Title
Climate, Fire, and Environmental Dynamics at Lake Elsinore, California, from Late Marine Isotope Stage 3 through the Holocene

Author
Martinez, Lisa Nicole

Publication Date
2020

Peer reviewed|Thesis/dissertation

UNIVERSITY OF CALIFORNIA

Los Angeles

Climate, Fire, and Environmental Dynamics at Lake Elsinore, California, from Late Marine Isotope Stage 3 through the Holocene

A thesis submitted in partial satisfaction
of the requirements for the degree of Master of Arts
in Geography

by

Lisa Nicole Martinez

2020

ABSTRACT OF THE THESIS

Climate, Fire, and Environmental Dynamics at Lake Elsinore,

California, from Late Marine Isotope Stage 3

through the Holocene

by

Lisa Nicole Martinez

Master of Arts in Geography

University of California, Los Angeles, 2020

Professor Glen Michael MacDonald, Chair

Climate models predict increases in temperature and hydrologic variability for the remainder of the 21st century, threatening California's fire-prone ecosystems. To gain a better understanding of future climate-fire-environment dynamics, it is important to study how biomass burning changed in ecosystems as temperatures varied and fuel types changed from Late Marine Isotope Stage (MIS) 3 through MIS 1 (the Holocene). Continuous sedimentary records of fire activity can provide such evidence, but are rare in Southern California. Here, I present fire and environmental dynamics over 32,950 cal yr BP as recorded in a high-resolution macroscopic charcoal record from Lake Elsinore, California. Results are compared to orbital climate forcings and previously reported proxy environmental interpretations for the lake sediments. The lake's charcoal record shows that fire activity was quiescent during late MIS 3. Lake Elsinore's most dynamic charcoal influx occurs during the MIS 2/1 transition from the Bølling Allerød to the Younger Dryas chronozone. Moving into the Early Holocene, charcoal deposition decreased. During late MIS 1, fire frequency and variability increased as temperatures warmed, and human population density increased near the lake. The record shows millennial-scale variability in fire regimes corresponding to the climate changes associated with insolation changes. This study offers insights into fire, climate, and ecological dynamics from a lake in Southern California and may be key for projecting how ecosystems respond to disturbances under California's projected climate change.

The thesis of Lisa Nicole Martinez is approved.

Marilyn N. Raphael

Thomas Welch Gillespie

Glen Michael MacDonald, Committee Chair

University of California, Los Angeles

2020

For my family--Dad, Mom, David, and Eric.

Table of Contents

List of Figures

List of Tables

ACKNOWLEDGEMENTS

I would like to acknowledge my advisor Glen MacDonald for his guidance, enthusiasm, inspiration, and patience. I would like to thank my committee members Tom Gillespie and Marilyn Raphael for their advice, valuable feedback, and support. Special thanks to Matthew Kirby who shared his sediment cores and data. Matt went above and beyond with his mentorship and enthusiasm. Much thanks to Nick Burkhart, Bridget Gonzalez, and Rachel Meyer.

I am thankful for my lab mates: Elly Fard, Jessie George, Jiwoo Han, Jason Kindinger, Scott Lydon, and Ben Nauman. Your friendship and professional advice make this work possible. Thank you, as well to Lauren Brown and Marcus Thomson.

To my friends, Josie Flores and Brett Wong, who supported and encouraged my graduate journey. Summera Howell and Lottie (cat), you have been the best roommates. Summera, our late-night conversations, movie watching, and frozen yogurt runs will always be appreciated.

Finally, I would like to express my gratitude to my family, who have been by my side, always. My Dad is one of the hardest working people I know and one of my greatest supporters. From a young age, you instilled a lifelong love of nature and animals, curiosity, and perseverance. To my Mom, the bravest and strongest woman that I have ever met. Though you left this world before I could finish this work, your support was always at the forefront of my heart. You taught me to never let fear dictate my life. My brother David, your kindness and selflessness aspires me to be a better person. My brother Eric, your amiable personality and strive to do what you love encourages me to do what I love. Bros, our many conversations and laughs provided me with much needed moments of fun. To my furry children (cats), Cuddles and Boo, your companionship and love has been greatly appreciated. There are many more people that I have not mentioned, and I thank you as well for your feedback and support.

