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Variability in California's Fire Activity during the Holocene, across Space and Time

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Variability in California's Fire Activity during the Holocene, across Space and Time

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by

Benjamin Cole Nauman

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ABSTRACT OF THE THESIS

Variability in California's Fire Activity during the Holocene, across Space and Time

By

Benjamin Nauman

Master of Arts in Geography

University of California, Los Angeles, 2020

Professor Glen Michael MacDonald, Chair

Over the past several decades, there has been an increase in wildfire activity in California. These wildfires have occurred during a period of warmer temperatures and lower precipitation than the averages of the 20th century. To improve understanding of the response of fire activity to warm and dry periods, periods in the past with similar climates were examined. A suitable method to examine paleofire is charcoal that is preserved in lacustrine sediment. To examine long-term changes in fire in California, 16 sedimentary charcoal records were collected, including four records analyzed over the past few years at UCLA, as well as 12 existing records that were collated from a database of charcoal data. These records are predominantly located in the Sierra Nevada range and the Klamath mountains. Records of charcoal accumulation at these sites were compared to determine the response of fire to known warm and dry periods during the

Holocene, such as the Medieval Climate Anomaly (MCA) and the Holocene Thermal Maximum (HTM). The data collected shows there was no statewide rise in fire activity during the MCA or the HTM, but several regional trends were seen in the data. Sites in the Klamath mountains generally had a rise in charcoal influx over the course of the Holocene, and this rise was likely correlated with increasing forest coverage over time. The UCLA sites located in the Sierra Nevada mountains experienced a rise in charcoal influx during the last 2000-3000 years. The lack of statewide signal of increased burning during events such as the MCA or HTM indicates that the fire conditions seen in the present may be without precedent during the period of the Holocene. However, there are important caveats to interpretation of the results, as charcoal accumulation data are subject to several factors, of which only one is the presence of a specific fire event. Despite these limitations, this study allowed for the determination of regional responses of fire during the Holocene and allowed us to examine how those responses compared to what is seen during the present.

The thesis of Benjamin Nauman is approved

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Introduction

Wildfires in California pose a threat to lives, property, and ecosystems on an annual basis, with the worst effects experienced in the dry summer and fall seasons (Westerling et al., 2003). Impacts from these events include the deaths and property damage that fires cause, as well as secondary effects, like negative impacts on human health, reduced air quality, and economic losses due to wildfire damage and evacuations (Jin et al., 2015;Künzli et al., 2006; Phuleria et al., 2005). Additionally, there are also long-term repercussions that result from severe wildfires, including greenhouse gas emissions from combustion of vegetation that help to accelerate global warming, and lower birth weights among infants born following severe wildfire events (Holstius et al., 2012;Bonnicksen, 2008). Frequent and severe wildfires can also slow recovery of native vegetation after disturbance and lead to declines in animal species diversity (Lippitt et al., 2013; Rochester et al., 2010). Given the numerous impacts these fires have, it is important for researchers to understand how fire activity has changed over time, to make predictions of future conditions and mitigate negative effects of these events.

During the early 2010's, California was hit by a historic drought that was accompanied by the warmest 5-year period on record, as well as low precipitation, leading to moisture deficits that were the most severe in at least 1200 years (Griffin & Anchukaitis, 2015). This drought set the stage for severe wildfire events that occurred in the latter part of the decade. In 2017, wind-driven wildfires burned thousands of homes in communities in Northern California in a matter of hours (Nauslar et al., 2018). That served as a prelude to the 2018 fire season, which was the worst wildfire season in state history by nearly all measures (Calfire). This season included the deadliest and most damaging fire in state history, as well as the most acres burned in a single year (Calfire). These events are evidence of a broader trend, as the area burned by wildfires in

California has increased by 405% during the period from 1972-2018 (Williams et al., 2019). Summers with higher positive temperatures and vapor pressure deficits have also been correlated with higher area burned, especially in the North Coast and Sierra Nevada regions of the state (Williams et al., 2019). Additionally, under the A2 climate scenario, the number of large fires (>200 hectares) is projected to increase by 34% by 2070-2099 over the already higher modern baseline level (Westerling & Bryant, 2008).

Based on the worsening conditions of the last few decades, it is crucial to improve our understanding of the response of fire to warm and dry climates, like those experienced in California currently. This will include examining periods that have occurred in the past that had climates like those seen in the 21st century. One of these past periods of warm and dry condition in the Western United States is known as the Holocene Thermal Maximum, which has been recorded as occurring from ~9000-5000 years before present (y.b.p.) in North America (Renssen et al., 2012). Multiple records from paleoclimate proxies indicate that the warmest period in the Holocene in the Sierra Nevada mountains was reached towards the end of the MCA (Potito et al., 2006; Scuderi, 1994). Another warm period is known as the Medieval Climate Anomaly; this period was characterized by warm temperatures from 950-1250 C.E. (Mann et al., 2009). Temperature records reconstructed from tree ring data indicate persistent positive temperature anomalies starting at ~900 y.b.p. in sites in the southern Sierra Nevada mountains (Graumlich, 1993; Stine, 1994).

Extensive documentation of wildfire extent and activity in California has only existed since the late 19th century (Keeley & Zedler, 2009). Therefore, reconstructions of wildfire activity before this period will have to come from paleoecological proxy data that will stand in for direct measurements. There are several proxies that are used to reconstruct fire history, including the use of fire scars in tree ring data, as well as charcoal particles that are preserved in sediment cores (Caprio & Swetnam, 1995; Whitlock & Larson, 2001). Charcoal is produced from the incomplete combustion of organic material during a fire and is transported into a lacustrine site by several means, including wind-driven or fluvial processes (Whitlock & Larson, 2001). This transportation of charcoal can occur in the initial period of the fire, and for several years after due to runoff from in a watershed (Whitlock and Larson, 2001). Deposition on differential time scales will need to be considered in interpretation of charcoal records, especially in sites with high sediment accumulation rates. The use of charcoal is the best method to produce records of paleofire that extend back to the beginning of the Holocene, as sediment core records can extend further in the past than tree rings. Several existing records of sedimentary charcoal in the state can date to the Pleistocene-Holocene transition period or further (Beaty & Taylor, 2009; Brunelle & Anderson, 2003). This allows for an examination of fires over a long period of changes including Holocene Thermal Maximum (HTM), as well as the Medieval Climate Anomaly (MCA).

The sediment cores in the mountainous regions of California are typically collected from either meadows or lacustrine sites. All the sites that will be included in this study come from lake sites in mountainous regions of central and northern California. To analyze a sediment core for charcoal, organic components of the sediment are digested through a multistep processing, ensuring that primarily charcoal remains to be analyzed (Glew et al., 2001). The method of charcoal analysis used for this project involves the use of macroscopic charcoal particles (>125 μm), which ensures that particles are derived from the local (<7km) proximity of a fire event (Whitlock & Larson, 2001). This use of macroscopic charcoal is applied to build a record of fire activity for the local area near a study site. Typical macroscopic charcoal studies will focus on records for a single site or a few in close proximity (Brunelle & Anderson, 2003; Long et al., 1998). However, several studies have used sedimentary charcoal data on a regional or global basis to determine broader trends in fires on a regional or global scale (Power et al., 2008; Whitlock et al., 2008). For this study, charcoal data will be examined from 16 sites in California, and this data will be used to reconstruct past fire conditions statewide, as well as attempt to determine the utility of examining macroscopic sedimentary charcoal records on a broad scale.

To provide a geographically holistic view of fire conditions throughout the Holocene in California, 16 macroscopic charcoal records have been obtained from mountainous locations throughout the central and northern portions of the state. Small natural lakes that are ideal for charcoal analysis are very sparse in many other regions of the state. All of the records used here extend at least as far back as the Holocene Thermal Maximum, which will allow us to reconstruct fire activity during that warm and dry period, as well as other periods of warm conditions similar to those seen in the 21st century, notably the MCA (Rennsen et al., 2012). Four of these records consist of charcoal data from sites that were cored by University of California, Los Angeles researchers during the early 2000's. The four sites cored by our university were processed and analyzed for charcoal at UCLA over the past 18 months. These sites are: Starkweather, Hidden, Greenstone, and Funnel Lakes. These four sites are located along a rough north-south axis along the crest of the central and southern Sierra Nevada Mountains at around 200 km from north-south. Additionally, 12 charcoal records were also collated from studies that have already been published and have had data uploaded to paleoecological databases. These records were predominantly sourced from the Global Charcoal Database, which is a clearinghouse of charcoal data from around the world (Paleofire). These 16 charcoal records are predominantly located in the montane forests of the Sierra Nevada mountains and the Klamath mountain ranges in far-northern California. Due to a limited amount of available data, no sites were chosen in southern California or in the central coast ranges of the western portion of the state.

The charcoal records from the 16 sites will be compared to answer several crucial questions about fire in California, and about the use of a meta-analysis of macroscopic charcoal data. Important considerations are: 1. What was the response of fire in California to past periods of warm and dry activity in the state, such as the MCA or HTM? 2. Was there regional variation in the response of fire activity over the course of the Holocene? 3. Is there utility in applying sedimentary macroscopic charcoal records in a statewide approach in order to understand past fire regimes?

