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Tree Ring Isotopic Reconstruction of Hurricane Dolores

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TREE RING OXYGEN ISOTOPE RECONSTRUCTION OF HURRICANE DOLORES

by

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BY

Jonathan Kane

B.S., Environmental Sciences, University of New Mexico, 2018

M.S., Earth and Planetary Sciences, University of New Mexico, 2022

ABSTRACT

Tree rings contain high-resolution climate proxies of temperature and precipitation (Hughes et al., 1982; Fritts 2012; Scuderi 1993). The objective of this study was to use tree ring cellulose, specifically measuring δ18O - the oxygen-18 to oxygen-16 stable isotope ratio- to investigate the impact of Hurricane Dolores, a tropical cyclone that produced heavy precipitation in the Sierra Nevada in July 2015. Prior studies (Berkelhammer and Stott, 2008, 2009) have shown that conifer forests in California record the influence of varying precipitation regimes in their ring alpha-cellulose.

Hurricane Dolores produced an intense precipitation event that inundated parts of the Mojave Desert (Means, 2019) and the southern Sierra Nevada, California (Scuderi 2017). Rainfall from this event fell during the middle of a multi-year drought minimizing potential water sources for plant growth with the exception of Dolores. Radar imagery and soil sensor data record Hurricane Dolores infiltrating and saturating the soil of some sites to below the

rooting zone while other sites were unaffected without measurable precipitation. This study investigated whether trees located at inundated sites in the southern Sierra Nevada recorded this extreme Hurricane Dolores precipitation event within their cellulose. It was hypothesized that due to the hurricane's lighter isotopic values that this event would be recorded as depleted isotopic cellulose values reflecting Dolores' impact at inundated sites.

Alpha-cellulose analysis shows that while the six study areas had varied isotopic responses, no response was indicative of Hurricane Dolores. Potential explanations for this lack of a hurricane signal include the mixing of soil waters, the height of condensation, and more importantly evaporation. The most likely explanation for a lack of isotopic signal within the cellulose is that evaporation during the drought surrounding 2015 enriched available soil water leading to a manifestation of heavier isotopic values within the cellulose record. These intricate relationships altering source water make it difficult to correlate extreme storm events with isotopic values of tree cellulose in California (Bale et al., 2010; de Boer et al., 2019).

TABLE OF CONTENTS

LIST OF FIGURES

TABLES

Chapter 1

Introduction

Oxygen isotope values in tree ring cellulose from tree ring records reflect water used in growth. Under ideal conditions, this oxygen isotope record has been proposed as a store of a possible record of precipitation isotopic values (Berkelhammer and Stott., 2008, 2009; Miller et al., 2006;Rinne et al., 2013; Voelker and Meinzer 2017). A plethora of studies now exist that use stable isotopes to correlate climatic events through time within the tree ring record (Berkelhammer and Stott., 2008, 2009; Miller et al., 2006; Poage and Chamberlain 2001) and to reconstruct past climatic conditions. Isotopic records are one method that can be used to overcome the lack of directly measured meteorologic and climatic data before ~1850 AD. Other research uses records from speleothems (Managave 2014), lake cores (Anderson and Smith 1999), ice cores (Epstein 1995), and other paleoclimate proxies (van Hengstum and Scott 2011) to reconstruct past meteorological/climatic events.

Before the mid-1900's sparse meteorological records make it difficult to extract long-term fluctuations and changes in precipitation regimes. Weather stations have limited coverage over the United States and have reliably recorded weather conditions for the past 120 years at best. Technological advances have greatly increased our ability to correlate proxies with past climate. In recent decades, stable isotopes have opened a wide range of avenues to research past climates and have greatly improved our understanding of the history of climatic events.

The state of California is currently facing drought impacting industries like agriculture and land management. Four-fifths of all business and residential water use in California relates to agriculture (Hanak et al., 2011). Currently precipitation projections trend toward occurring less frequently while precipitation extremes intensify (Dettinger et al., 2011). Adding to the drought predictions, population growth in California will likely result in significant increases in water demand. Along with the previously mentioned predicted changes, projections show snowmelt occurring earlier in the season resulting in a less sustainable water supply in spring and summer. These compounding trends suggest a less secure water supply with insecurity intensifying as the climate continues to warm (Dettinger et al., 2001). We know which direction projected precipitation will trend, however, there is still a large uncertainty associated with future water supply estimations (Hanak et al., 2011). Hence, it is essential to understand how extreme precipitation regimes may be changing to improve predictions of California's water supply and long-term trends.

Understanding the frequency of extreme precipitation events is especially important in California. Extreme precipitation falls on California as atmospheric rivers, tropical cyclones, and subtropical cyclones. California receives most of the expected annual precipitation over a few large storm events with some of the largest three-day storm events in the United States. (Dettinger et al. 2011). Furthermore, large precipitation events frequently end droughts in the western United States (Dettinger 2013). Hence, to better predict California's future water supply, one must quantify the occurrence of extreme precipitation events.

Prat and Nelson (2013) noted that landfalling tropical cyclones caused the United States over 370 billion dollars in economic losses and resulted in more than 3750 deaths between the early 1950s and the mid-2000s. This statistic is important and of concern, as the number of humans exposed to tropical storms has tripled since the 1970s (Peduzzi et al., 2012). Projections show the frequency of tropical storms fluctuates with changing climate, and the predicted heightened intensity of tropical cyclones will likely significantly increase damage in the future (Emanuel, 2008). Understanding how extreme precipitation event frequency and magnitude change over time will allow for better risk assessment to better mitigate future catastrophes.

This study will use the oxygen isotope record within tree rings to evaluate the impact of a singular extreme precipitation event on the southern Sierra Nevada , namely Hurricane Dolores. Hurricane Dolores traversed the southern Sierra Nevada during a period of extreme drought. Ongoing evaporation associated with drought leads to enrichment of isotopic values of waters which we believe will contrast with the isotopically light values of tropical hurricanes. (Roden et al., 2000). Therefore, we hypothesized that we will see precipitation from Hurricane Dolores manifested within the tree ring record as isotopically light oxygen isotope values.

Chapter 2

Scientific Background

Isotopic Measures from Tree Rings

Paleotempestology is an emerging field studying past extreme storm events utilizing tree rings, ice cores, speleothems, corals, and other paleoclimate proxies as a solution to filling gaps in the climate record (Hippensteel, 2010; Managave 2014; Muller et al., 2017). Trees are a useful paleoclimate proxy due in part to their global spatial distribution unlike proxies such as ice cores or corals that only exist in limited geographic distributions. Tree rings have the potential to provide both annual and sub-annual resolution proving useful information on recurrence intervals of tropical storms long past the reach of instrumental records (Muller et al., 2017).

The first paleotempestologic application of dendrochronology was by Pillow (1931) who noted that trees form reaction wood in response to high-velocity winds. More recently, studies in the southeastern United States (Lewis et al., 2011; Miller et al., 2006) have used oxygen isotope records in longleaf pine (*Pinus palustris* Mill.) tree rings to track cyclonic events. On the western coast of the United States, coastal redwoods (*Sequoia sempervirens*) in California have shown the potential to capture climatic conditions within intra-annual variation in the stable oxygen and carbon isotope ratio within tree ring cellulose. (Carroll et al., 2014; Johnstone et al., 2013). Oxygen isotopic analysis of ponderosa pine (*Pinus ponderosa*) chronologies in the southwest have the shown cellulose's isotopic values reflect precipitation composition in the region (Roden and Ehleringer, 2007). Complimentary studies in California's White Mountains utilizing bristlecone pine (*Pinus longaeva*) (Berkelhammer and Stott, 2008, 2009) have attempted to track precipitation regime change in the White Mountains. However, no Californian studies have addressed the issue of documenting extreme precipitation events through isotopic studies.

In the southeastern United States, several studies exist tropical cyclone activity to the isotopic values of tree rings (Miller et al., 2006; Lewis et al., 2011). The extremely light isotopic values associated with hurricanes are potentially distinguishable within the tree ring record from other normal precipitation years in this area. Dansgaard (1964) coined the term 'amount effect', defined as precipitation preferentially raining out heavier isotopes over lighter isotopes. This effect results in precipitation events raining out larger percentages of heavier isotopes first, leaving precipitation isotopically lighter. Hence, extreme storm systems leave behind isotopic signals unique to the amount of rainout occurring. The question asked by this study is whether the isotopic signature from Hurricane Delores is visible in the cellulose record.

Precipitation's isotopic values are controlled by temperature, humidity, condensation height, and atmospheric circulation (Berklehammer et al., 2007). Once water percolates into the soil it has the opportunity to be altered before and after being incorporated by trees, leaving waters with distinct isotopic values. Evaporation is the most important factor altering isotopic values in dry places such as the southern Sierra Nevada (Roden et al., 2000). Soil water under evaporation will get heavier as the lighter isotopes preferentially evaporate (Tang and Feng 2001). Water can also change as the plant incorporates the water; the movement of water affects the fractionation of oxygen isotopes. The transportation of water from roots to stems and then stems to leaves alters the original composition (Roden et al., 2000).

Trees use available soil water and incorporate that water into their annual cellulose records (Roden et al. 2000, Saurer 2003). For the forests of the Sierra Nevada to store climatic information related to precipitation events, they must primarily be utilizing the water from precipitation. Vegetation in the Sierra Nevada has access to several reservoirs of precipitation stored below ground. More recent storm events are stored near the surface as soil water (Hubbert et al., 2001). Previous years' residual precipitation is stored within eroded bedrock and bedrock fractures (Hubbert et al., 2001). The conifer species selected for study in the Sierra Nevada (*Pinus balfouriana*, *Pinus contorta, pinus flexilis, and pinus jeffreyi*) have relatively shallow root growth but are known to tap into deeper reservoirs if water availability is sparse (Hubbert et al., 2001, Thaw et al., 2021).

Precipitation from each year is stored below ground in the soil and eroded bedrock. This store provides a source of water that is a combination of rainfall from multiple precipitation seasons. Large tropical cyclone events like Hurricane Dolores have rainfall that produces artificial isotopic tracers displayed as relatively light oxygen isotope values compared to the average precipitation event and has the potential to be identified in tree-ring records (Dansgaard 1964). Since summer rainfall typically is heavier with evaporative processes further enriching soil water, we predict that the light oxygen values from the anomalous Hurricane Dolores stand out even more.