1. Introduction

Climate model projections for the remainder of the 21st century predict increases in temperature and hydrologic variability, perhaps with overall enhanced aridity, indicating increased threats to California's fire-prone ecosystems through increasing fire activity (Beuhler, 2003; Overpeck et al., 2013). Fire activity responds to long-term global climate changes and shorter-term regional changes in climate, human land use, and vegetation (Power et al., 2008). Regional climatic changes such as warmer spring and summer temperatures and changes in the magnitude and timing of moisture availability have increased the duration and intensity of California's fire season leading to greater annual area burned (Westerling et al., 2006; Whitlock et al., 2008; Marlon et al., 2009; Sommers et al., 2014; Yoon et al., 2015). In terms of acres burned in the past 10 years, 2018 marks California's worst fire season (CAL FIRE, 2020).

Quantifying long-term relationships between fire and climate, and the natural variability in this system, is crucial for understanding present and future fire regimes and ecological responses to this disturbance. Historical records of fire activity in California only extend back to the 18th century and the earliest records are sparse and qualitative (Reynolds & Pierson, 1941; Minnich, 1988). California vegetation is often said to be 'fire-adapted', but there is little way of knowing if historical fire activity represents conditions over the past millennia. Paleoclimate and paleofire studies, such as analysis of lake sediments can provide unique opportunities to study fire, geochemical responses, climate, and environmental dynamics over a range of timescales extending centuries to millennia (Whitlock & Larsen, 2001; Cohen, 2003; Gavin et al., 2007; Kirby et al., 2007). On century and longer timescales, large-scale changes in the climate system caused by variations in insolation seasonality, atmospheric composition, and atmosphere-ocean interactions emerge as important controls on fire activity (Whitlock & Bartlein, 2003). There is evidence of prolonged decreased fire activity in Southern California during the last glacial period (Glover et al., 2020). Moreover, retrospective studies are key as potential past analogues for present and future conditions related to rapid anthropogenic climate change. For example, the late glacial/Early Holocene transition, 20,000 to 8,000 cal yr BP, was a period of rapid, high amplitude warming and environmental change (Dansgaard et al., 1993; Alley & Clark, 1999; Marlon et al., 2009) and may be the closest in the magnitude of warming relative to projections for future climate change scenarios (IPCC, 2013).

Several regions in North America experienced large and abrupt changes in climate, biota, and fire activity during the Bølling Allerød (14,700-12,900 cal yr BP) to the Younger Dryas chronozone (12,900-11,700 cal yr BP) (Marlon et al., 2009). The Bølling Allerød was a warm, moist interstadial period that ended with the rapid cooling that interrupted the warming climate of the deglaciation during the Younger Dryas. Mechanisms for the Younger Dryas cooling include the abrupt slowdown of the Atlantic Meridional Overturning Circulation (AMOC) in response to the meltwater discharges released from Northern Hemisphere ice sheets (McManus et al., 2004; Jennings et al., 2006) and the controversial impact hypotheses (van Hoesel et al., 2012). The Firestone et al. (2007) hypothesis proposed that a catastrophic extraterrestrial impact event at 12,900 cal yr BP triggered massive wildfires across North America. Similarly, to the hypothesis postulated by Firestone et al. (2007), Thackeray et al. (2019) hypothesized that the impact of a large meteorite crater beneath the Hiawatha glacier in Northern Greenland is evidence of a strike that led to biomass burning and dust being dispersed on a global scale, thus leading to a temporary decline in atmospheric and oceanic temperatures.