Study Sites

Starkweather Lake

This lake site is 1.1 hectares in area and is in the San Joaquin watershed in the central Sierra Nevada mountains near the Sierra Crest. It is located at 37.663°, -119.07°, at an elevation of 2424 meters. The lake has a maximum water depth of 11.0 meters (MacDonald et al., 2008). The vegetation in the surrounding area consists of *Abies*, *Pinus contorta* and *monticola, Tsuga mertensiana,* and *Juniperus occidentalis* (MacDonald et al., 2008). The mean annual air temperature at the lake is 4.4° Celsius, and the average annual precipitation is 76.2 centimeters (Prism Climate Group).

Hidden Lake

This lake is 2.0 hectares in area, and it is in the Walker River watershed in the Eastern Sierra Nevada region. It is located at 38.26°, -119.52°, at an elevation of 2379 meters above sea level. The lake has a maximum depth of 9.7 meters (Potito et al., 2006). Vegetation in the surrounding region primarily consists of *Pinus contorta*, *Pinua jeffreyi,* and *Juniperus occidentalis* (Potito et al., 2006.). The annual mean temperature at the lake is 3.8° Celsius, and the annual mean precipitation is 99.7 centimeters (Prism Climate Group).

Greenstone Lake

This lake is 8.9 hectares in area, and it is in the Mono Lake endorheic basin in the Eastern Sierra Nevada region. It is located at 37.98° and -119.29°, at an elevation of 3092 meters above sea level. The lake had a depth of 5.11 meters at the coring location. Vegetation in the surrounding region consists of sagebrush and bare rock with stands and scattered individuals of *Pinus albicaulis,* as the site is located at the tree line. The annual mean temperature at the lake is 1.5° Celsius, and the annual mean precipitation is 119 centimeters (Prism Climate Group).

Funnel Lake

This lake is 2.6 hectares in area, and it is in the Owens River Watershed. The lake is located at 37.20°, -118.51°, at an elevation of 3161 meters. The lake had a depth of 10.36 meters at the coring location. Vegetation in the surrounding region consists of various subalpine conifers, including *Pinus contorta*. Because the area is at treeline, most of the vegetation surrounding Funnel lake consists of barren terrain and various low shrubs, herbs, and grasses. The annual mean air temperature at the lake is 2.11° Celsius, and the annual mean precipitation is 61 centimeters (Prism Climate Group).

Previously Published Charcoal Sites

Table 1 – Previously Published Study Sites

Lake Site	Latitude	Longitude	Elevation (m)	Annual Mean Air Temperature (°C)	Annual Mean Precipitation (cm)	Publication
Barrett	**37.60°**	**-119.01°**	**2816**	**2.99**	**136**	**(Hallett & Anderson, 2010)**
Bluff	**41.35°**	**-122.56°**	**1921**	**6.86**	**119**	**(Mohr et al., 2000)**
Campbell	**41.53°**	**-123.11°**	**1750**	**7.17**	**174**	**(Briles et al., 2011)**
Cedar	**41.21°**	**-122.50°**	**1950**	**7.04**	**174**	**(Whitlock et al., 2004)**
Crater (California)	**41.38°**	**-122.58°**	**2288**	**5.54**	**165**	**(Mohr et al., 2000)**

East	**37.18°**	**-119.03°**	**2863**	**3.39**	**129**	**Unpublished Research in Database**
Kirman	**38.34°**	**-119.50°**	**2174**	**5.54**	**76**	**(MacDonald et al., 2016)**
Lower Gaylor	**37.91°**	**-119.29°**	**3062**	**1.45**	**114**	**(Hallett & Anderson, 2010)**
Mumbo	**41.19°**	**-122.51°**	**1859**	**7.04**	**174**	**(Daniels et al., 2005)**
Sanger	**41.90°**	**-123.64°**	**1547**	**9.48**	**245**	**(Briles et al., 2008)**
Siesta	**37.85°**	**-119.66°**	**2340**	**5.56**	**136**	**(Brunelle & Anderson, 2003)**
Taylor	**41.36°**	**-122.97°**	**1979**	**7.21**	**123**	**(Briles et al., 2011)**

The data from the 12 previously published sites has already been reported in peer-reviewed journal articles, except for one unpublished record, East Lake, which was an unpublished work included in a database of sedimentary charcoal records. The resource used to obtain most of these charcoal records was the Global Charcoal Database (Paleofire). This database is by the Global Paleofire Working Group and exists to “provide the scientific community with a global paleofire dataset for research and archiving sedimentary records of fire” (Paleofire).

Seven of the 16 sites are in far-northern California, mostly situated in the Klamath Mountains region. The other nine records were from sites located in the Sierra Nevada Mountains, including the four study sites analyzed at UCLA for this study, as well as five previously existing sites located in the region. The sites in the Sierra Nevada’s were separated because the UCLA sites were predominantly located along the Sierra crest, and the previously published sites were predominantly located along the western slopes of the Sierra Nevada’s. Limitations of this data in terms of spatial extent are apparent. The sites in the Klamath region are limited into a rather narrow geographic corridor in the northwest of California. In addition, the sites in the Sierra Nevada Mountains are also concentrated in a narrow region in the central section of the mountain range.

Figure 1 - Sierra Nevada Study Sites

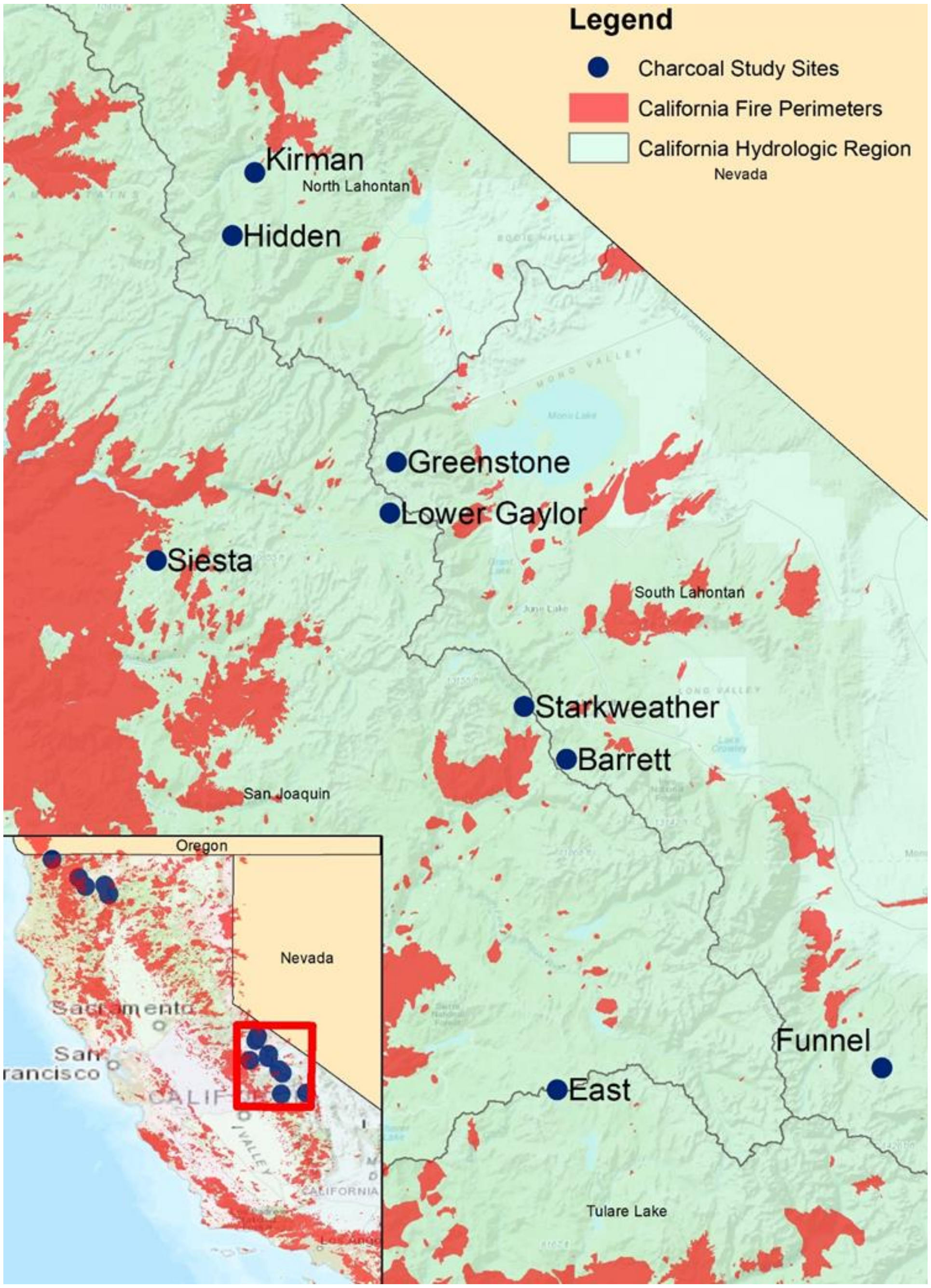
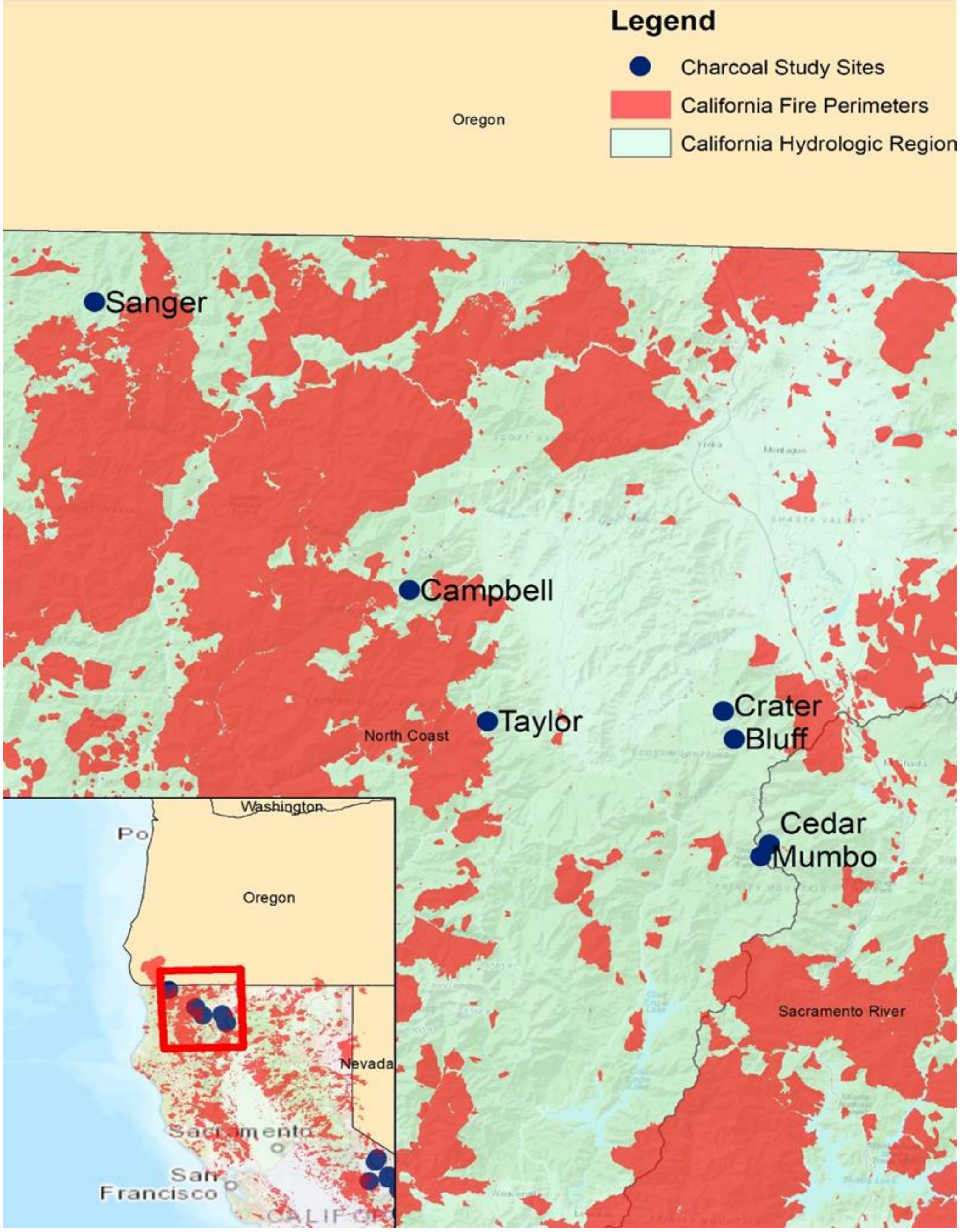