Another large determining factor of the isotopic values of source water is the height of condensation. Buenning et al., 2012 modeled the isotopic values of precipitation along the western United States and found the main driver of isotopic values of precipitation is the height of condensation. Winter precipitation is generally light isotopic values compared to heavier summer precipitation values (Buenning et al., 2012). This is due to a vertical isotopic gradient, where winter precipitation derives from the upper/middle troposphere and summer precipitation originates in the lower troposphere (Buenning et al., 2012).

The western United States lacks the same coverage of isotopic studies related to precipitation and there exists a need to understand the complex relationship between precipitation regimes and the tree ring record in the region. The spatial distribution and intensity of Hurricane Dolores coupled with the ongoing drought in California at the time of inundation offer an ideal experiment to test whether trees in the Sierra Nevada will be useful proxies for identifying extreme precipitation events in the state.

Hurricane Dolores occurred in the middle of a multi-year drought at a time when the more accessible water sources were more likely to be depleted. At that point, trees begin to access deeper water sources including isotopically depleted water in bedrock fractures (Thaw et al., 2019). During a drought, water is scarce, so the trees are more likely to use the water supplied by Hurricane Dolores once the precipitation fell (Thaw et al., 2019) in California.

Stable isotope values of stream water and groundwater (Williams and Rodini, 1997) show that both stream and soil water from the Sierra Nevada have an oxygen isotope values range of ~10 ‰. Winter rainfall in the Sierra Nevada averages oxygen values of -8 ‰ due to the increased distillation from atmospheric river events (Johnstone et al., 2013). Thaw et al., 2019 found that the values from an observatory adjacent to our study areas at a similar elevation (2000m) have rainfall values that range from – 14.82 ‰ to 2.95 ‰. Thaw found a sinusoidal relationship in terms of precipitation seasonality with heavier precipitation values in the summer and lighter values in the winter (Thaw et al., 2019). Precipitation monitoring in the Sierra (Friedman et al., 1992) showed that the nearby Lone Pine California averaged -9.55‰ with 6-month measurements over several years. A study probing Hurricane Olivia found isotopic values that averaged -18.35‰ and -21.85‰ (Gedzelmen et al., 2003). Values of hurricanes are lighter than the normal precipitation in the Sierra therefore we expect to see this manifestation in the tree record. While we do not know the exact isotopic value for Hurricane Dolores' rainfall, given the storm's rainout and tropical origins, we expect to see light isotopic values (Dansgaard, 1964). We predict that isotopic tracers associated with Hurricane Dolores will manifest in the cellulose record within our study area.

Study Area

The two general study areas for this research were Beach Meadow (BM) and Horseshoe Meadow (HM) in the southern Sierra Nevada (Figure 1). Study site locations are mid- to-high-altitude mountainous and subalpine areas, with elevations ranging from 2300 to 3000 meters. Increment coring occurred at six locations: three were inundated by

Hurricane Dolores and three were untouched by the extreme precipitation event. The selection of sites for analysis was determined based on radar data from the area at the time of Hurricane Dolores. Prioritization of trees for coring was also related to the species present at each site and the ease of access.

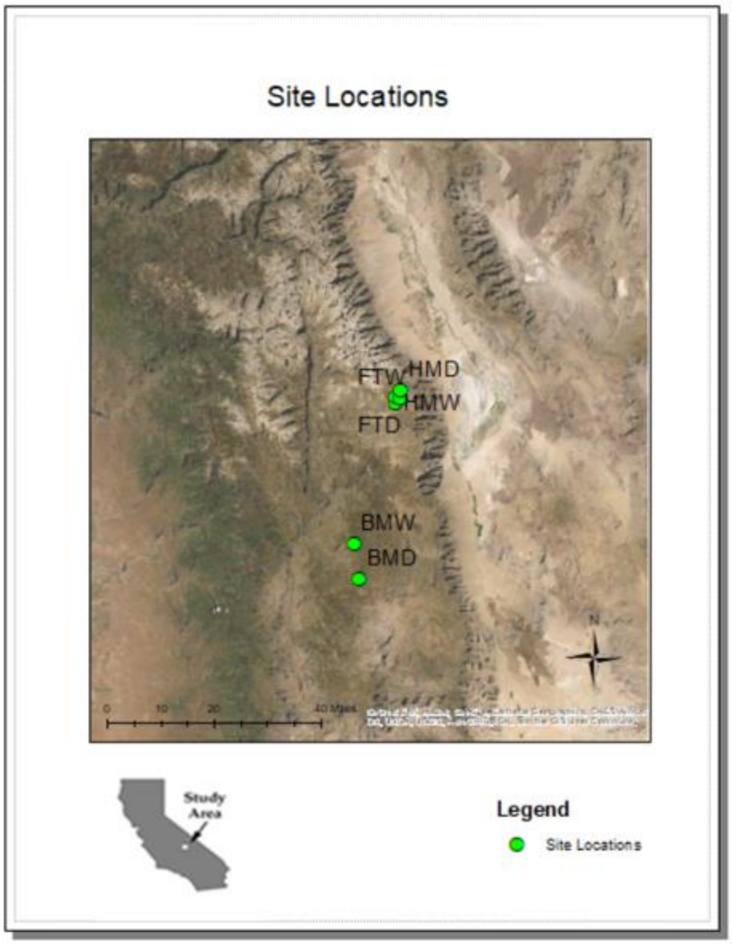


Figure 1: Study area map. Sites are Horseshoe Meadow (HM), Foxtail (FT) and Beach Meadow (BM). D and W designate Dry and Wet subsites respectively.

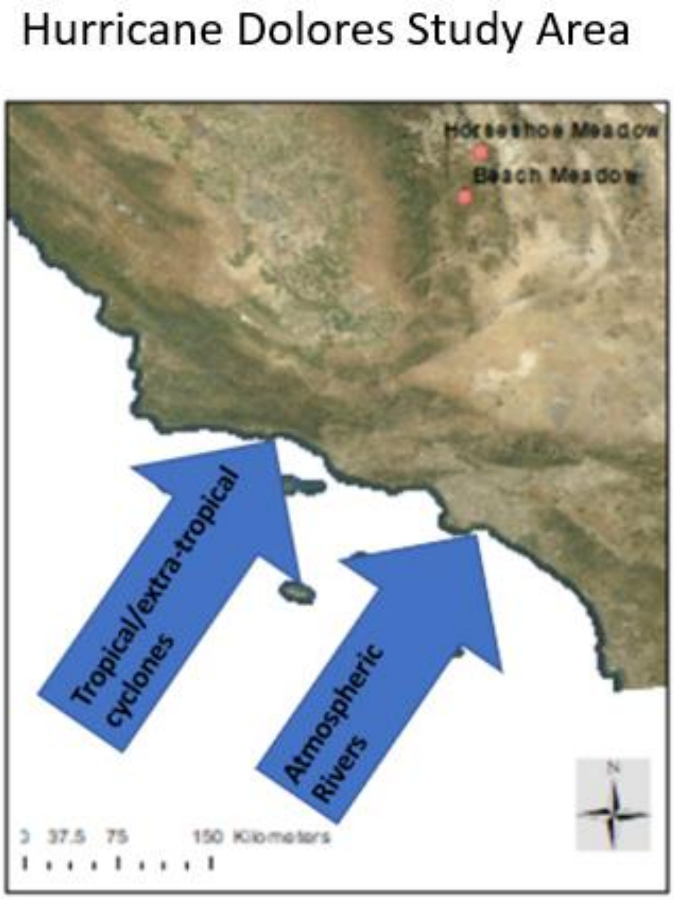


Figure 2: Map of the study area displaying southwesterly precipitation inputs for the region.

Climatology, storm tracks and isotopic variability

California's Sierra Nevada (Figure 1) receives most of its precipitation from a few large storm events each year, relying mostly on warm and wet winter storms (Dettinger et al., 2011). The study area within the southern Sierra Nevada (Figure 2) has complex local meteorology with precipitation input from the North Pacific, tropical cyclones, atmospheric rivers, subtropical cyclones, and rare monsoonal storms generating a range of precipitation isotopic values (Friedman et al., 2002). The general climate of the region is Mediterranean with dry summers and wet winters. Meteorological conditions in the region both preceding and following Hurricane Dolores were dry with the southern Sierra Nevada undergoing the worst multiyear drought on record (Swain 2015). The year 2015 was one of the driest on record with little to no winter snowfall at all sites and above-average temperatures (Swain 2015).

The Sierra Nevada experiences precipitation from storms derived from several different source areas. The region experiences precipitation with varying isotopic values both seasonally within a given year and occasionally from storms originating far beyond the normal source regions, and specifically eastern Pacific hurricanes and atmospheric rivers. Storms originating in the North Pacific have relatively depleted isotopic values lacking in heavier oxygen isotopes (Benson and Klieforth, 2013), summer storm precipitation that generally originates in the subtropics has relatively enriched isotopic values lacking in lighter oxygen isotopes (Benson and Klieforth, 2013).

General Geology/Geomorphology

The Sierra Nevada has a complex geologic history shaped over tens of millions of years by uplift, erosion, volcanism, and glaciation (Mix et al., 2016). The Sierra Nevada batholith forms the core of the mountain range exposed at the surface primarily as granite and granodiorite (Royce and Barbour 2001). Soils eroding from the batholith are generally thin and rocky with low fertility (Erman et al., 1997). Despite the low nutrient availability and high soil permeability, the Sierra Nevada supports a variety of diverse plant life.

Coarse soil eroded from the granitic batholith drains quickly and allows precipitation to percolate through the surface layer before absorption of the water by plants (Mastrogiuseppe and Mastrogiuseppe, 1989). Beneath this rocky surface layer lies weathered bedrock with a relatively large water storage capacity (Hubbert et al., 2001). Conifers and shrubs in the area have the potential to root into the weathered bedrock giving them access to water from past precipitation and snowmelt (Thaw et al., 2021). Fractures within the bedrock have additional water storage capacity (Hubbert et al., 2001)

The existence of course soil and underlying bedrock retaining water are why we believe that trees used the precipitation from Hurricane Dolores at sites inundated by the event. A recent study (Thaw et al., 2021) showed that forests in the Sierra tend to switch water sources from soil water to deeper water stored within the bedrock matrix depending on availability. Due to the ongoing drought in the area, we hypothesized that deeper water sources were becoming more and more depleted over time due to evaporation. We hypothesize that once Dolores precipitation began, vegetation in the area used the much-awaited rainfall. Vegetation growth in the Sierra Nevada is largely dependent on both the availability of water as well as access to deeper water sources so we expect to see noise associated with past precipitation in the record.