Past climate and fire event reconstructions that extend back for centuries to millennia rely heavily upon lacustrine records. Lake Elsinore, the largest of a limited number of natural freshwater lakes in coastal southwestern North America (i.e., greater Southern California), offers an opportunity to reconstruct long-term records of fire variability and relationships to climate and vegetation forcing factors. The region surrounding the lake is highly susceptible to hydrologic variability (i.e., droughts) and fire, and heightened fire activity could impact millions of people (Grenda, 1997; Behuler, 2003; CDWR, 2005; Kirby et al., 2006). As such, the hydrologically and fire sensitive region is an ideal site for documenting climate, fire occurrence, and environmental change over long time scales. Previous research indicates that the lake holds a sediment record extending back 32,000 years (Kirby et al., 2018, 2019). Long histories of regional climate changes have been inferred from lake-level fluctuations indicated by the sedimentary record at Lake Elsinore (Kirby et al., 2007, 2010, 2013, 2018, 2019).

High-resolution sedimentary macroscopic charcoal analysis from Lake Elsinore allows the construction of a fire record spanning the Late Marine Isotope Stage (MIS) 3 to the Holocene (32,950 cal yr BP to 1994 AD). MISs are alternating cold and warm periods inferred from oxygen isotope data derived from marine sediments and ice cores. Stages are bounded by dates as reported in Lisiecki and Raymo (2005): late MIS 3 (32,950-29,000 cal yr BP), MIS 2 (29,000-14,000 cal yr BP), and MIS 1 (<14,000-Present). The record is used to address the following questions: (1) Is the Holocene fire activity as represented by macroscopic charcoal different than fire activity during the preceding MIS 2 and late MIS 3 and how have orbital-scale and millennial-scale climatic drivers influenced the paleoenvironmental and fire changes observed at the site? (2) How have local climate changes, documented by lake level changes and by other regional evidence of temperature and precipitation changes, been reflected in fire activity? (3) Several North American paleoclimate studies suggest increased fire activity occurred during the late glacial (15,000 to 10,000 cal yr BP), particularly during the Younger Dryas. Does Lake

Elsinore's charcoal record indicate that increased fire activity occurred during this period. If so, why? (4) How does the Lake Elsinore paleoclimate and fire record compare with other similar studies from the broad region? By answering these questions, I offer insights into ecological responses to past fire and climate dynamics from a site within coastal southwest North America that may be key for projecting how these increasingly vulnerable ecosystems respond in the future.

2. Setting

2.1 Regional Climate, Fire, and Humans

Coastal southwestern California occupies North America's Mediterranean climate zone and is characterized by dry, warm summers and wet, cool winters due to seasonal changes in insolation and shifts in the location of the storm track (Barry & Chorley, 2009). Winter hydrologic variability is strongly impacted by ocean-atmosphere interactions such as the inter-annual tropical El Niño and Southern Oscillation (ENSO) and the inter-decadal cycle of the extratropical Pacific Decadal Oscillation (PDO) (Castello & Shelton, 2004; MacDonald & Case, 2005; Barron & Anderson, 2011). During El Niño winters, drainage basins in southwestern United States tend to receive stronger and more frequent precipitation than during La Niña winters (Gershunov & Barnett, 1998; Kirby et al., 2010; Barron & Anderson, 2011).

Summer precipitation, although infrequent, is produced by either an expansion of the North American Monsoon (NAM) or waning tropical cyclones (Tubbs, 1972). Gulf of California and Mexico sea surface temperatures, easterly wave activity, and the position of the Gulf of Mexico high pressure system modulates the amount of moisture advected by the NAM. The storms' effects can be severe, resulting in floods, landslides, and/or lightning-formed forest fires (Tubbs, 1972; Kirby et al., 2010).

Climate is an important driver of historical fire in the southwestern United States (Heyerdahl et al., 2002). In California, climate driven changes in fire regimes primarily work through altering spatial patterns in fuel structure and temporal patterns of fuel moisture (Pausas & Keeley, 2014). Fuel conditions are influenced by seasonal to interdecadal variability in lightning regimes, precipitation, temperature, and wind (Swetnam & Betancourt, 1998). During La Niña events, the southwest tends to receive reduced precipitation and experience more frequent fires. Whereas, the reverse is the case during El Niño events (Marlon et al., 2012). In California, before human populations increased in the Mid-Holocene, lightning was the most common source of ignitions and likely played an increasing role in altering fire activity (Jones, 1992; Keeley, 2005).