Figure 2 - Klamath Region Study Sites



Methods

Field Methods and Lab Storage

Four cores were collected by UCLA researchers from the period of 2000-2002. A sediment core from Hidden Lake was obtained in February 2002 using a modified Livingston piston corer (Potito et al., 2006). Sediment was recovered from Starkweather Lake in October 2001, also using a modified Livingston piston corer (MacDonald et al., 2008). Funnel Lake was cored in July 2000, and Greenstone Lake was cored in July 2001; both cores were also obtained using modified Livingston piston corers. Cores were labeled, wrapped in plastic and aluminum at the field sites, and were stored in a cold room at MacDonald Biogeography Laboratory at UCLA. Cold storage allowed for preservation of sediment material until June 2018, when sampling for charcoal analysis had begun.

Lab Methods

Macroscopic charcoal analysis is a multistep process involving the digestion of sediment to remove as many of the non-charcoal components as possible. The first step in this process involves the sampling of sediment from a core, which is done along continuous 1-cm intervals for the entire length of all the cores from a site. Sample volume for this study was 1 cm^3. Consistent sampling intervals and volume were used throughout all four of the sample sites to standardize data. Samples are taken from the sediment using syringes, which allows for accurate measurement of sample size. Samples are then transferred to 200 ml Erlenmeyer flasks, which reduces spillage and improves mixture of sediment with solution. Sediment is then treated with 6% hydrogen peroxide (H_2O_2) solution to remove organic components and to aid disaggregation of the sediment. Samples are then heated in muffle furnaces at 60° C for a period of 24 hours. The second step of charcoal processing involves removing samples from the furnace and sieving the samples to ensure only larger particles of charcoal remain to be counted. Samples are sieved using a 125-micron sieve that ensures that charcoal comes only from local fires (Whitlock & Larson, 2001). This allows researchers to obtain a clearer picture of fire activity in the vicinity of the site that they are analyzing. The sieved samples are then transferred to petri dishes using distilled water (H_2O). A drop of Sodium Hexametaphospate ($(NaPO_3)_6$) is then added to the petri dish to aid in disaggregation of charcoal particles. These dishes are then dried in the same ovens as the first day for 24 hours at 60° C. After 24 hours, samples will be dehydrated and will now be able to be analyzed for charcoal.

After drying, samples are ready to count using a stereo microscope. The procedure for macroscopic charcoal counting is to identify specific pieces of charcoal within one of the petri dishes. Pieces are counted and a grid sheet is placed beneath the sample to ensure that there are no repeats in counting. Charcoal is identified based on pitch black color, angular appearance, and breakability. Counts are marked off for the number of pieces of charcoal for every cell on the grid and then added up for the entire slide. This process was repeated for all the samples from the four lake sites used for this study. Processing and analysis for the 12 previously published core records followed similar guidelines to those used for the four UCLA sites.

Dating Techniques

Samples for radiocarbon dating were taken from each of the four UCLA cores to build chronologies of how sediment has accumulated over time at each of these sites. A starting goal was to obtain at least 10 radiocarbon dates for each study site, as this would reduce gaps in the age-depth models. Because charcoal or plant macrofossils were rare or not present in any of the cores from these four sites, bulk sediment samples were selected for radiocarbon analysis. Bulk sediment dates can provide radiocarbon results that are older than the actual age of the deposits.

This is often due to old carbon that is released from dissolved carbonates (Grimm et al., 2009). This has led to a decline in their use in many contemporary studies involving radiocarbon dating. However, few carbonate rocks are found in the Sierra Nevada region, which also reduces the potential for old-carbon error in bulk sediment dates. Samples were collected with plastic syringes and were stored in refrigerated glass sample vials before being sent to a laboratory for analysis. Radiocarbon dating was conducted at the UC Irvine Keck Radiocarbon lab using a 500-kV compact AMS (accelerator mass spectrometer) unit from National Electrostatics Corporation. Bayesian age-depth models were created for the four sites using Bacon 2.3.9.1 (Blaauw and Christen, 2013), a software using the R programming language. Radiocarbon Dates were calibrated to calendar ages using the INTCAL13 radiocarbon age curve for the atmospheric reservoir in the northern hemisphere; this involved the use of OxCal calibration application (Reimer et al., 2013; Bronk, 1995). After calibration, 0 calibrated years before present is set as the year 1950.

Interpretation of Charcoal Data

There are several methods for interpretation of sedimentary charcoal records, but all start from the raw counts of sedimentary charcoal. Raw charcoal counts from the sites can provide some information about fires at the site, but there is no temporal information included for these counts, as sediment is often deposited at different rates in different sections of a sediment core. Charcoal counts need to be converted into charcoal accumulation rate data (CHAR), to account for differences in sediment accumulation rate at different levels along the cores (Long et al., 1998). Charcoal accumulation rate data allows for temporal reconstruction of fire occurrence along every centimeter of sediment for a site. To generate charcoal accumulation rate data, raw counts of charcoal for every centimeter are first converted to concentration in particles/cm^3 (to account for the volume of the sample), and then divided by sample deposition time in years/cm. The final CHAR equation is seen in terms of Particles of charcoal*cm^{-2}*year^{-1} (Long et al., 1998). This will allow determination of the rate of charcoal accumulation along every centimeter of the sediment core.

