the varying degrees of resilience among Great Basin farming communities, none survived the MCA.

6. THE FUTURE OF DROUGHT IN NEVADA

Whatever the weaknesses of existing climate records—observational, archaeological or paleoclimatological —they consistently show that Nevada is an arid state prone to both long and short periods of time when conditions were even drier than they are today. The paleoclimate perspective demonstrates that Nevada climates could return to conditions even drier than today, particularly because of the exacerbation of drought from rising temperature. Aridity and climate variability have long challenged Nevadans and caused them to adapt. There is no reason to think that the sort of variability shown in those records will fundamentally change in the coming decades and centuries. Nor are precipitation projections based on climate models included in the most recent IPCC report (CMIP6) particularly informative for Nevada, because of uncertainty about whether it will get wetter or drier and, if precipitation changes, by how much. Cook et al. (2020) indicate that northern Nevada, in fact much of the West, may be wetter in the winter under moderate emission scenarios, but there is not a clear change signal in other seasons. Temperatures are expected to rise (Hayhoe et al., 2018; McAfee et al., 2021). Higher temperatures have worsened and extended the current drought (Williams et al., 2020; 2022), and would have worsened past droughts that impacted the region had they occurred now (Woodhouse et al., 2021).

Understanding the potential for and consequences of future droughts and how megadrought has and will manifest across Nevada's landscapes, livelihoods, and communities in the context of temperature-driven aridification will require thoughtful integration of records of droughts prior to the 20th century with projected changes in climate and emerging information about the impacts of the current drought. The past has clearly shown that Nevada experiences many kinds and durations of drought, with diverse impacts, but future drought may be different still, owing to the impacts of much warmer temperatures and higher rates of warming. The current drought may be an exemplar of future droughts—an anticipated regional hazard that is exacerbated by climate change and contains local and seasonal complexities that influence the extent to which different people and environments experience the drought.

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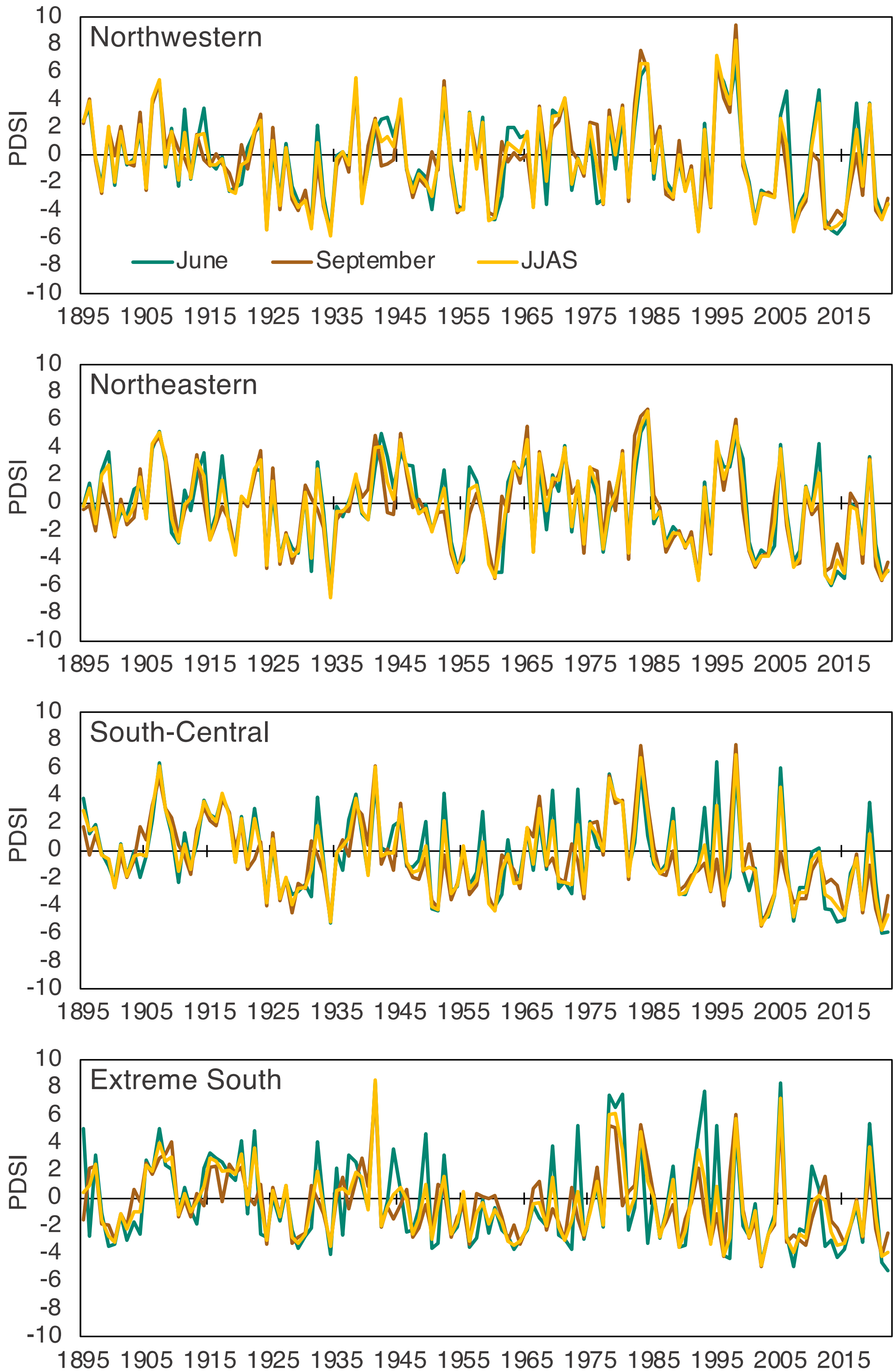

Supplemental Figure 1 Time series (1895-2022) of the June, Juen-September (JJAS) and September Palmer Drought Severity Index (PDSI) provided by NOAA Climate at a Glance for each climate division.