In lowland coastal Southern California, with its scrubland and shrubland-dominated landscapes that are conducive to high-intensity wildfires, most large fires occur in the autumn when fuel is extremely dry, and are influenced by high winds under hot and dry conditions (Santa Ana winds) (Keeley et al., 2009). Over the past 100 years, large areas in the Southern California foothills have experienced 4-10 (or more) fires (Figure 1; CAL FIRE, 2020; Keeley, 2001). The largest of these fires burn through chaparral or sage scrub fuels and are largely replaced by invasive exotic grasses and forbs (Mack and D'Antonio, 1998; Keeley, 2001; Jacobson et al., 2004). The danger and increasing complexity of fire control efforts is further exacerbated by increasing human population in the Southern California foothills (Keeley et al., 2009). In recent decades, humans have been increasingly modifying fire regimes (CAL FIRE, 2020).

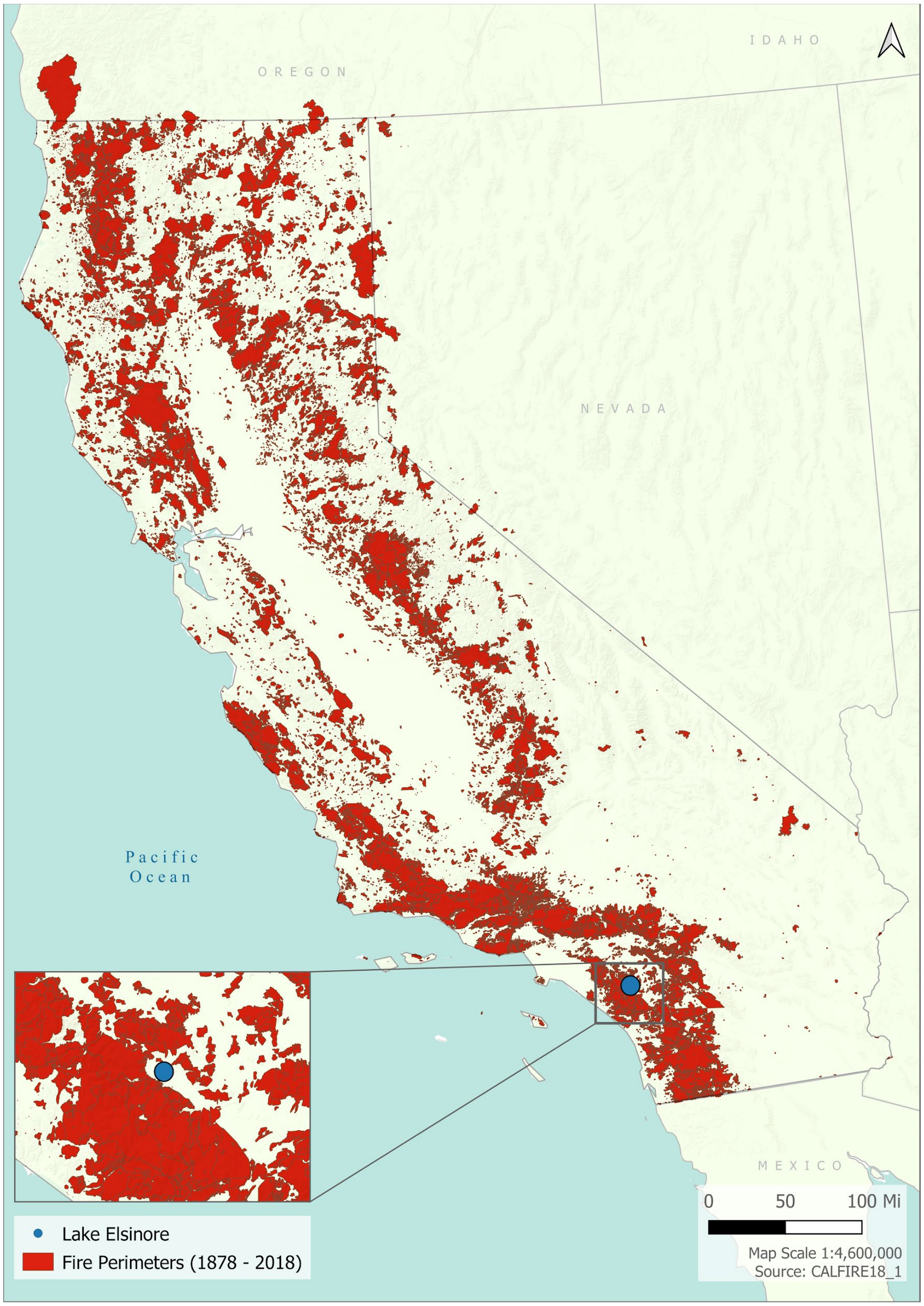

Figure 1. California's fire perimeters depicted by red polygons from 1878-2018 CE (California's Fire Perimeter dataset; available at https://frap.fire.ca.gov/frap-projects/fire-perimeters/). The inset shows Lake Elsinore's location within California.