Once the CHAR values have been obtained, this data could either be the final product, or it could be used for a more complex fire-frequency analysis that attempts to determine individual fire events that have occurred in the past (Long et al., 1998). This is the typical method used in many contemporaneous sedimentary charcoal studies, but it will not be the method used in this study. Past research has focused on the deconstruction of these charcoal accumulation rates into multiple components, to determine specific fire events over the course of a charcoal record (Brunelle & Anderson, 2003; Long et al., 1998; Mohr et al., 2003). In this method, the charcoal record is broken into two main components: the background component, and the peak component. The background component represents the general production of charcoal for a site and is created using a locally weighted average of the CHAR data (Long et al., 1998). The peak components represent the original CHAR values, and values above a certain ratio of the peaks to the background components are then considered to be individual fire events (Long et al., 1998). This method has been the standard practice for macroscopic charcoal studies for a few decades, but in the past several years, questions have been raised about this data. A study in publication from a research team at the USGS indicates that variability in charcoal counts in the same depth could indicate problems with this method (Anderson et al., 2019). Many of the samples within the same depth exhibit count differences large enough to not be considered from the same population of charcoal. Uncertainty arises because of non-random distribution of particles, as clumping of sedimentary charcoal particles could lead to differences in counts even in the same depths of the core (Anderson et al., 2019). Because of this, this paper will not use the dual component method be trying to identify fire events in the sediment, as research indicates that many past those records could have been overanalyzed in the past due to uncertainties in charcoal counts. My research will focus on the CHAR values and on interpretation of broader trends in charcoal accumulation that may be representative of changes in fire activity over time.

Results

Radiocarbon dates were taken from sample material for the four UCLA sites. Samples were generally taken at either defined intervals along the core, or during changes in stratigraphy. A general goal was to obtain 10 or more radiocarbon dates for each of these cores, to improve chronological control for the age-depth models.

Starkweather Lake Chronology

Table 2 – Starkweather Lake Radiocarbon Dating Results and Age Calibration

Core ID	UCI AMS#	Depth (cm)	Material	14C age	+- (σ)	Cal. Age Range YBP (2σ)	Mean Cal. Age (YBP)
SWL-01-1	**216132**	**10.5**	**Bulk Sediment**	**Modern**			
SWL-01-1	**205610**	**26.5**	**Bulk Sediment**	**365**	**15**	**327-496**	**418**
SWL-01-1A	**205611**	**89**	**Bulk Sediment**	**995**	**15**	**832-957**	**920**
SWL-1C	**216133**	**110.5**	**Bulk Sediment**	**1665**	**20**	**1531-1612**	**1569**
SWL-1C	**216134**	**137**	**Bulk Sediment**	**2020**	**15**	**1926-2001**	**1967**
SWL-1C	**216135**	**167**	**Bulk Sediment**	**3525**	**15**	**3722-3866**	**3790**
SWL-1C	**216136**	**180**	**Bulk Sediment**	**3930**	**15**	**4296-4425**	**4374**
SWL-1D	**216137**	**210**	**Bulk Sediment**	**4320**	**15**	**4842-4957**	**4866**
SWL-1D	**216138**	**235**	**Bulk Sediment**	**6630**	**20**	**7474-7570**	**7524**

SWL-1D	216139	265	Bulk Sediment	8430	20	9430-9500	9466
SWL-1E	Beta-164175	290.5	Bulk Sediment	9410	50	10511-10757	10643
SWL-1E	Beta-160790	301	Fragment	10300	70	11822-12398	12116
SWL-1E	Beta-161881	312.5	Bulk Sediment/Twig	11490	50	13234-13451	13340

13 radiocarbon dates were obtained from Starkweather Lake, including two from a surface core, and 11 from the main cores. Dates were generally taken at changes in appearance or stratigraphy in the core, along generalized intervals that would ensure there were no large gaps in the age-depth model. This core dates to the beginning of the Holocene, which will allow reconstruction of fire conditions throughout this period.

Funnel Lake Chronology

Table 3 - Funnel Lake Radiocarbon Results and Calibrated Ages

Core ID	UCIAMS#	Depth(cm)	Material	14C age	+-	Cal. Age Range YBP (2σ)	Mean Cal. Age (YBP)
FL-PT	210760	30.5	Bulk Sediment	415	20	341-514	486
FL-PT	210761	45.5	Bulk Sediment	785	20	679-731	704
FL-1A	205618	65	Bulk Sediment	2625	20	2740-2770	2753
FL-1A	205619	96	Bulk Sediment	3295	15	3475-3570	3519
FL-1A	205620	140.5	Bulk Sediment	4840	15	5491-5604	5585
FL-1B	205621	170	Bulk Sediment	5280	20	5950-6179	6073
FL-1B	205622	194	Bulk Sediment	6145	20	6967-7158	7063
FL-1B	205623	215	Bulk Sediment	7005	20	7790-7930	7856

FL-1B	216150	235.5	Bulk Sediment	5740	20	6474-6632	6537
FL-1B	205624	239	Bulk Sediment	5490	20	6220-6313	6290
FL-2D	Beta-155616	286	Bulk Sediment	8460	70	9305-9546	9459
FL-2D	Beta-168125	325	Bulk Sediment	10330	130	11625-12574	12137
FL-2D	Beta-153813	353	Aquatic Moss	11260	40	13054-13204	13120
FL-2D	216151	375.5	Bulk Sediment	11595	25	13372-13486	13433
FL-2D	216152	400.5	Bulk Sediment	11025	25	12786-13001	12887
FL-2D	NSRL-12024	401-402.5	Bulk Sediment	11050	50	12806-13017	12914

17 dates were obtained from the Funnel Lake site, including 15 from the main cores. Dates were generally taken at differences in appearance or stratigraphy, or at defined intervals when no changes were apparent. This cores dates to the beginning of the Holocene, which will allow for reconstruction of fire conditions throughout this entire period.

Hidden Lake Chronology

Table 4 – Hidden Lake Radiocarbon Results and Calibrated Ages

Core ID	UCIAMS#	Depth(cm)	Material	14C age	+-	Cal. Age Range YBP (2σ)	Mean Cal. Age (YBP)
HDL-02-PT	**210759**	**25.5**	**Bulk Sediment**	**415**	**20**	**341-514**	**486**
HDL-02-PT	**216153**	**60.5**	**Bulk Sediment**	**990**	**15**	**803-952**	**913**
HDL-02	**205625**	**70**	**Bulk Sediment**	**1130**	**15**	**979-1064**	**1022**
HDL-02	**216153**	**95.25**	**Bulk Sediment**	**1340**	**20**	**1190-1302**	**1278**
HDL-02	**Beta-179731**	**143.5**	**Twig**	**2540**	**40**	**2490-2752**	**2624**
HDL-02	**205626**	**200**	**Bulk Sediment**	**3550**	**15**	**3731-3895**	**3845**
HDL-02	**216153**	**202.75**	**Bulk Sediment**	**3530**	**15**	**3724-3873**	**3799**
HDL-02	**Beta-179732**	**247.25**	**Pine Needle**	**4460**	**40**	**4894-5295**	**5122**
HDL-02	**Beta-179733**	**310.25**	**Pine Needle**	**5880**	**40**	**6568-6795**	**6702**
HDL-02	**N/A**	**349.25**	**Tephra**	**7015**	**45**	**7740-7945**	**7853**
HDL-02	**205627**	**380**	**Bulk Sediment**	**8055**	**25**	**8786-9029**	**8971**
HDL-02	**Beta-179734**	**407.25**	**Twig**	**8660**	**40**	**9539-9697**	**9613**
HDL-02	**205628**	**425**	**Bulk Sediment**	**9475**	**20**	**10607-10774**	**10720**
HDL-02	**Beta-167869**	**461.5**	**Bulk Sediment**	**9460**	**60**	**10555-11074**	**10749**
HDL-02	**Beta-168954**	**473.5**	**Bulk Sediment**	**11170**	**40**	**12935-13126**	**13044**
HDL-02	**Beta-167277**	**493.5**	**Bulk Sediment**	**12700**	**40**	**14935-15289**	**15126**

16 dates were obtained from Hidden Lake, including 14 from the main cores. Dates were generally taken to ensure there were no large gaps in depth for the age-depth models. According to radiocarbon dating, this core is the oldest of the four, dating to towards the end Pleistocene epoch. This will allow us to reconstruct conditions during the entire Holocene at this site.