Species Studied

The Sierra Nevada is home to a variety of diverse flora with much of the region classified as vegetated (Fites-Kaufman et al., 2007). Host to more than 3,500 native species of plants; the Sierra Nevada accounts for more than 50% of California's plant diversity (Erman et al., 1997). The species present in the Sierra Nevada used in this study consists of a variety of coniferous trees. Specifically, lodgepole pine (*pinus contorta var. murrayana*), foxtail pine (*pinus balfouriana*), limber pine (*pinus flexilis*), and jeffery pine (*pinus jeffreyi)* are used in this study.

Lodgepole pine is a two-needled pine present throughout much of the Sierra Nevada. This resilient species has large environmental tolerance living in a wide variety of environments. The lodgepole pine grows in association with many plant species but also grows in pure stands (Lotan and Critchfield, 1990). Lodgepole pines are more tolerant of poor soils than other species (Fites-Kaufman et al., 2007). Groups of lodgepole pines are often found on the poorly drained and infertile soils of the granitic batholith present in the Sierra Nevada where no other tree species will grow (Lotan and Critchfield, 1990). Average heights of lodgepole pines range from 28 to 30 meters in the Sierra Nevada with a greater sustained diameter growth than in other lodgepole pine forests (Lotan and Critchfield, 1990).

In addition to greater diameter growth, lodgepole pines have shallow root systems. First-season seedlings have an average root depth of approximately 10 cm (Lotan and Critchfield, 1990). The combination of greater yearly diameter growth and shallow root systems makes lodgepole pines an ideal species for this study. The greater diameter will result in more available cellulose material for sampling. Shallow roots ensure that the trees sampled will take advantage of the nearest water source within the root zone.

The dominant subalpine species in the Sierra Nevada is foxtail pine (Fites-Kaufman et al., 2007) which is found within an elevation range of 2300m to 3600m (Bailey 1970; Scuderi 1987, 1993). Foxtail pines have five needled fascicles and are distinguishable from related species by their 1–2-centimeter cone peduncles hanging from branches with a shallow rounded cone base (Mastrogiuseppe and Mastrogiuseppe, 1989; Tomback et al., 2011). In the Sierra Nevada, foxtail pine populations exists in extensive and nearly pure forests with widely separated trees and little understory vegetation (Mastrogiuseppe and Mastrogiuseppe, 1989). The trees often grow in twisted and distorted forms allowing for easy identification (Mastrogiuseppe and Mastroguiseppe, 1989). Foxtail pines are long-lived trees with individuals attaining maximum ages of 2500-3000 years in the Sierra Nevada (Mastrogiuseppe and Mastroguiseppe, 1989; Scuderi, 1987, 1993). The longevity of foxtail pines makes for an ideal species for this study, as it allows cross-dating and the creation of a long site chronology.

Limber pine (*pinus flexilis*) and jeffery pine (*pinus jeffreyi*) were sampled due to the availability of tree species at sampling sites Beach Meadow Wet and Beach Meadow Dry respectively. Identifiable by five needles per fascicle, limber pine is distinguishable from other white pine species by a lack of resin dots on needles. Limber pine is a highly adaptable species and is found all over North America in a wide range of growing conditions. Within the Sierra Nevada, limber pine grows on steep and eroded sites, soils that are generally nutrient-limited (Fites-Kaufman et al., 2007). In the Sierra Nevada, limber pine forests tend to be limited to the 2500m to 3000m range (Millar et al., 2007). Limber pine is a long-lived species and is useful in dendrochronological studies (Millar et al., 2007).

Recognized by three relatively long three-needled fascicles, jeffrey pine is a potentially long-lived species that provides an extensive climate record (Valliant and Stephens 2009). Jeffrey pine’s climate record has proven useful in dendrochronological studies, and the species is widely used in climatological studies. (Valliant and Stephens 2009). Jeffery pine has been known to access water stored in bedrock fractures making the species more resilient to climate change (Hubbert et al., 2001).

Data Collection Rationale

For isotopic variations within tree ring cellulose tree ring isotope records to be useful for quantifying past precipitation regimes, we must be certain that trees in the study are utilizing soil water (Managave, 2014; Berklehammer and Stott, 2008, 2009). Within the Sierra Nevada, the bulk of precipitation arrives in the winter, unused until the forests’ growing season in mid-to-late spring to mid-summer. Precipitation percolates through the soil matrix and is stored beneath the surface. This soil water is representative of a mix of waters from the winter snowpack as well as any other accumulated precipitation (Berkelhammer and Stott 2008). However, evaporation and transpiration processes can alter both soil water and tree water’s isotopic composition (Tang and Feng 2001). Additionally, different tree species have varying root system depth and organization potentially allowing access to water from both near-surface and underground storage

(Thaw et al., 2019). Forest trees in the Sierra Nevada have been shown to use different water sources as water supply changes (Thaw et al., 2019). This places constraints on two important factors, available soil water and depth of root systems.

Likely, the inundation from Hurricane Dolores, which occurred during one of the driest periods in the historical record from the Sierra Nevada (Figure 3) replaced existing, and possibly high-depleted soil water stores with precipitation from the storm itself. Images from the inundated sites following the Hurricane Dolores event show massive sediment overland flows resulting from the large downpour (Figure 4. See also Scuderi, 2017). Soil temperature sensors at a depth of 10cm, first emplaced in 2012 at the Horseshoe Meadow site, indicate that the soil in the rooting zone was rapidly saturated to at least 10-15cm during the rainfall event with temperatures dropping rapidly from ~15C to near 0C in ~15-30 minutes (Figure 5). Soil temperature sensors combined with radar data (Figure 6) allow us to identify areas impacted by Hurricane Dolores precipitation.

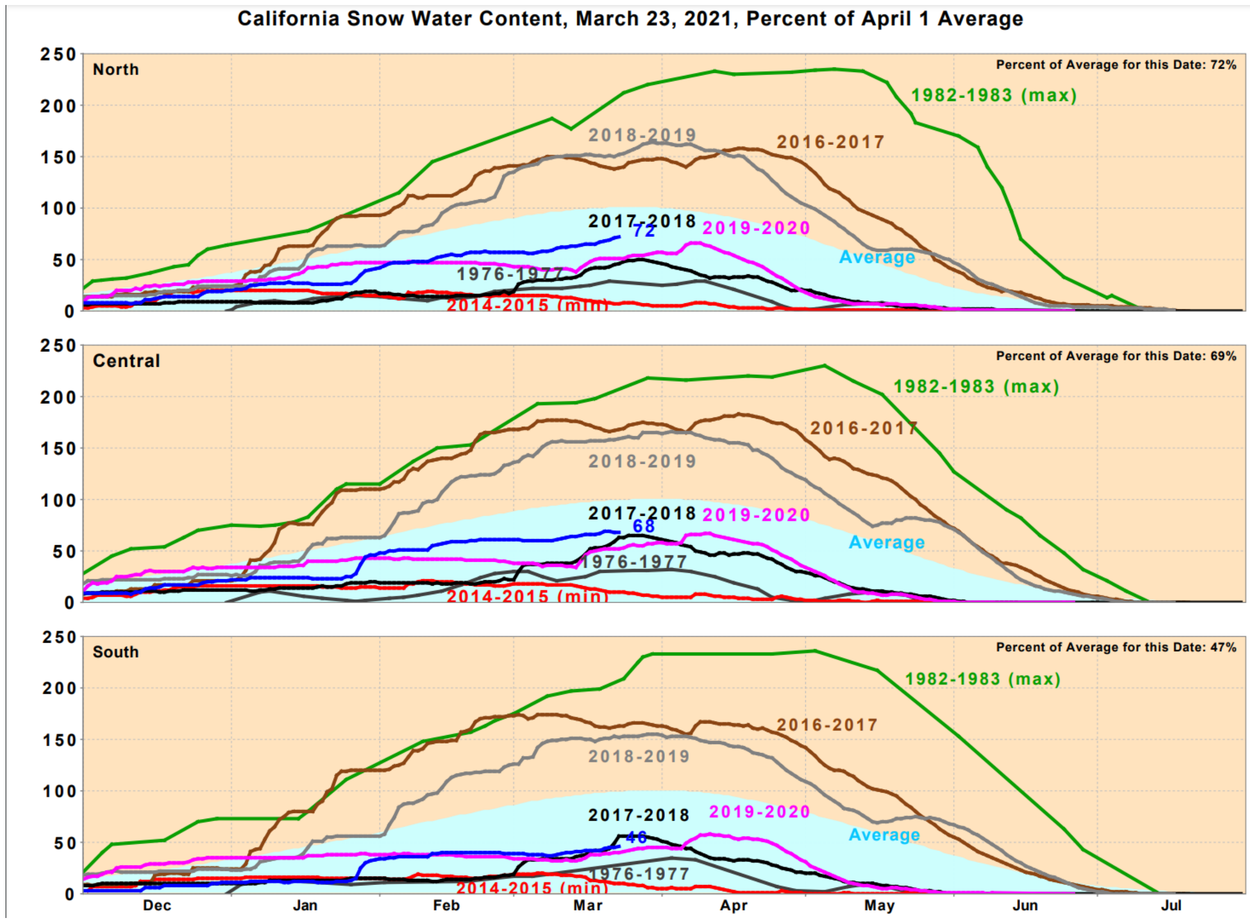


Figure 3. Snow water content for Sierra Nevada sites derived from snow course and sensor data 1931-2021. The minimum in all Sierra Nevada zones was at an extreme minimum during the winter of 2014-2015 occurring during a persistent drought from 2012

to late 2016.