The Southern California coast has long been a site of human occupation. The earliest human remains thus far have been found on the Pacific Coast, dating back to ~13,000 cal yr BP (Erlandson et al., 2011; Ejarque et al., 2015) and archaeological evidence of human presence along the shores of Lake Elsinore exists for at least the past 8,400 years. Throughout this time, nearly continuous water supply and a diverse set of avian, aquatic, and terrestrial fauna and flora species likely enabled humans to reside throughout the region (Grenda, 1997; Kirby et al., 2003). Thus, humans may have been a factor in the fire regime of the Lake Elsinore region for most of the Holocene.

2.2 Study Site

Lake Elsinore (33° 39' 44.26'' N, 117° 21' 4.24'' W) is in Riverside County, approximately 120 km southeast from Los Angeles and 36 km inland from the Pacific Ocean in coastal southwest North America (Figure 2). The lake lies in a prominent graben along the Elsinore Fault zone formed by fault step-over movement from the Wildomar Fault to the Glen Ivy North Fault (Mann, 1956; Hull & Nicholson, 1992). Geologically, the region surrounding the lake consists of predominantly plutonic igneous rocks and mildly to moderately metamorphosed sedimentary rocks (Engel, 1959; Hull & Nicholson, 1992). The lake has a maximum modern surface size of approximately 2.5 km wide by 11 km long, making it the largest, natural permanent lake in coastal southwestern North America. Its maximum modern depth only extends 13 m; therefore, it is typically classified as a shallow polymictic lake (Anderson, 2001; Kirby et al., 2010).