Greenstone Lake Chronology

Table 5 – Greenstone Lake Radiocarbon Results and Calibrated Ages

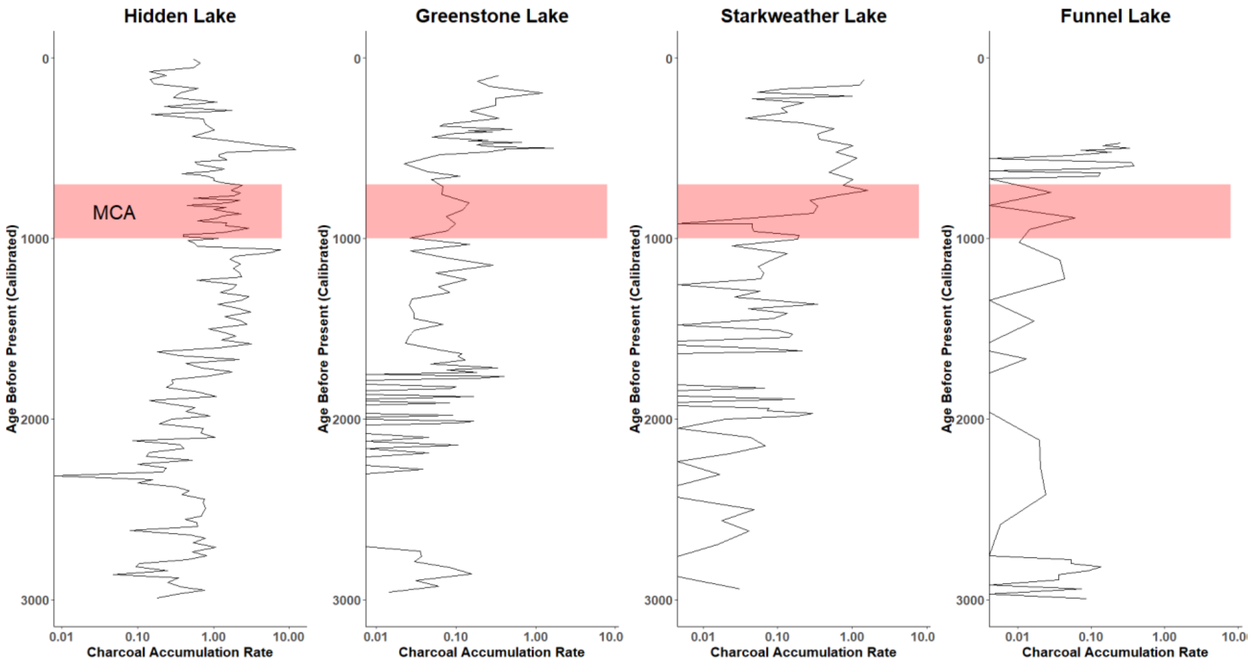
Core ID	**UCIAMS#**	**Depth(cm)**	**Material**	**14C age**	**+-**	**Cal. Age Range YBP (2σ)**	**Mean Cal. Age (YBP)**
GSL-01-PT	**216143**	**10.5**	**Bulk Sediment**	**650**	**20**	**560-667**	**609**
GSL-01-1A	**210762**	**25.5**	**Bulk Sediment**	**660**	**20**	**561-670**	**615**
GSL-01-1A	**205612**	**57**	**Bulk Sediment**	**1770**	**15**	**1619-1724**	**1671**
GSL-01-1B	**205613**	**88**	**Bulk Sediment**	**2040**	**15**	**1945-2051**	**1991**
GSL-01-2B	**216144**	**120.25**	**Bulk Sediment**	**2720**	**15**	**2775-2853**	**2813**
GSL-01-2B	**216145**	**150.25**	**Bulk Sediment**	**4220**	**20**	**4657-4847**	**4785**
GSL-01-2B	**216146**	**180.25**	**Bulk Sediment**	**6080**	**20**	**6889-6999**	**6941**
GSL-01-2C	**216147**	**210.25**	**Bulk Sediment**	**8305**	**25**	**9154-9430**	**9337**
GSL-01-2C	**216148**	**240.25**	**Bulk Sediment**	**10100**	**25**	**11411-11970**	**11705**
GSL-01-2C	**216149**	**270.25**	**Bulk Sediment**	**11430**	**90**	**13101-13444**	**13273**

10 radiocarbon dates were obtained from Greenstone Lake, including nine from the main cores. Dates were generally taken at defined intervals to reduce gaps in the age-depth model. Like the other three cores, this one dates to the beginning of the Holocene, which will allow reconstruction of fire conditions during this period.

Sedimentary Charcoal Records

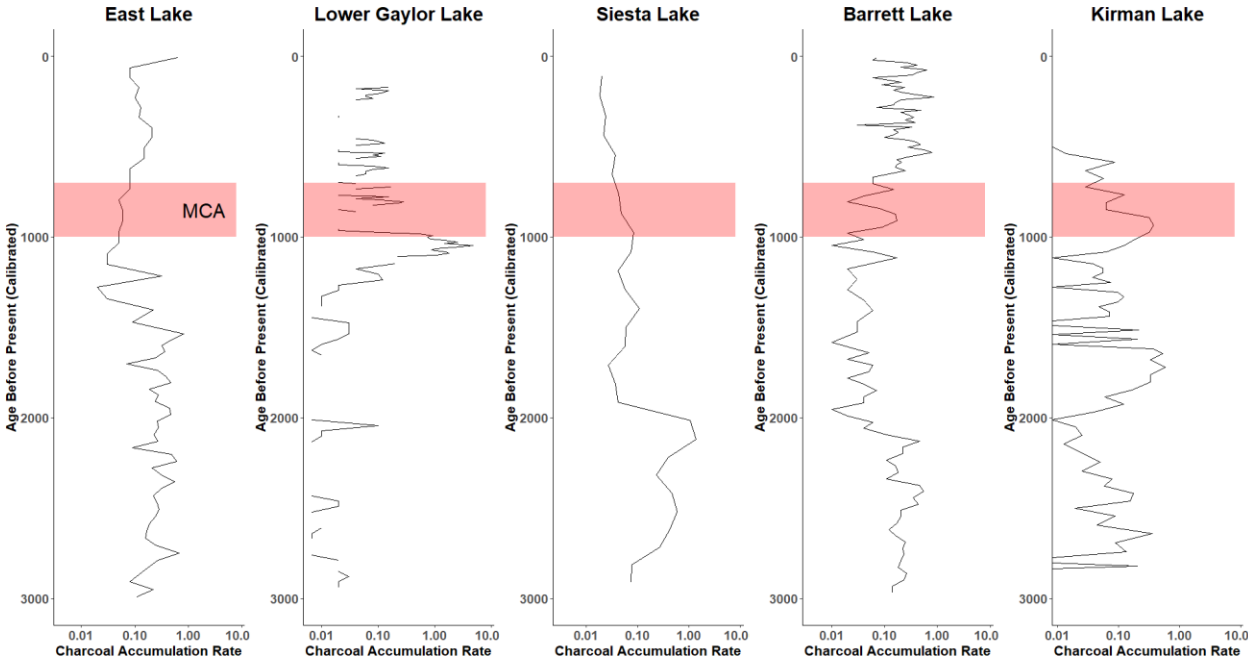
To better determine the response of fire on a regional and temporal basis, the charcoal records for the 16 sites were grouped spatially and temporally. Firstly, the records were split regionally in terms of the UCLA cored sites located in the Sierra Nevada's, the previously published records also located in the Sierra Nevada's, and the previously published records that are located in the Klamath region of Northern California. The UCLA Sierra Nevada sites and the previously published Sierra Nevada sites were separated because the UCLA sites are mostly located along the Sierra crest, and the previously published sites are predominantly located along the western slopes of the Sierra's, meaning they will likely have different environmental conditions and potentially different fire histories. Additionally, in order to more closely examine the response of fire to dry and warm periods, the record has been split into several temporal components, which will allow determination of the response of fire to the MCA, HTM, as well as for the entire Holocene.

Figure 3 – UCLA Charcoal Record – Late Holocene and MCA



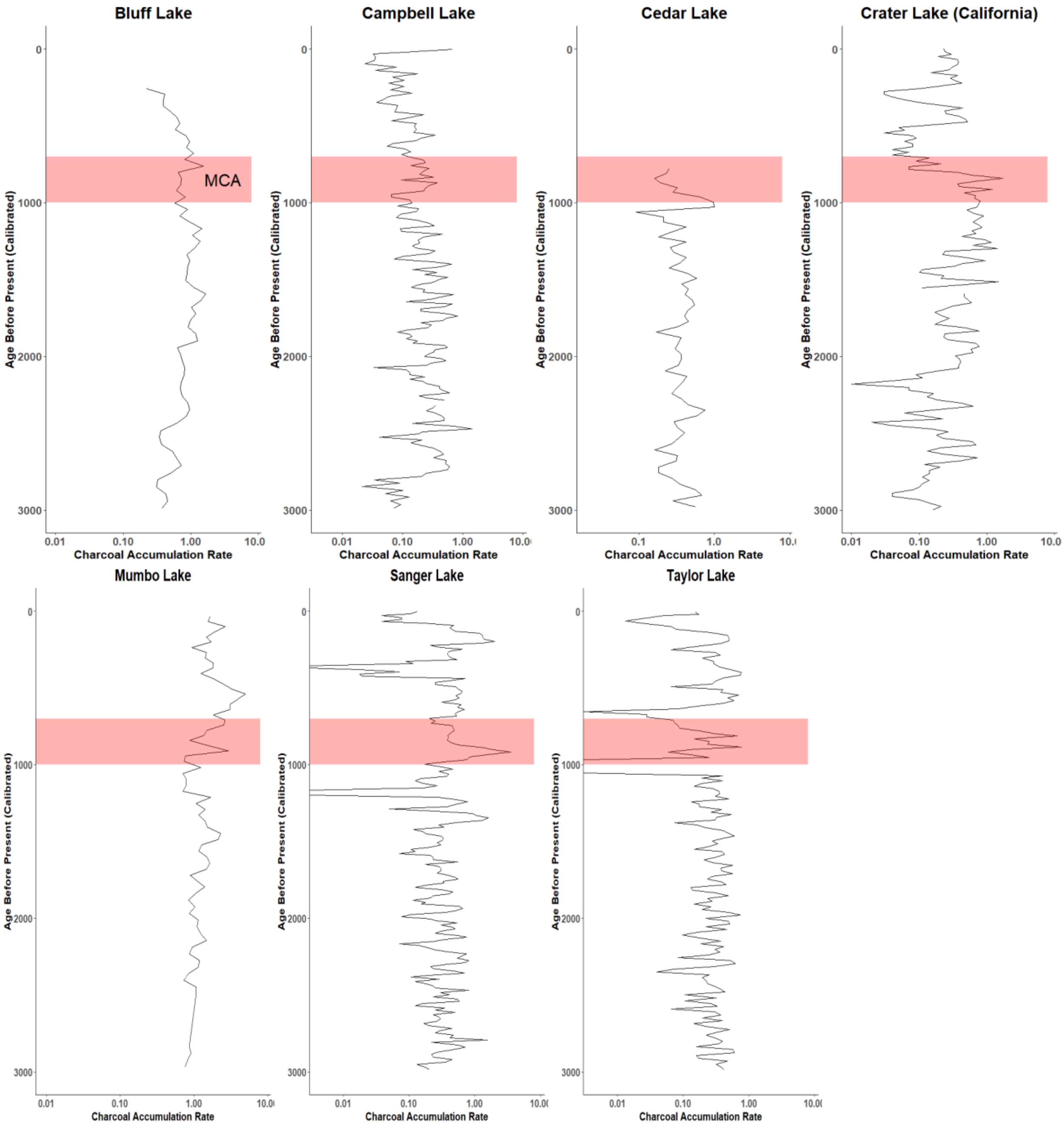
Plotted above are the stratigraphic diagrams for each of the UCLA sites. The y-axis of this chart and following charts indicates the calibrated age before present in terms of radiocarbon dates. The x-axis is plotted in log-10 scale to reduce the considerable variability that exists between depths of the core, which will help to better visualize long-term trends in charcoal accumulation. The timing of the medieval climate anomaly is shown as the red band. In general, there are some similarities between the records of Hidden, Greenstone, and Starkweather Lakes, as all three sites have a rise in charcoal accumulation after 2000 calibrated years before present (cal yr BP). This rise in charcoal accumulation correlates with an increasing number of El Niño–Southern Oscillation (ENSO) events during same time frame, as ENSO frequency increased from 3 events per century to about 10 per century from 2000-1000 cal. yr BP (Moy et al., 2002). Increased ENSO frequency would indicate more variable climate conditions, and in return more frequent fire events (Swain et al., 2018). During the period of the MCA, there are few consistent signals of increased fire activity, as only Starkweather Lake experiences a rise in charcoal accumulation during this period.