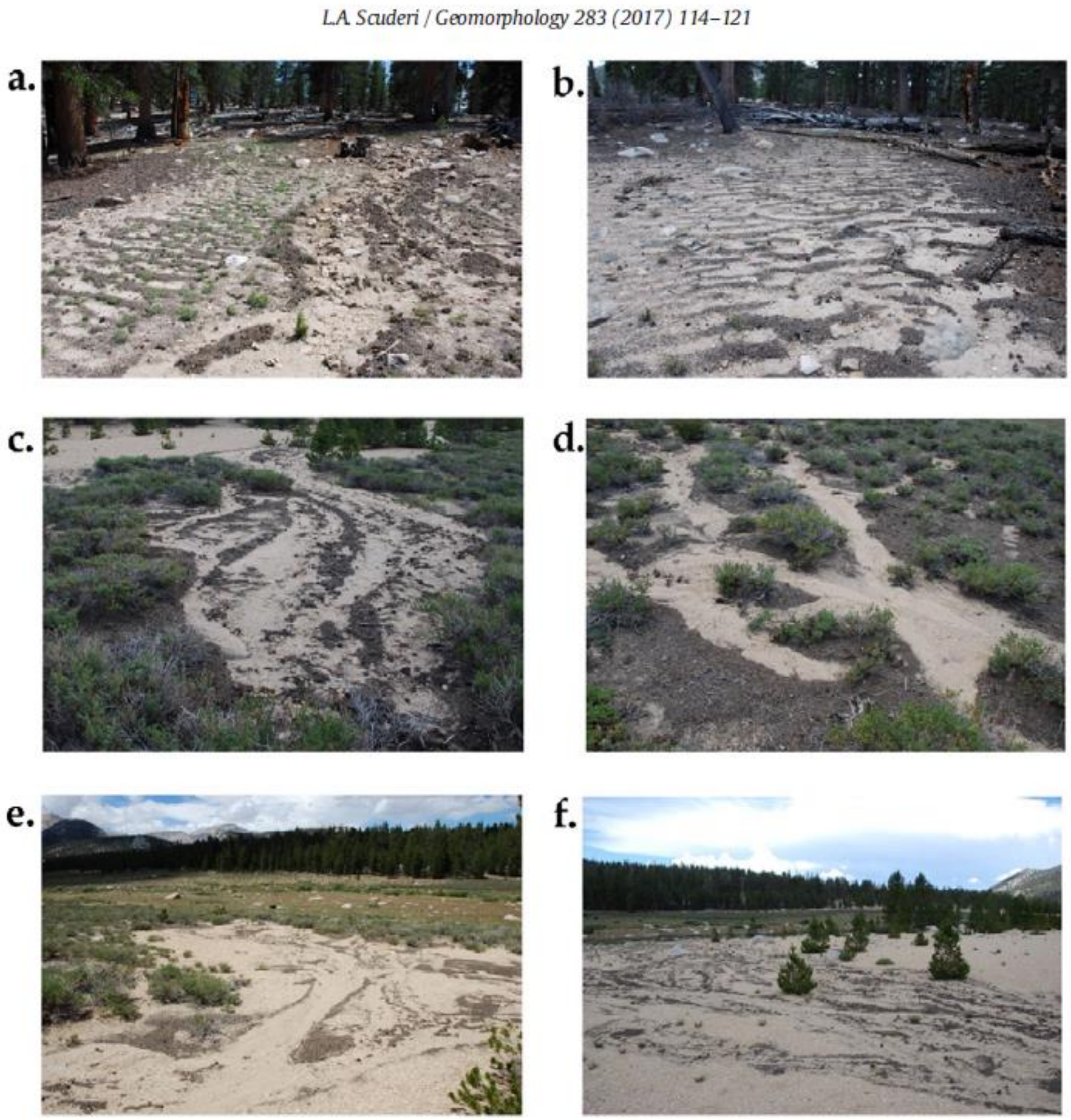


Figure 4. Depiction of the significant impact of Hurricane Dolores at Beach Meadows. After, Scuderi, 2017.

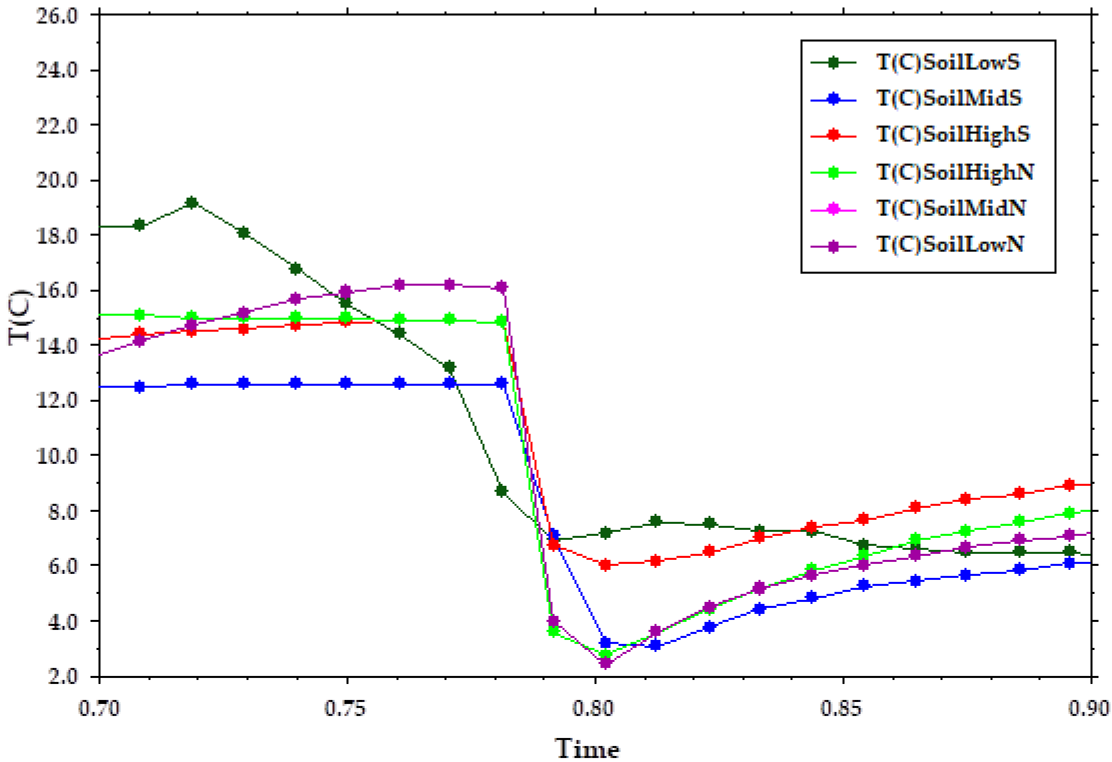


Fig. 5. Soil temperatures from the Hurricane Dolores event. The sudden temperature drop of 12 to 15C in 15 minutes is associated with the saturation of the soil from the precipitation event. The time axis is decimal day for the July 21, 2015 Hurricane Dolores event.

Royce and Barbour (2001) found that average drought-period precipitation does little to replenish soil moisture. Replacement of old and depleted soil water is possible with large storms exceeding 100 mm of precipitation (Tang and Feng, 2001). With an ongoing drought occurring in the Sierra Nevada during the 2014-2015 water year, we assume that replacement of soil water was minimal until the next major storm. The next large precipitation event did not occur until late 2016. Therefore, the soil water available for the trees at our inundated sites during 2015 and 2016 likely and predominantly includes water from Hurricane Dolores.

We hypothesize that the trees in our study site used the precipitation from Hurricane Dolores as a significant water source for the 2015 year. We predict this use of Dolores water will manifest as a light isotopic signal in the latewood cellulose of trees inundated by the storm event. Hurricane Dolores brought over 200 mm of precipitation in the first two hours of the storm (Figure 6) which is sufficient to replenish soil moisture at depths up to 50cm below the surface (Tang and Feng, 2001).

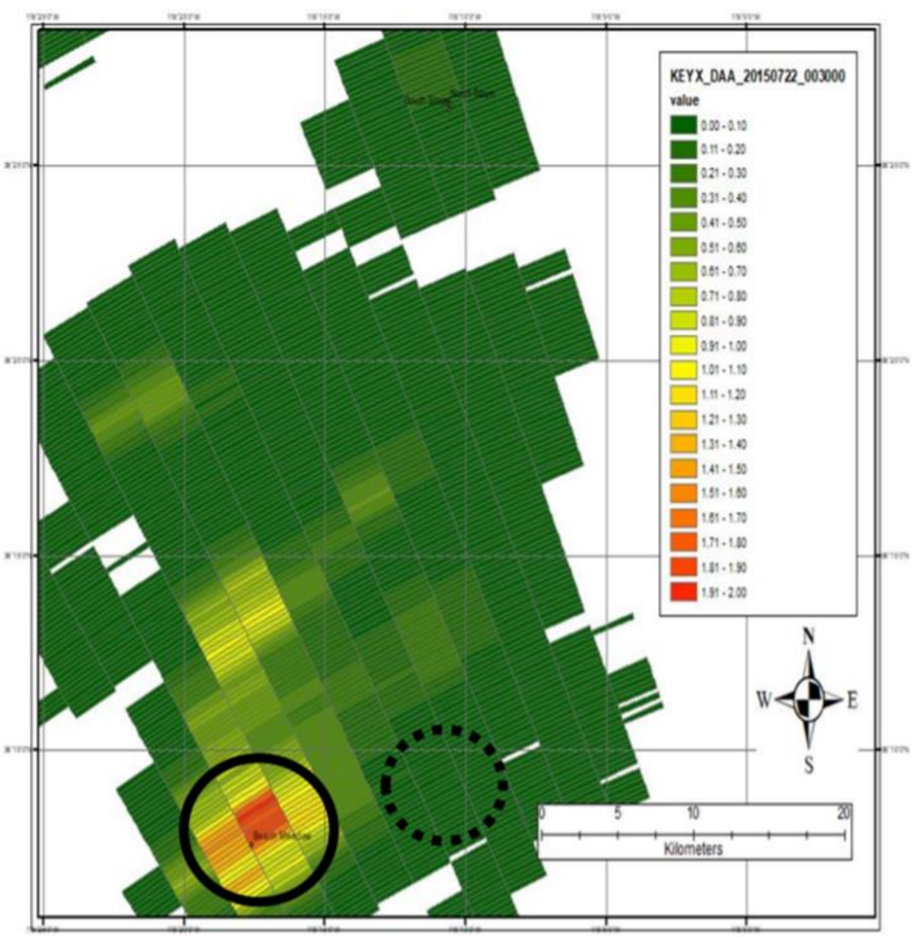


Figure 6: Six-minute precipitation rate radar data (00:30 UTC July 22, 2015 = 5:30PM PDT July 21, 2015). Beach Meadow Sample Area (solid circle - 11.8cm event rainfall) and non-inundated control site (dashed circle - 0.0cm event rainfall). This cell rapidly moved northward and inundated the Horseshoe Meadows site ~ 45 minutes later.