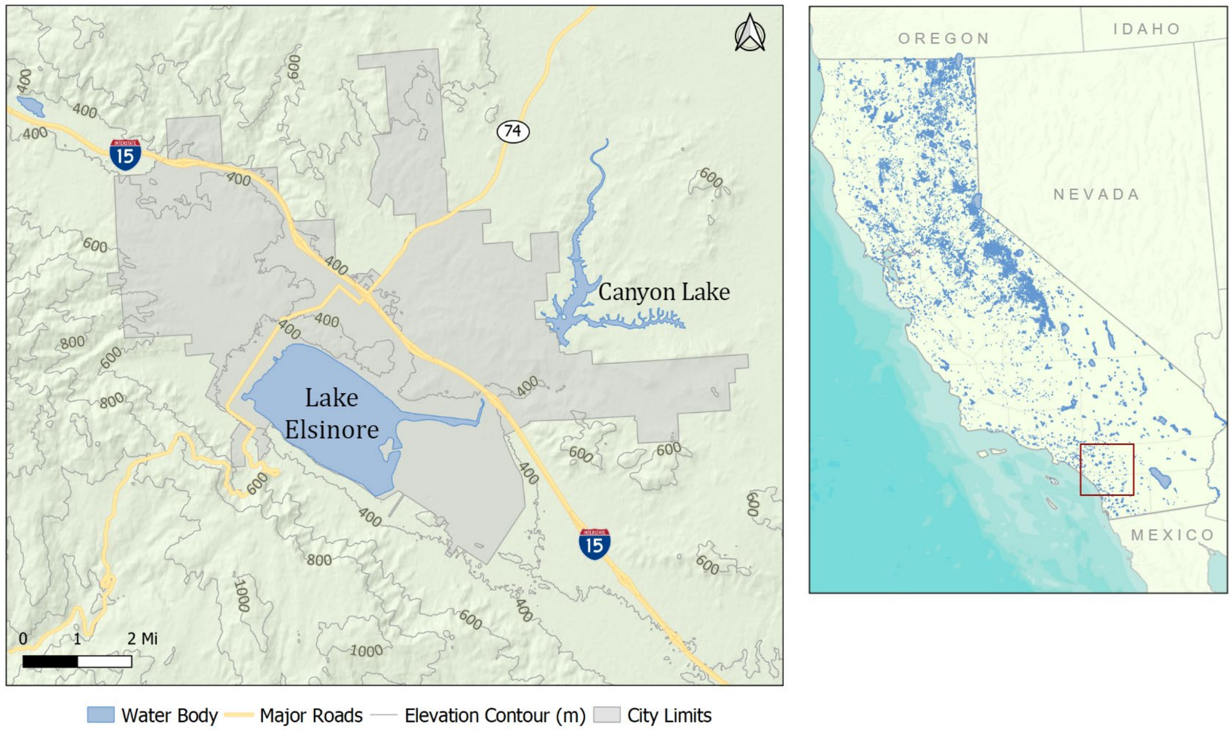

Figure 2. Topographic map of Lake Elsinore, California. Contour interval = 100 m. Data Source: USGS Earth Explorer (https://earthexplorer.usgs.gov) and Riverside County Mapping Portal (https://gisopendata-countyofriverside.opendata.arcgis.com/).

Primary water sources for the lake include the San Jacinto River in the Peninsular Range and direct run-off from the nearby Santa Ana Mountains (locally known as the Elsinore Mountains) (Kirby et al., 2013). Lake levels fluctuate significantly based on interannual variations in precipitation and evaporative losses, and can be influenced by ENSO conditions (Lawson & Anderson, 2007; Martinez & Anderson, 2013; Kirby et al., 2019). Hydrologically, Lake Elsinore is considered as a closed basin as it rarely overflows; however, during extremely wet years, historical records indicate that the lake has overflowed to the northwest 20 times since 1769 AD. Contrarily, since 1769 AD, Lake Elsinore has desiccated four times during historical droughts (Lynch, 1931).

Lake Elsinore experiences a Mediterranean climate (Kirby et al., 2004; Martinez & Anderson, 2013). Meteorological records from 1897 to 2016 for the City of Lake Elsinore show average monthly temperature varying from winter lows (18.5 °C in January) to summer highs (36.7 °C in July and August), and a mean precipitation of 305.05 mm. Peak precipitation occurs during the winter between December and March (Figure 3). Snow is rare at lake elevations with an annual amount of 15.24 mm recorded exclusively in December and January (WRCC, 2019).