Figure 4 – Previously Published Sierra Nevada Sites – Late Holocene and MCA



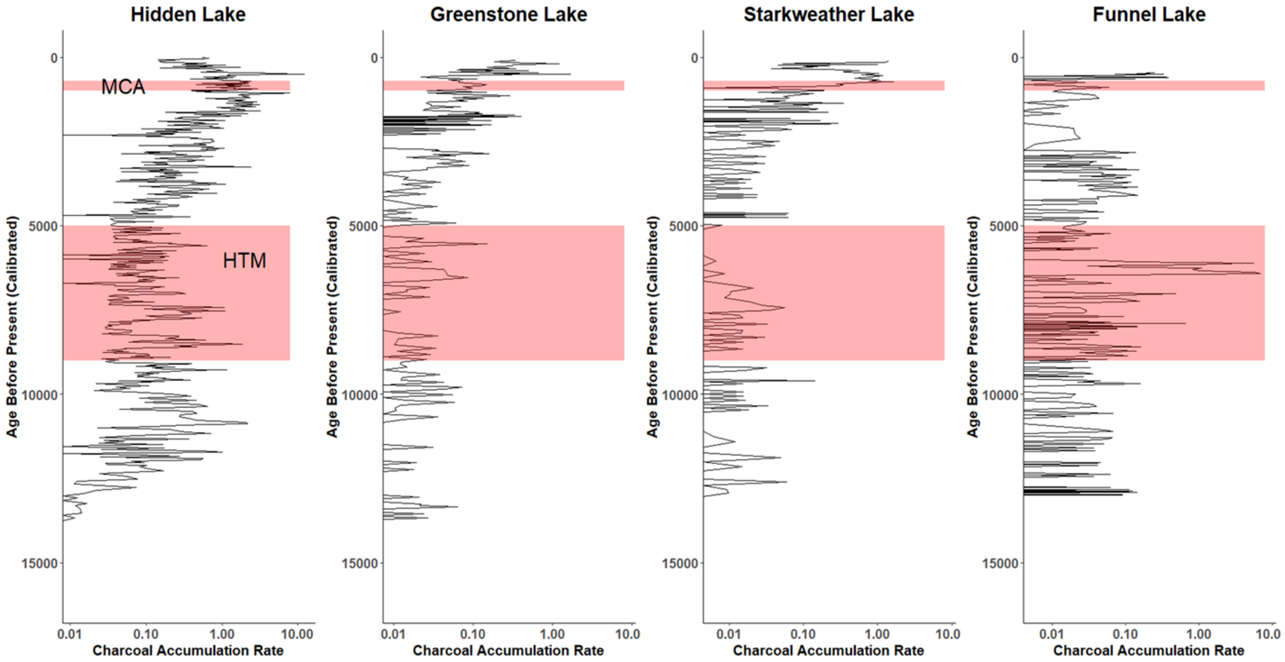
This chart represents the late Holocene charcoal record for the five Sierra Nevada sites that were a part of previously published studies. These 5 sites have inconsistent signals in their charcoal records, in contrast with the general rise in charcoal as seen in many of the UCLA sites. No consistent trends are seen during the time frame of the MCA. In addition, no sites exhibit consistent rises in charcoal accumulation that are correlated with ENSO, unlike the UCLA Sierra Nevada sites that are predominantly located along the Sierra Nevada crest.

Figure 5 – Klamath Region Sites – Late Holocene and MCA



As opposed to the long-term variability of the sites located in the Sierra Nevada region, the seven sites located in the Klamath region of the state generally fluctuate around consistent values during the period of the Holocene. Despite this consistency, many of these sites do have a signal of typically short-lived peaks in fire activity during the MCA. These peaks in the charcoal record could represent specific fire events in the record, and the presence at numerous sites suggests the possibility of widespread fires during the MCA (Higuera et al., 2010).

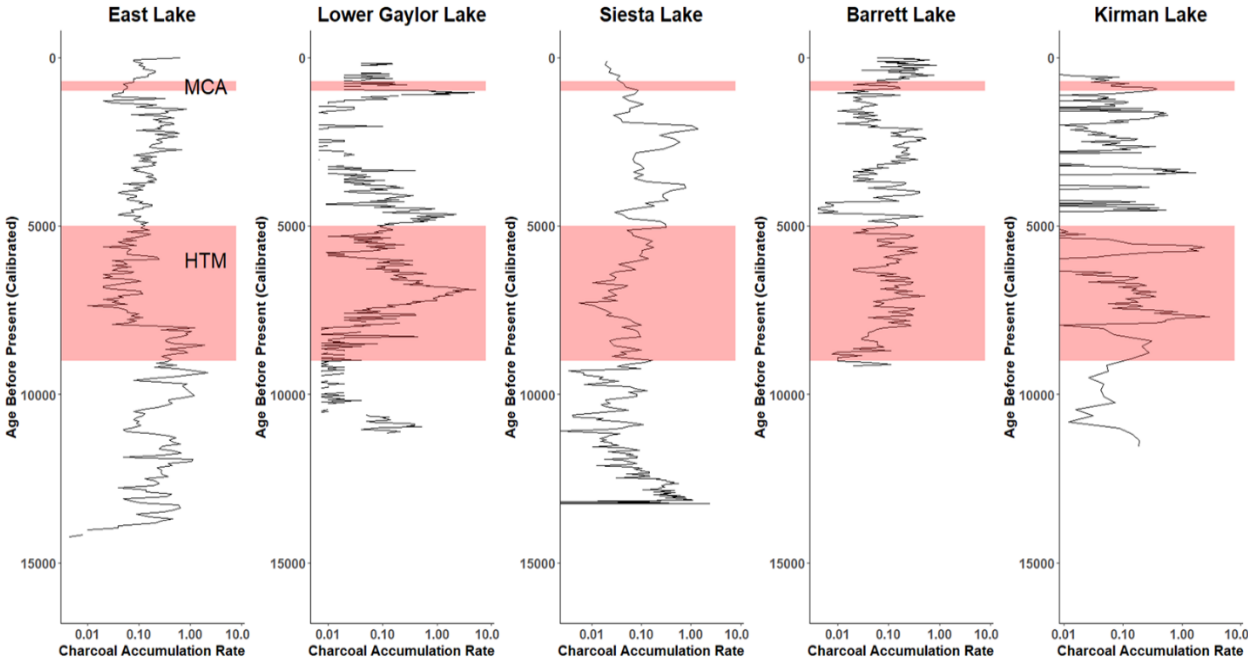
Figure 6 – UCLA Sierra Nevada Sites – Entire Period of Record



The entire record for each of the four UCLA sites is included to construct a complete picture of fire for the sites for the entire period of the Holocene. Charcoal values at these sites are generally low during the early part of the Holocene. The warm period of the HTM does not seem to have led to any significant increases in charcoal accumulation at these sites, except for a short-lived peak at Funnel Lake.