Severe long-term drought before and after inundation by Hurricane Dolores provides the ideal conditions to determine whether tree ring cellulose stores the isotopic signals of variable precipitation in the Sierra Nevada. Persistent drought surrounding the Dolores event minimizes recent inputs into soil water other than Hurricane Dolores. The local variability in precipitation, with some areas immediately adjacent to (less than 2 kilometers away) our primary study sites receiving no input from Hurricane Dolores nor from any other precipitation source prior to precipitation from a subsequent January 2016 snowstorm provides a control on our results. As such, we expect these control sites to show no change in the isotopic signal.

In selecting tree species for sampling, additional selection criteria for short root systems were applied. Conifers in the Sierra Nevada used soil water available to them and the isotopic composition of the soil water reflects in the cellulose δ18O record (Johnstone et al., 2013; Thaw et al., 2019). Species with shallower root systems are less likely to have access to underlying aquifers and thus more likely to use available soil moisture from the inundation event (White et al., 1985, McCarroll and Loader 2004). These controls are more reasons why we expect to see Hurricane Dolores in the cellulose record.

Chapter 3

Methods

Field area

Trees were sampled in the Sierra Nevada at two sites: Beach Meadow and Horseshoe Meadow over a five-day period in July 2021. The Beach Meadow wet site had experienced rainfall from Hurricane Dolores exceeding 200mm in the first two hours of the downpour (Figure 6). Analogous inundation is recorded at the Horseshoe Meadow wet sites. Control (dry) sites, as evidenced from radar data, are adjacent sites that remained dry during the Hurricane Dolores event (Figure 6).

To ensure that we collected samples from trees that use shallow soil water, we first identified tree species with shallow root systems; preferentially foxtail pine and lodgepole pine. Forests in the Sierra have decreased root density due to the poorly developed soils but trees with taproots in bedrock have the potential to expand more extensively (Hubbert et al., 2001). However, an absence of these species in abundance at the Beach Meadow site led to alternatively sampling both limber pine and jeffrey pine.

Multiple trees were sampled from each site, with two or more cores extracted from each tree to ensure sufficient material for isotopic evaluation. Cores were collected according to standard dendrochronological controls: breast height extraction, the increment borer penetrating to the pith, and a minimum of two cores per tree. An initial goal was to create short, ~150-year chronologies for each study area to allow accurate cross dating of samples. The collected core set consists of one hundred and ten cores. Chronology creation only used 75 cores due to difficulties processing and dating samples involving breakage and visibility of ring boundaries after sanding.

We predict that due to the magnitude of the precipitation input from the tropical Pacific storm Hurricane Dolores, trees at inundated sites will reflect lighter δ18O values. Unaffected sites were our control sites, as they received no measurable precipitation from Hurricane Dolores. We hypothesized that non-inundated sites, in contrast to inundated sites, would exhibit shifts in δ18O values that trend toward heavier values relative to the affected sites. This extreme precipitation event occurred in the middle of an extraordinarily dry year; hence, we also assumed that the trees used precipitation from Hurricane Dolores and predicted that the δ18O of our tree rings will then reflect the isotopic value of the source water.

Standard dendrochonologic field collection typically uses 10-20 trees per site to create a replicated chronology, however, isotopic analysis requires fewer trees with some studies reporting significant results from the analysis of a single tree (Leavitt 2010). Maximizing the numbers of cores collected was implemented in part to have ample cores in case of any errors during sample processing. Owing to the limited availability of cellulose material due to narrow rings, most samples required two cores to provide sufficient cellulose for isotopic analysis. Additional motives behind collecting a surplus of samples are to provide enough material for isotopic analysis and future research projects.

LABORATORY WORK

Processing of the tree cores starts with sanding to a progressively finer grain. Scanning of the cores after sanding used a high-resolution scanner to develop images of the cores. The counting of growth rings in individual cores from the imagery was semi-automated with each ring measured to the nearest 0.001mm using Cybis' CooRecorder and standardized using readily available tree ring analysis software CDendro (L Larsson, L. (2022) CooRecorder and Cdendro Programs of the Coorecorder/Cdendropackage Version 9.8).

Standardized cores were cross-dated with the collection of cores from each site to compile the cores into roughly 150-year chronologies at each site. Response functions were created for all sites using local meteorological data (https://cdec.water.ca.gov/index.html). Sample selection for isotopic analysis is based on several attributes, including but not limited to the availability of material from the Hurricane Dolores year, correlation with the chronology in earlier years, ring growth sensitivity, and a lack of alteration of samples such as compressed or missing rings.

Cross-dated samples allowed absolute identification of specific annual target rings for δ18O analysis. To perform this analysis, we identified target year rings under magnification and then isolated samples from each site using a scalpel. Samples were weighed to ensure they provide sufficient material for isotopic analysis. Our procedure required a minimum of 9 mg of cellulose for analysis. If samples did not meet the weight requirement, then the additional samples collected from each tree were used to supplement the initial sample. Using two cores from each tree was required for most sites to have sufficient material for analysis. It is necessary to process cellulose to remove mobile components in the wood as well as to remove components that have compositions that are not isotopically stable. (Berklehammer and Stott, 2009). Therefore, after isolation of individual rings, cellulose was converted to α-cellulose for analysis.

This study uses a modified Brendel method to convert cellulose to α-cellulose (Boettger et al. 2007, Gaudinski et al., 2005). The modified Brendel method is used due to the method's efficiency and ability to accommodate small sample sizes. Resins and waxes leftover from the traditional Brendel method can alter oxygen and carbon values, making it a flawed method for alpha-cellulose extraction (Gaudinski et al., 2005). The modified Brendel method uses a NaOH wash that effectively removes any plant matter left behind from the traditional Brendel method (Gaudinski et al., 2005).

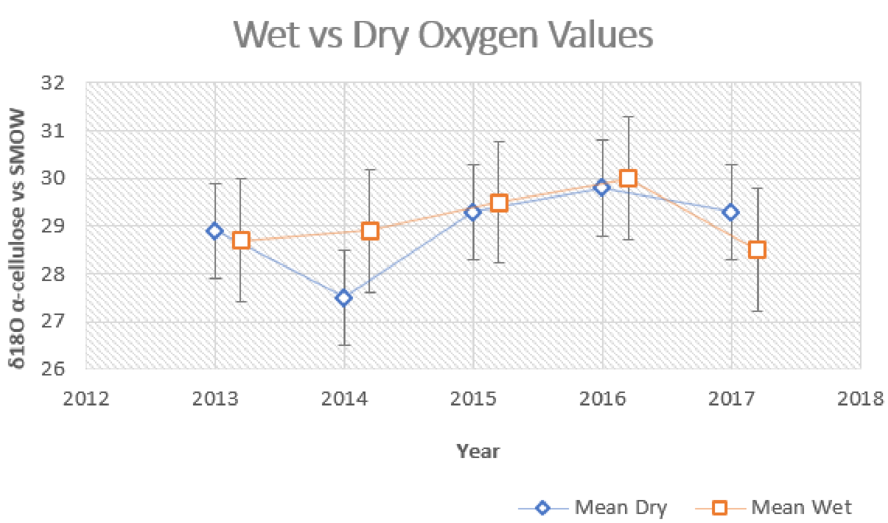
Individual rings were cut into fine pieces by hand to avoid potential contamination or a loss of material consistent with grinding (Brienen et al., 2013). Cellulose digestion in a soxhlet apparatus using toluene and ethanol removed resins within the wood. This was followed by bleaching of the sample with acetic acid and sodium chlorite with intermittent distilled water washes. Finally samples were subjected to rinsing and purification of the samples using a sodium hydroxide solution.

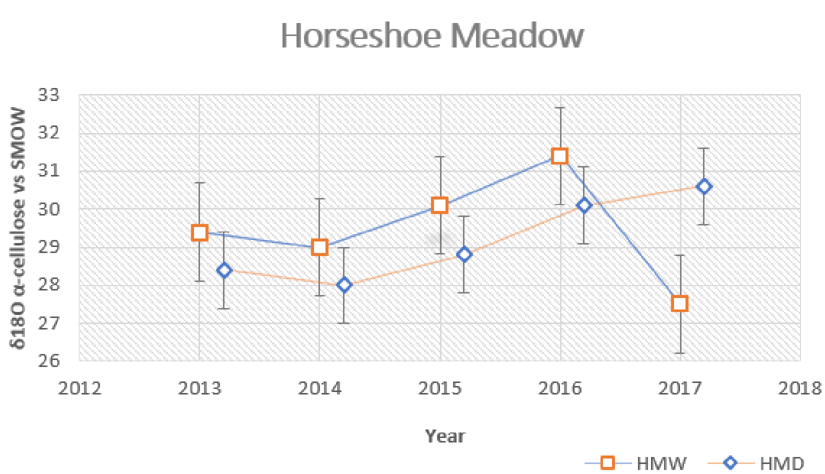
Oxygen isotope analysis occurs using the Thermo Scientific High-Temperature Conversion Analyzer calibrated to the SMOW reference standard. Instead of attempting to separate earlywood from latewood we used the entire ring due to the deficiency of growth rings in the years surrounding Hurricane Dolores. The lack of cellulose material is in part a product of the drought surrounding the Hurricane Dolores event. The inclusion of the whole ring adds correlation from year to year due to trees utilizing stored photosynthates from prior years at the beginning of the growing season (Hill et al., 1995). The preliminary analysis consists of five years surrounding the Hurricane Dolores event from each sampling site. Owing to the expensive cost associated with isotopic analysis, we chose the best sites based on the results of the initial analysis.

Chapter 4

Results

Inundated sites at Beach Meadow, Horseshoe Meadow and Foxtail did not display isotopic evidence of Hurricane Dolores and did not exhibit significantly lighter oxygen isotope values (Figure 7). Instead, values at both the inundated and non-inundated sites do not trend lighter in the ring associated with the 2015 Hurricane Dolores, and overall the differences in isotopic values are not statistically significant.