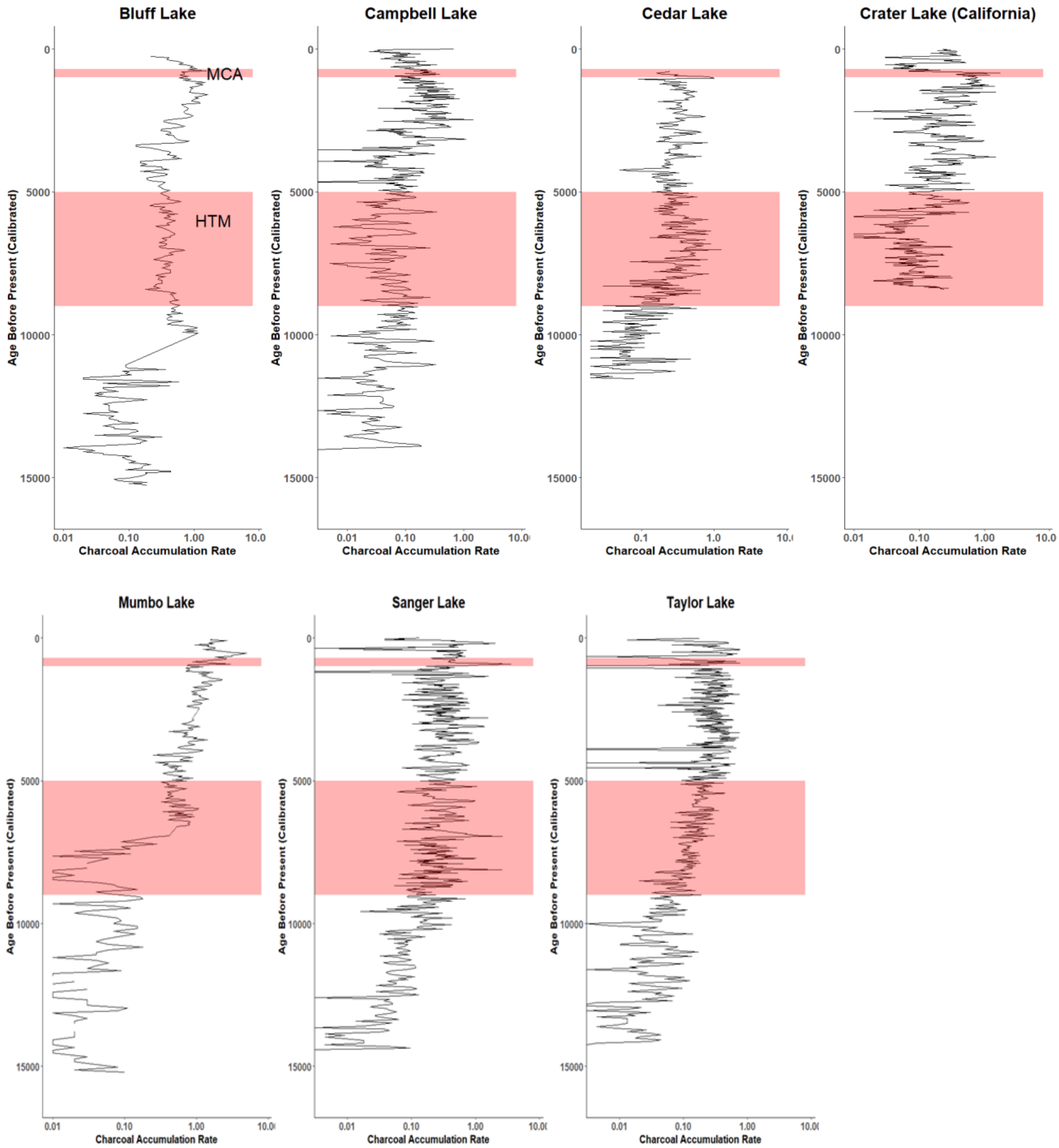
The rise in the late Holocene for Hidden, Greenstone, and Starkweather Lakes is seen more clearly in this broader-scale view, and this may be linked to changing ENSO conditions during this timeframe (Moy et al., 2002; MacDonald et al., 2016). More research will need to be completed to examine the linkages between this rise in charcoal accumulation and human activity in the region during the same period, as models indicate that native burning would need to be widespread during this period to approximate conditions seen in a pollen and charcoal record located in the Southern Sierra Nevada Mountains (Klimaszewski-Patterson et al., 2018).

Figure 7 – Previously Published Sierra Nevada Sites – Entire Period of Record



Records at these five sites exhibit considerable variability during the Holocene. Kirman Lake experiences with many periods of high charcoal accumulation, as well as periods where no charcoal is present. Barrett Lake generally experiences consistent values throughout this period, with a short drop in charcoal accumulation during the later parts of the Holocene. Siesta experienced lower values during periods of warmer temperatures such as the HTM or MCA, possibly suggesting reduced fuel load during those periods that would mean less vegetation is combusted. Lower Gaylor Lake also experiences significant variability in charcoal accumulation, and there is a peak in charcoal during the driest part of the HTM, suggesting a rise in fire activity at this site during that period (Higuera et al., 2010). East Lake experiences a sharp drop in charcoal during the HTM, which suggests that either changes in lacustrine geology or local vegetation might have led to a phase shift in the amount of charcoal that would be deposited at a lake site.

Figure 8 – Klamath Region Sites – Entire Period of Record



Unlike the inconsistent records of the other regions, the sedimentary charcoal records for study sites located in the Klamath region relatively exhibit consist patterns. During the period of the early Holocene, sites located in the Klamath region had values of charcoal accumulation that generally rose or maintained relatively constant levels over time. Campbell, Crater, and Bluff Lakes experienced generally consistent values during the HTM, but other sites had a rise in CHAR during this long period of drier and warmer than normal conditions. Including Taylor, Mumbo, Cedar, and Sanger Lakes. The rise in charcoal accumulation is linked to establishment of modern forests in the region during the early part of the Holocene, as vegetation at these sites typically transitioned to more woody forests over the course of the Holocene (Marlon et al., 2006). This transition to more wooded vegetation would lead to generally higher production of charcoal than grassy vegetation and would likely also lead to more intense fires that would also enhance production of charcoal (Marlon et al., 2006). Many of the sites located in the Klamath region also experience generalized rises in charcoal accumulation during the entire Holocene epoch. In all sites, the CHAR values are higher at the youngest parts of the records when compared to the older parts of the records.

Discussion

Response of Fire to Warm and Dry Periods

Sites included in this study exhibited inconsistent signals of fire activity when compared with the broad, state-wide increase in fire that has been seen in the California over recent decades (Williams et al., 2019). The first period of the interest that was examined was the Medieval Climate Anomaly, which is a period lasting from 950-1250 CE that was associated with persistent positive temperature anomalies in California (Graumlich, 1993). In both the UCLA and the previously published Sierra Nevada sites, few signals of increased burning were present during this time. Of the nine sites located in this region, only one, Starkweather Lake, exhibited a sharp rise in charcoal accumulation during this period which would suggest increased fire activity. These results are not consistent with dendrochronological studies which show increased fire activity during the MCA (Swetnam et al., 2009). This lack of a consistent signal in this period could owe to several factors. One of these factors could be that CHAR amounts are the product to several factors, only one of which is actual fire activity in the region. Site-specific factors like lake bathymetry, geology, and local vegetation could all affect these records, which might limit interpretation in this study (Whitlock & Larson, 2001). Another factor could be the length of the MCA when compared the rate of sediment accretion for these sites. The MCA was a period lasting ~300 years, and the sediment accretion rates for these sites varied from 20-50 years per centimeter for most of the sites in the Sierra Nevada's. These charcoal records might not be of high enough resolution to pick up changing conditions during this period. A possible solution would be to use tree-ring data to examine changes in fire activity during this period, as this data has annual resolution. The sites located in the Klamath mountain region in the northern part of the state exhibited a different response when compared to those located in the Sierra Nevada region. The seven sites in this region experienced small peaks in fire during some part of the MCA, and these peaks were generally short in nature. These short peaks above the baseline charcoal accumulation at these sites would possibly represent individual fire events at the lake sites in the region (Higuera et al., 2010). The fact that these spikes occurred in all of these sites would suggest the possibility of widespread fire activity in the MCA in the Klamath region, which would mirror the conditions that have occurred in modern times, as the region has experienced widespread large fires in the past few decades (Williams et al., 2019).

During the HTM period, the UCLA Sierra Nevada sites experienced generally low charcoal accumulation values. The five previously published sites located in the Sierra Nevada region had inconsistent signals during the HTM, as three of the sites experienced generally flat or declining levels during the HTM, and the other two had no consistent rise in charcoal accumulation rate during this period. However, the sites located in the Klamath mountain region did experience commonalities in the response of fire to the HTM. In general, these sites either experienced relatively consistent CHAR values during the HTM or gradual increases during this period. This rise in charcoal is likely a result of the long-term process of the establishment of denser forests in Northwest California that occurred over the course of the Holocene (Marlon et al., 2006). These dense forests would have increased charcoal production when compared to sparse forests that existed at the beginning of the Holocene, accounting for a similar rate of fire activity.

Spatial variability in Charcoal Records.

Another aim of this research was to analyze the response of fire during the Holocene along spatial gradients as well as temporal. By examining the response of fire on a spatial basis we will be able to see whether the statewide increase in fire in the modern period is a novel response to the warm and dry conditions of the present, or whether this has been a process that has occurred in the past.