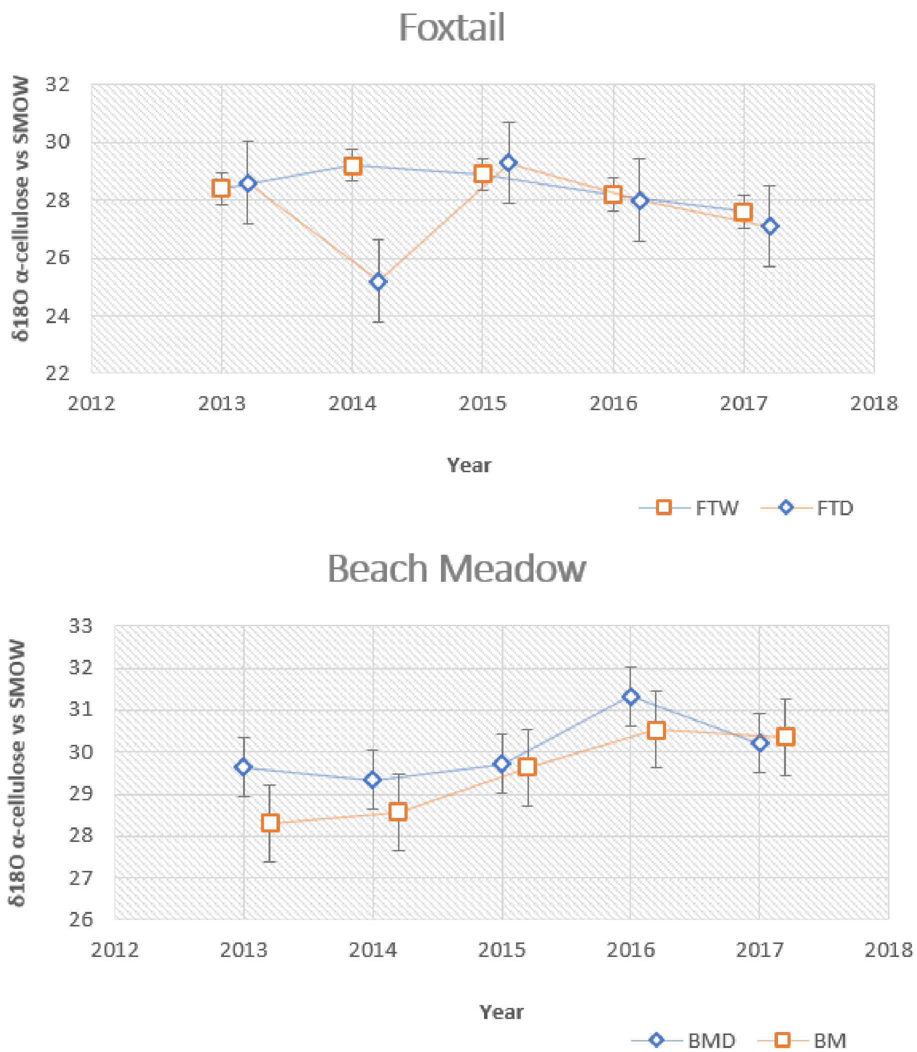


Figure 7: Raw Isotope delta 18 O compared to the SMOW (Standard Mean Ocean Water) derived from alpha-cellulose. Values from both inundated (wet) and non-inundated (dry) sites as well as overall mean isotopic values. Data points are slightly offset to better display the error bars. Error bars are representative of standard deviations between values. It is clear from the significant overlap of error bars there is no meaningful trend to extract.

Looking at the raw isotopic values of the individual sites there appears to be no discernable pattern. Overall, the error bars overlap for all the study sites with the exception of a year or two (Figure 7). This overlap makes it difficult to discern any sort of pattern within the values. The standard deviation for the inundated sites is smaller than the standard deviations for the non-inundated sites further signaling this lack of coherence. The only difference between the two sets of values is that the inundated sites are slightly heavier than the non-inundated sites for the majority of the time period under evaluation. Additionally, in 2015 both non-inundated and inundated sites did not trend toward lighter values, nullifying our initial hypothesis.

The lack of significant differences in our data from wet and dry sites appears to nullify our initial hypothesis. The relatively light isotopic values resulting from the rainout effect did not manifest within the oxygen isotope record, and even with the extensive constraints placed upon our study area, there was little difference in the response between the two sites' oxygen isotope values. We conclude extreme precipitation events are not visible in the oxygen isotope record of cellulose raising issues with the use of the approach in western conifers to extrapolate precipitation regimes.

RESPONSE FUNCTIONS

Response functions are created to better understand the relationship between local climatic data and tree growth. Analysis using data from 1920 to 2000 was used to create response functions for each site. Tree growth data was fit to a 2nd order polynomial and then standardized (Cdendro). Prism climate data, specifically temperature and precipitation, were extracted using a data point in Beach Meadows (Prism Climate Group, 2021). Standardized tree growth was compared to the climatic factors to create response functions. The analysis shows that sites analyzed in the Sierra Nevada are sensitive to drought, and this drought response likely greatly affects isotopic values. Drought causes decreased growth due to scarcity of water and increased evaporation will cause potential enrichment of isotopic waters. Our site is sensitive to warm winters, as warmer winters generally have more precipitation. The majority of sites respond positively to December and January temperature and precipitation. A negative correlation between sites' spring temperatures with growth are a result of colder spring temperatures leading to a more sustained snowpack with snowmelt occurring well into early spring.

Table 1: Beach Meadow Wet site response function values.

Beach Meadow Wet

	Coefficient	Std. Error	Std. Coeff.	F-to-Remove
Intercept	.209	.185	.209	1.275
PAugT(C)	.035	.014	.243	6.769
MayT(C)	.040	.012	.350	10.478
MayP(mm)	.002	.001	.206	4.156
AugP(mm)	.005	.002	.249	8.383

Count	107
Num. Missing	20
R	.502
R Squared	.252
Adjusted R Squared	.223
RMS Residual	.217

Table 2: Beach Meadow Dry site response function values.

Beach Meadow Dry

	Coefficient	Std. Error	Std. Coeff.	F-to-Remove
Intercept	1.062	.080	1.062	174.746
PSepT(C)	-.025	.007	-.285	14.377
PDecT(C)	.017	.007	.193	6.325
PJunP(mm)	.001	4.685E-4	.194	7.178
PJulP(mm)	.003	.001	.296	16.522
PAugP(mm)	.002	.001	.160	4.803
POctP(mm)	.001	.001	.154	4.464
PNovP(mm)	.001	2.988E-4	.245	11.009
JanP(mm)	2.843E-4	1.151E-4	.180	6.107
JulP(mm)	.002	.001	.210	8.101

Count	125
Num. Missing	2
R	.643
R Squared	.414
Adjusted R Squared	.368
RMS Residual	.139

Table 3: Horseshoe Meadow Wet site response function values.

Horseshoe Meadow Wet

	Coefficient	Std. Error	Std. Coeff.	F-to-Remove
Intercept	.843	.026	.843	1031.607
MarT(C)	-.014	.005	-.235	7.209
JanP(mm)	.001	1.793E-4	.418	23.045
JulP(mm)	.003	.001	.285	10.597

Count	101
Num. Missing	1
R	.520
R Squared	.270
Adjusted R Squared	.248
RMS Residual	.110

Table 4: Horseshoe Meadow Dry site response function values.

Horseshoe Meadow Dry

	Coefficient	Std. Error	Std. Coeff.	F-to-Remove
Intercept	1.211	.186	1.211	42.373
PriorJulT(C)	-.036	.015	-.211	5.501
PriorSepP(mm)	.003	.001	.241	7.373
JanP(mm)	.001	3.269E-4	.215	5.805
JunP(mm)	.003	.001	.230	6.671
JulP(mm)	.005	.002	.234	7.005

Count	102
Num. Missing	0
R	.513
R Squared	.263
Adjusted R Squared	.225
RMS Residual	.197

Table 5: Foxtail Wet site response function values.

Foxtail Wet

	Coefficient	Std. Error	Std. Coeff.	F-to-Remove
Intercept	.879	.035	.879	639.730
JanT(C)	.016	.006	.239	7.497
MarT(C)	-.017	.006	-.246	8.103
PriorDecP(mm)	.001	2.017E-4	.348	16.565
JanP(mm)	.001	2.022E-4	.362	17.565

Count	101
Num. Missing	1
R	.563
R Squared	.317
Adjusted R Squared	.288
RMS Residual	.121

Table 6: Foxtail Dry response function values.

Foxtail Dry

	Coefficient	Std. Error	Std. Coeff.	F-to-Remove
Intercept	1.170	.117	1.170	100.531
PriorJulT(C)	-.025	.009	-.230	7.320
PriorDecT(C)	.021	.006	.294	11.925
MarT(C)	-.015	.006	-.225	6.986
PriorSepP(mm)	.001	.001	.171	4.135
PriorDecP(mm)	.001	1.982E-4	.348	16.551
JanP(mm)	.001	1.914E-4	.305	13.452

Count	101
Num. Missing	1
R	.620
R Squared	.385
Adjusted R Squared	.345
RMS Residual	.114

The Beach Meadow Wet site shows moderate responsiveness to climate with R and R^2 values of 0.502 and 0.252 respectively (Table 1). This site is highly correlated with temperature in May and the temperature in the prior August. These months are representative of the beginning and end of the growing season respectively indicating the dependence on temperature for growth. The southern Sierra is drier than the rest of the Sierra Nevada and our response function shows our site is located in an evaporation-dependent environment. A high May temperature likely leads to increased evaporation and decreased tree growth while the opposite is true when the region experiences lower May temperatures. Previous August temperature is critical and significant as it provides for the availability of water for the next growing season. If August is hotter than average the trees experience higher levels of evaporation resulting in thinner growth rings. August precipitation therefore likely delays the end of the growing season and results in the production of a thicker annual ring.

The dry Beach Meadow site has moderate responsiveness to climate with R and R^2 values of 0.513 and 0.225 respectively (Table 2). Prior September temperature and prior July and November precipitation show the strongest correlation with growth. A hot prior September depletes water stored in the soil and the bedrock matrix which reduces growth in the following year. Other than prior September values, this site does not correlate well with temperature. The dry Beach Meadow site grows better when it is wetter, especially when there is water from previous years stored away. The site’s relationship with precipitation is seen in the high correlation with prior July and prior November precipitation.

The wet Horseshoe Meadow site has moderate responsiveness to climate with R and R^2 values of 0.520 and 0.270 respectively (Table 3). The wet site exhibits a strong winter precipitation signal with emphasis on January precipitation. This strong correlation with winter precipitation is indicative of this site's dependence on snowpack. This site shows a negative growth response to high March temperatures, which furthers evidence of the site's dependence on snowpack. Higher march temperatures result in earlier snowmelt.

The dry Horseshoe Meadow site is moderately responsive to climate with R and R^2 values of 0.513 and 0.263 respectively (Table 4). The dry site is strongly dependent on winter and summer precipitation. Prior September precipitation and July and June precipitation of the growth year show the highest correlation with growth for this site. The site's south-facing slope microclimate is dry and hot. A negative correlation with prior July temperature also limits available water as well as subsequent growth.

The Foxtail sites show the strongest responsiveness to climate. The wet Foxtail site has R and R^2 values of 0.563 and 0.317 respectively (Table 5). This site shows the strongest correlation to prior December and January precipitation. This positive response is indicative of dependence on snowpack at this site. Additionally, the wet foxtail site has a positive correlation with prior December and January temperature furthering the evidence for the site's dependence on warm wet winter storms. This site has a negative correlation to March temperature response. This places importance on cold spring temperatures to preserve snowpack and sustain snowmelt.

The dry Foxtail site responds similarly to the wet foxtail site. The dry Foxtail site has R and R^2 values of 0.620 and 0.385 respectively (Table 6). This dry site shows the strongest response to January precipitation and prior December precipitation. This positive response suggests that winter snowfall is critical for growth. The importance of warm wet winter storms is furthered by the site's positive correlation with prior December and January temperature. The dry site's negative response to March temperature indicates the site's dependence on cold spring temperatures to preserve snowpack and soil water.

Isotopic Residual Analysis

Residuals of the isotopic analysis are calculated by performing a two-year moving average on the mean datasets for each site. This moving average was subtracted from observed mean values resulting in the residual. Residuals were calculated for each study area as well as for the overall dataset. Negative residuals account for underestimated oxygen values in any given year and positive residuals indicated overestimation of oxygen values. Values closer to zero are indicative of the predicted values being close to the actual values.

Overall, between the mean values of the wet and dry sites, the error associated with the wet sites is less than the dry sites. This trend is continued when we look at the individual Foxtail sites with the Foxtail Dry Site having a large deviation from the predicted values in the 2015 year compared to the wet site. The Beach Meadow Dry Site follows the same pattern with a large deviation in the 2016 year compared to the wet site. However, the Horseshoe Meadow Wet Site actually has larger residuals than the Dry Site. Particularly the 2017 year where the wet site has a deviation of approximately -2 compared to the dry site's approximate 0.2 deviation.

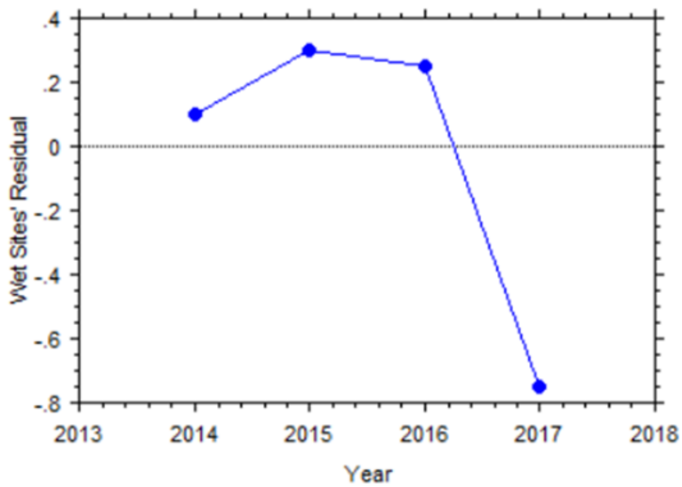


Figure 8A: The combination of all our Wet sites' residuals. The analysis overestimates the values in the first few years while greatly underestimating 2017 relative to the rest of the dataset. The 2015 Hurricane Dolores year is overestimated for the dataset.

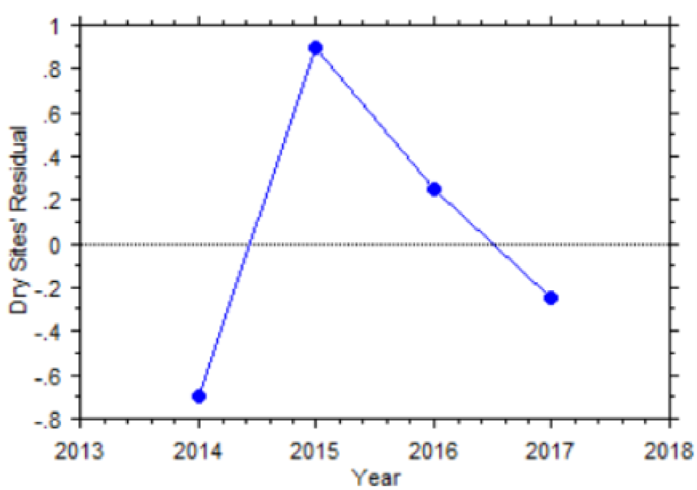


Figure 8B: The combination of all our Dry site's residuals. The analysis underestimates, overestimates and then underestimates the data. The 2015 Hurricane Dolores year is a peak positive residual, with the dataset greatly overestimating the values for that year relative to the rest of the data.

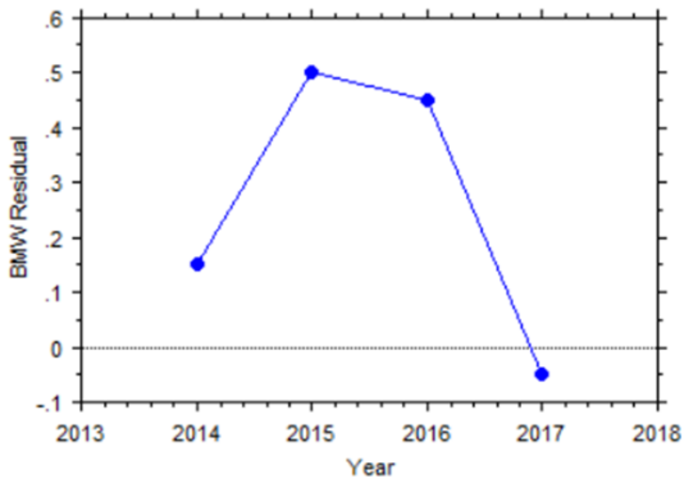


Figure 8C: Beach Meadow Wet site's residuals from isotopic analysis. The values are consistently overestimated. The 2015 Hurricane Dolores year is overestimated with the highest positive residual for the study years.

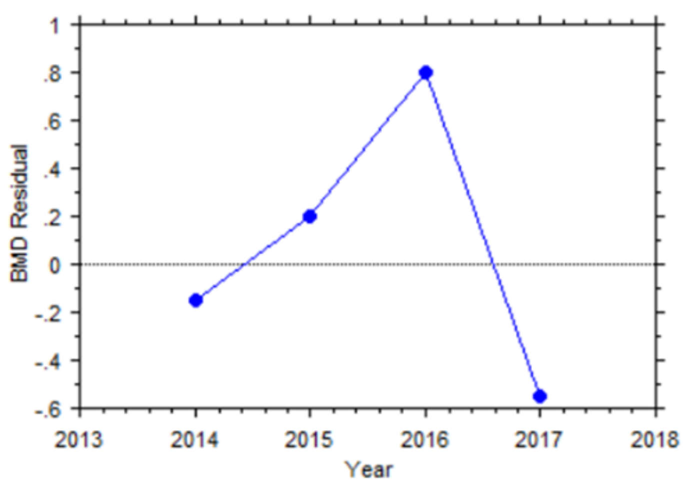


Figure 8D: Beach Meadow Dry site's residuals from isotopic analysis. The model underestimates, then, overestimates and then underestimates again. The 2015 Hurricane Dolores year is slightly overestimated.

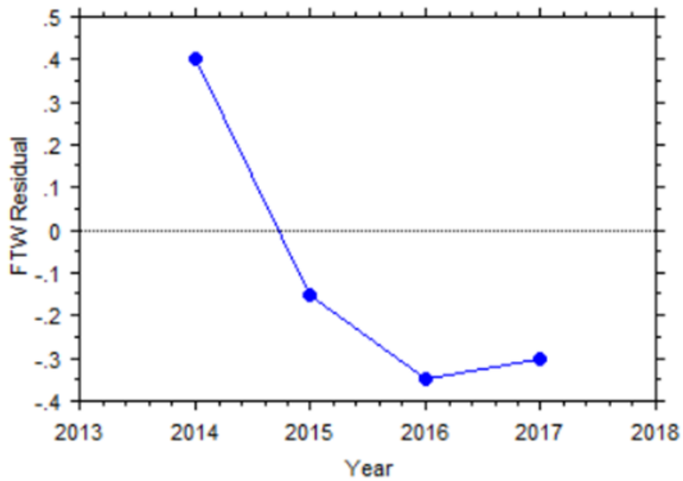


Figure 8E: Foxtail Wet site's residuals from isotopic analysis. The 2014 year is overestimated in the analysis. The 2015 Hurricane Dolores year is slightly underestimated.

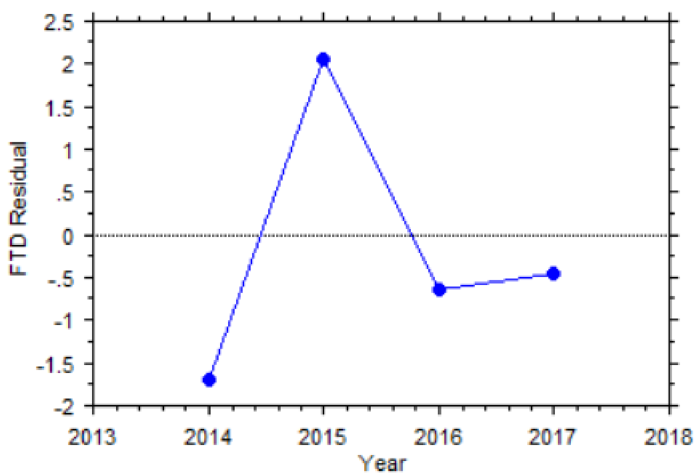


Figure 8F: Foxtail Dry site's residuals from isotopic analysis. The analysis underestimated the predicted values in 2014, 2016 and 2017 while overestimating the values for the Hurricane Dolores year in 2015.