As opposed to the consistent rise in fire activity seen in the modern period, sites in this study exhibited sharp regional differences in their records of fire. The Sierra Nevada sites cored by UCLA had some commonalities in their charcoal response. Three out of the four sites in this group experienced a rise in charcoal starting at 2000-3000 cal yr BP. This rise in charcoal frequency might be representative of increased ENSO activity that would possibly lead to increased fire activity (Moy et al., 2002). This consistency contrasts with the previously published Sierra Nevada sites, which experienced significant site-by-site variability in their charcoal values. At Lily Lake, in the Lake Tahoe drainage basin, a late Holocene decrease in CHAR was reported (Beaty and Taylor, 2014). No consistent trends were seen in these sites over the course of the Holocene, including the MCA and HTM. It is possible that these sites, predominantly located in the western Sierra Nevada mountains, have charcoal records that respond more strongly to local factors such as topography, local vegetation, and human activity than they do to broader-scale changes in climate over the course of the Holocene (Whitlock & Larson, 2001). Sites in the Klamath region experienced the most consistent response of the three. In general, nearly all the sites in the region experienced a rise in charcoal accumulation that began at the beginning of the Holocene and continued to the modern period. Sites in this region experienced a general rise in fire over the course of the Holocene. This is correlated with the establishment of modern forests in this region, which has been correlated with increased fuel loads, and therefore more burning in the forested regions of this area (Daniels et al., 2005; Marlon et al., 2006).

These regional differences in charcoal records suggests that over the period of the Holocene, fire responded more strongly to local or regional factors than it did to broad-scale changes in climate. This is in marked contrast to the past few decades where fire activity has risen in every major region of the state, including the Sierra Nevada and Klamath mountain regions (Williams et al., 2019). This suggests that the changes in fire activity currently experienced are without precedent during the Holocene. It is possible that the climate conditions and human activity of the modern period have extreme enough to overrule any local factors that might typically influence charcoal production and fire activity.

Utility of Statewide Analysis

Many studies of sedimentary charcoal have been completed in California over the past several decades, as this method has become established as common practice in paleoecological studies. However, most of these publications have centered on a single-site and have typically used a multi-proxy approach that involved macroscopic charcoal and other proxies such as pollen or magnetic susceptibility. This study is the first to examine sedimentary charcoal records across California during the entire Holocene epoch. Based on the data collected and synthesized in this paper, there are several important insights that came as a result of this methodology, including the determination of regional responses of fire activity, and the ability to make broader conclusions about how past fire activity compares to that in the present. However, there are also several major limitations to this study, both in terms of the use of meta-analysis of data, as well as in macroscopic charcoal as a proxy for fire.

There were several insights found from the data in this study that have established the utility of examining charcoal data on a broader scale. One of the first positives to come out of this study is that we were able to make broader interpretations than just being able to determine the history of fire at a single site. By using this study, we were able to determine a broad regional trend of increased charcoal production in the Klamath region of the state over the course of the Holocene. A similar situation was observed with the rise in charcoal in the last 2000-3000 years at most of the UCLA Sierra Nevada sites. Future work will be necessary to make firm conclusions about changes in charcoal accumulation at these sites and their causes. Another positive outcome of the study was the ability to determine whether the wildfire conditions on the modern period truly are exceptional when compared with conditions experienced during the Holocene. Our results show that this is likely the case, as the statewide increase in burning experienced over the past few decades was without analogues during the Holocene.

However, there are several factors that serve to limit the interpretation of the charcoal records in this study. The first of these would be the inevitable uncertainty in data that is introduced as studies are examined from multiple researchers at multiple institutes conducting research at different points in time in the history of the field. Studies included in this research were examined for methodological rigor, but unknown errors could also be present in data that has been uploaded to a database. The main concern with many of these studies is in variations in chronological control for radiocarbon dating, as the other steps in macroscopic charcoal analysis have been kept relatively constant over the past few decades. One example of this would be the radiocarbon dating for Siesta Lake, which was one of previously published sites located in the Sierra Nevada’s. This site only utilized three radiocarbon dates for a record that extend to the Pleistocene-Holocene transition period (Brunelle & Anderson, 2003). This paucity of dating is likely due to the prohibitive cost of extensive radiocarbon analysis during the period in which the study was completed. This limited radiocarbon dating increases the chance that nuances of the sediment accretion will be missed, particularly in terms of events like landslides that could lead to situations where a large amount of sediment is deposited quickly, sedimentation hiatuses due to drying, or situations where sediment actually becomes younger as you move deeper in certain parts of the core. In any case, sparse chronological control makes detection of sedimentation rate changes, and the subsequent changes in CHAR, more uncertain over the course of a record.

A second issue present in this study is the limited spatial extent of the records that were utilized for this study. The records for this study were in two narrow regions, one of which was the central Sierra Nevada region, and the other of which was the Klamath mountain region located in the far-northwestern portion of California. While the results of this study were able to help to inform about the regional response of fire in these locations, a truly statewide reconstruction of fire activity in the state will necessitate the analysis of sedimentary charcoal from more regions of the state. Regions of interest for expanding the scope of this study are the

Mendocino ranges north of the San Francisco Bay Area, the northern portion of the Sierra Nevada mountains, and the Transverse range mountains in Southern California.

The most serious limitation with interpretation of this study data is in the basic nature of sedimentary macroscopic charcoal as a fire proxy. As previously mentioned, past studies have separated the values of CHAR into background and peak components and used high peak values to represent individual fire events (Long et al., 1998). However, new research indicates that many studies that use this method are overanalyzing charcoal data, as considerable variability exists even among samples collected in the same depth from the same core (Anderson et al., 2019). Therefore, this study focuses on the pure CHAR values, which come from raw charcoal values that are adjusted to the sediment accretion rate along every depth of a sediment core. However, these CHAR values are the result of numerous factors that influence charcoal production and deposition, and only one of these factors is an actual fire event itself (Whitlock & Larson, 2001). Factors that can influence charcoal production at a lake site include steep slopes at a lake site, size of watershed compared to the size of a lake, and presence of vegetation that will produce more charcoal during combustion. (Whitlock & Larson, 2001). Two sites in the same geographic region may have different topography, soils, and vegetation, and as a result may have different fire and charcoal production regimes. Since macroscopic charcoal records are a result of local fires only, the two sites can have very different records. In addition to uncertainties that exist because of local site conditions and depositional factors, there are also inherent problems involved in the raw counts of charcoal data. Particles of charcoal can break during processing, which will inflate the raw charcoal counts, and there are also could be mistakes made in the determination of individual pieces of charcoal. Because of these limitations, interpretations of the CHAR record can only truly be made with great confidence if information about lake geology, hydrology, and ecology is well known, and data are typically limited in meta-analysis of these records. Therefore, interpretations of CHAR records on a regional spatial scale should only be made in general terms where there is a similar signal recorded in many different sites, such as the interpretation of the data from sites located in the Klamath region, where sites experienced a general increase in charcoal accumulation during the course of the Holocene.

Further Research

This study provides one of the first steps in determining the response of fire activity in California on a broad spatial and temporal scale. By examining charcoal records from sites located in the Sierra Nevada and the Klamath mountain region, we were able to determine several important trends in this region, including a rise in charcoal accumulation in the last 3000 years at sites cored by UCLA located in the Sierra Nevada mountains, as well as a generalized increase in sedimentary charcoal accumulation at sites located in the Klamath region. The results in this study indicate there is merit to analyzing sedimentary charcoal on a statewide basis if care is taken in site selection and enough sites are analyzed to detect common regional signals above local site to site noise. However, due the limitations of macroscopic charcoal discussed in this study, future work will need to incorporate the use of additional study sites and improved charcoal analysis methods in order to improve understanding of how fire activity changed in California during the course of the Holocene.

New methods of analyzing charcoal data will be examined to determine how charcoal data specifically relates to the presence and frequency of fires at a regional and statewide basis rather than only local conditions. One method that has been used in the past is the analysis of microscopic charcoal pieces, as these are deposited from the region around a study site, as opposed to the local area (Patterson et al., 1987; MacDonald et al., 1991). As macroscopic charcoal is deposited locally in most cases, site-specific factors might limit interpretation of the charcoal record. Another method that might help to reduce potential errors is to use other methods than counting charcoal pieces by hand. Another method that could be incorporated into future work would be to use image analysis software to reduce the errors that are possible when counting charcoal by hand (Thevenon & Anselmetti, 2007).

To expand the narrow spatial extent of the data included in this study, new sites will have to have sediment cores collected. As a part of a collaborative grant between UCLA and California State University at Fullerton, cores have been collected from sites in Northern California, with an emphasis on sites in the Mendocino mountains, which have up to now been understudied in terms of paleoecological research (National Science Foundation). Potential future locations for cores to be taken would be sites located in the northern Sierra Nevada mountains, as well as sites located in the mountain ranges of Southern California. An additional way to expand this research would be to examine more types of climate proxy data to examine the connections between vegetation and fire activity. Palynological analysis could be completed for the UCLA Sierra Nevada sites, which would help to improve our understanding of how vegetation and fire activity interacted during the Holocene. Additional sedimentary pollen data in California would be obtained from online databases, such as Neotoma, to expand research of the statewide response of vegetation and fires to past droughts in California. By expanding the methodology used to analyze charcoal, the sites available to study, and the proxies used, a more accurate picture of the linkages between fire and vegetation during the Holocene in California can be completed.

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