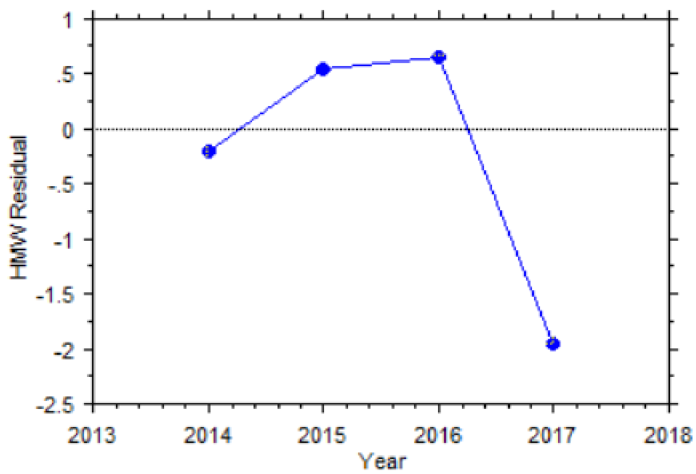


Figure 8 G: Horseshoe Meadow Wet site's residuals from isotopic analysis. The 2014, 2015 and 2016 values are relatively close to 0, however, the analysis underestimated the 2017 year severely with approximately a -2 residual. The 2015 Hurricane Dolores year is slightly overestimated.

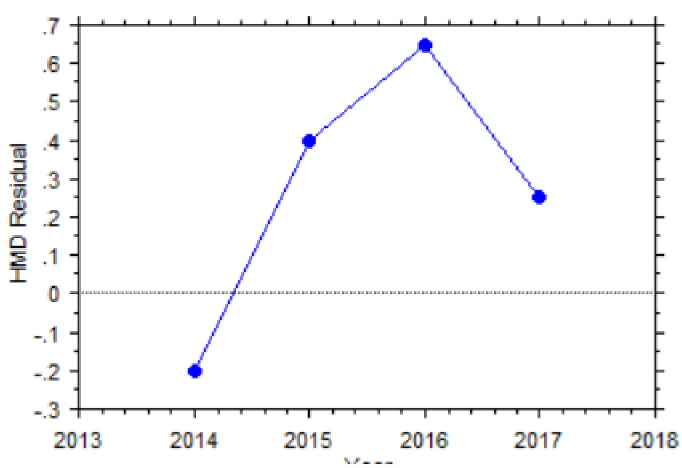


Figure 8 H: Horseshoe Meadow Dry site's residuals from isotopic analysis. Predicted values were consistently overestimated in this analysis with the tendency for positive residuals. The 2015 Hurricane Dolores year residual is overestimated for this site.

CHAPTER 5

DISCUSSION

Studies from the southeastern United States have shown the potential of correlating isotopic values within long-leaf pine rings to precipitation sources (Knapp et al., 2016; Miller et al., 2006). Within the White Mountains, Berklehammer and Stott (2008, 2009) have shown that bristlecone pine (*Pinus longaeva*) reconstructions have the potential for the same purpose. Studies looking at the influence of fog water on coastal forests were successful at parsing out the impacts of fog water on plant growth (Johnstone et al., 2013). However, our results indicate that utilization of isotopic data to draw inferences regarding precipitation regimes is not effective in dry Southern Sierra.

We hypothesized that we would see depleted isotopic values. We constrained our study by utilizing radar data and soil sensors to define areas where precipitation either fell or did not fall. We chose to sample a time frame in the middle of severe drought, therefore, minimizing the impact of other precipitation events. Species were chosen due to shorter root lengths to maximize the use of shallower water sources. However, we do not see any sort of coherent response to Hurricane Dolores within the tree ring record. Due to the anomalous light values derived from hurricanes, we expect this lack of a response is a result of but not limited to evaporation, condensation height as well as noise contributions from the competition, and the utilization of annual rings.

Before the Hurricane Dolores extreme precipitation event, California was experiencing a severe drought. Persistent drought conditions and the associated evaporation of soil water suggest that trees affected by Hurricane Dolores are more likely to absorb available precipitation (Royce and Barbour 2001). Furthermore, the continuous evaporation from the drought period will mean that any water integrated into the trees will have heavier values due to the preferential removal of light isotopes by evaporation (Tang and Feng 2001). This contrast between heavy evaporative values and light isotopic values of Hurricane Dolores maximizes the chance for the event to stand out in the isotopic record. Heavy rainfall from Hurricane Dolores equates to more than 200 mm of precipitation over 2 hours (Figure 6); well over the 100mm precipitation baseline needed to reset soil water at a depth of 50 cm allowing water to percolate down to deep soil horizons first suggested by Tang and Feng (2001). Therefore, we can assume that the tree rings after the storm the soil water replenished during Hurricane Dolores. However, we do not see any manifestation of lighter isotopic values.

Precipitation from hurricane events similar to Hurricane Dolores has proven to be a persistent source of light isotopic values (Gedzelman et al., 2003). Our results show that trees at the Beach Meadow and Horseshoe Meadow sites do not respond with lighter values. Constraints in this study to optimize results include identification of localized areas of inundation, prior (and ongoing) drought, and the use of tree species with shallower rooting systems. These constraints on our study led us to expect to see lighter oxygen isotopic values in our study year 2015.

We do not see the trees reflecting isotopic values derived from Hurricane Dolores, suggesting that our hypothesis was incorrect. Results of this kind suggest that conifer forests of the Sierra Nevada do not have the same isotopic response as conifers in other parts of the country (Lewis et al., 2011; Miller et al., 2006). Rather, this signal represents the multitude of processes altering the different inputs of water vapor as they evaporate, condense and mix. The varying processes and source waters contribute to more noise in the isotopic signal within cellulose in the interior of the western United States when attempting to tease out a single factor such as a precipitation source.

A large contributor to the isotopic record not displaying values indicative of Hurricane Delores is evaporation. Evaporation is more extreme in our study area relative to the study areas in the southeast US and coastal California used for prior isotopic studies (Miller et al., 2006; Johnstone et al., 2013). The years surrounding the Hurricane Dolores event were exceptionally dry with continued evaporation. Evaporative processes have proven to preferentially extract lighter oxygen and deuterium isotopes leaving behind heavier fractionation in soil water (Tang and Feng, 2001). Hurricanes have light isotopic values, so evaporative enrichment is one of the mechanisms responsible for diluting the signal of Hurricane Dolores. In addition to evaporation's enrichment, studies show that the summer precipitation is less impactful with high evaporation rates and radiative cooling at night attracting moisture to the surface from the warmer deep soil (Royce and Barbour 2001).

One major difference between the continental western and the coastal southeastern United States is humidity. The western United States has less water availability with constant evaporation of all water sources. The southeastern United States is humid with the air being more saturated than the western United States. As the air becomes more saturated with water vapor, evaporative processes happen less. Drier air can hold more moisture than humid air. This evaporative relationship is what we believe partially explains why the reconstruction of extreme precipitation works in the humid southeastern United States (Miller et al., 2006) and coastal western United States (Johnstone et al., 2013) but not in the dry interior of the western United States. Studies utilizing isotope-enabled general circulation models (GCM) find that near-surface humidity values prior to the storm are an important determiner of isotopic values (Berkelhammer et al., 2011).

The height of condensation's controls on isotopic value further complicates the interpretation of tree cellulose's oxygen isotope content in relation to the source water. In southern California modeling done by Buenning et al. (2012) found the height of condensation as the main driver of the seasonality of precipitation's isotopic values. The summer months are generally more enriched, and the winter months are more depleted (Buenning et al., 2012). This control on precipitation's isotopic value plays into the source water values used by trees in the area.

Adding to the evaporative enrichment diluting the light isotopic values of Hurricane Dolores within the soil-water is the interaction between the plant and the atmosphere via transpiration. Farquhar et al. (2007) show that water in leaves preferentially maintains heavier hydrogen and oxygen isotopes while transpiring lighter molecules. Processes affecting source water and climatic conditions affecting leaf-atmosphere interactions are independent and each combination of both inputs may result in different isotopic values in cellulose. Fractionation as water moves through the tree could further dilute this value. The addition of carbon isotopes to interpret water stress is a tool with the potential to better understand these fractionations (Roden et al., 2005).

Another potential explanation for the outcome nullifying our predicted results could be the influence of other storms or sources of precipitation dampening the isotopic signal (Gedzelman et al., 2003). Water is stored in the soil matrix and on top of the underlying bedrock. The accumulation of winter snowpack as well as any other more recent precipitation events could minimize the impact of Hurricane Dolores (Berkelhammer and Stott 2008). This dampening could provide insight into additional sources of water for conifers in the Sierra Nevada (Berkelhammer et al., 2020).

In addition to potential enriching processes, Hurricane Dolores' impact is minimized through the absorption of soil water by other biomass that is not trees. Grasses, shrubs, and other understory will also require water after the drought leading up to the Hurricane Dolores precipitation event (Royce and Barbour 2001). Drought and water competition could lead to the signal from the Hurricane Dolores event not being as pronounced as less water will be available for trees.

The availability of cellulose influences our outcome as drought leads to smaller tree ring growth increments. Our sites were sampled in the middle of a severe drought. This lack of growth results in the majority of sites utilizing two cores from the same tree to have sufficient isotopic material. Perhaps sampling at a sub-annual scale (Roden and Ehleringer 2007) or microscale intervals (Li et al., 2011) would illuminate more seasonal variance. Sampling a cross-section of the tree as opposed to a core sample in order to provide more cellulose material for each growth ring would allow for intra-annual sampling in the future. In our case, the paucity of cellulose and insufficient funding for running larger numbers of isotopic samples rendered this avenue obsolete.

This study serves as an evaluation of the coherence of multiple species' isotopic responses to source water inputs. Lodgepole, jeffery, foxtail, and limber pine groves were subjected to similar environmental conditions (drought, hurricane inundation) yet there was no statistically significant correlation between species nor any unified response. We hypothesize this is due to varying water sources in the Sierra Nevada. Additionally, differing microclimates between the sites contribute to the noise within the values.

Additional research would be necessary to discern why extreme precipitation is stored in conifers in the southeastern United States but not the southwestern United States. Successfully understanding isotopic reconstructions on the western coast could lead to potential reconstructions of precipitation. (Roden and Ehleringer 2007). If future studies can parse apart the precipitation inputs in the tree ring record, there is potential to look at the occurrence of extreme precipitation in the western United States. This research area presently lacks extensive oxygen isotope records looking back into the longer tree ring record. Future research examining the longer tree ring record could improve our understanding of precipitation patterns in California and further supplement historical meteorological data.

In addition to tropical cyclone reconstruction, other extreme events may be identified from the oxygen isotope record. Atmospheric rivers are common precipitation events in the Sierra Nevada that have the potential to supply up to 50 percent of California's yearly water supply (Dettinger et al., 2011). Future research could evaluate the incidence of atmospheric rivers in the area and further supplement California's climate record. Compilation of longer records of extreme storm incidence in the western United States will better our understanding of extreme rainfall in California.

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