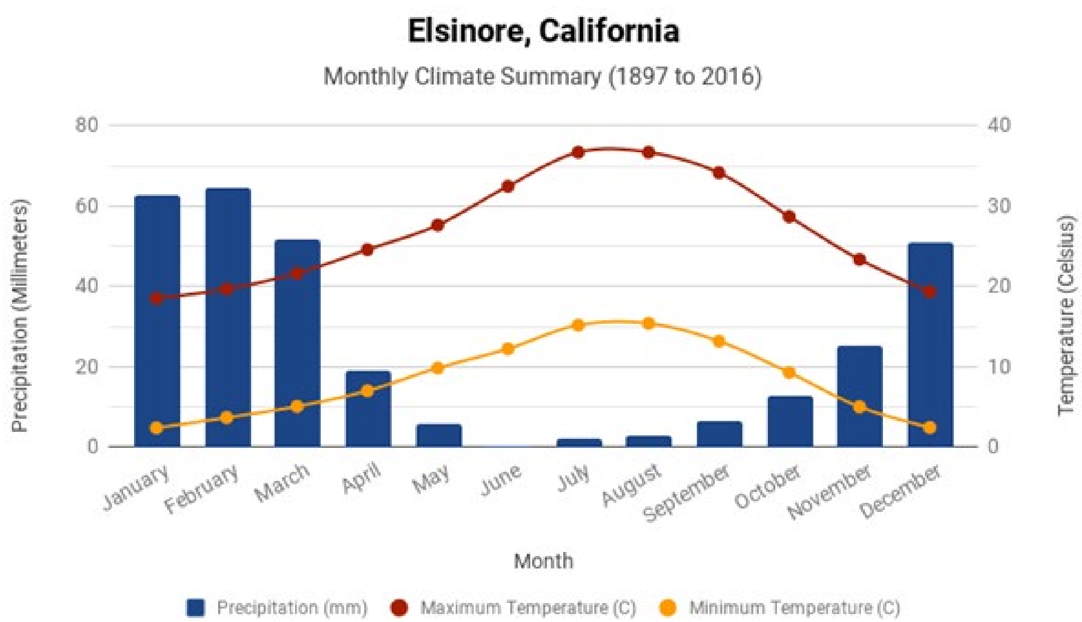

Figure 3. Monthly climate data from Elsinore, California (1897-2016). Data Source: Western Regional Climate Center (WRCC, 2019).

Orographic temperature and precipitation gradients influence the area around Lake Elsinore. Topographic relief ranges from 380 m at Lake Elsinore and up to 3,302 m in the San Jacinto Mountains. Generally, the nearby mountain ranges receive more precipitation than the lake, a low-lying inland region (Masi, 2005).

Geographic variations in precipitation strongly influence California's vegetation (Minnich et al., 2007). Modern vegetation at Lake Elsinore reflects elevational gradients in precipitation. At low- and mid-elevation, predominant vegetation includes mixed chaparral (*Ceanothus, Adenostoma, Quercus dumosa*), alluvial scrub, California sage scrub (*Artemisia californica, Eriogonum*), and oak and grass woodland (*Quercus agrifolia,* Poaceae) communities which generally require approximately 300 mm of annual precipitation. The chaparral community is considered to be highly adapted to periodic natural fires (City of Lake Elsinore: Biological Resources, 2011). Scrub-shrub, oak, and mixed evergreen oak-pine woodlands merge at approximately 1,300-1,500 m, requiring 625-650 mm of precipitation and mean annual temperatures of 12-15℃. South and southwest slopes of the nearby San Jacinto Mountains support single needle piñon pine (*Pinus monophylla)* and juniper woodlands (*Juniperus californica*). Mixed conifer forests, including oaks and pines (*Pinus coulteri, Pinus jeffreyi, Pseudotsuga macrocarpa, Abies concolor)* occurs above 1,850 m (Anderson & Koehler, 2003; Vasek & Thorne, 1977; MacHott, 2011).

3. Methods

3.1 Core Acquisition

Sediment cores LEGC03-3 and LEDC10-1 were acquired in 2003 and 2010, respectively (Kirby et al., 2007, 2013). LEGC03-3 (33°40.395 N; 117°21.250 W) was extracted from the modern sediment-water interface to 10.74 m below using a barge-mounted, split-spoon corer operated by Gregg Drilling Company (Kirby et al., 2007). To provide some overlap with core LEGC03-3 (10.74 m), LEDC10-1 (33°40 N; 117°21 W) was obtained from the profundal zone of Lake Elsinore 9 to 30 m below the modern sediment-water interface (Kirby et al., 2013). Core recovery was approximately 85% for LEGC03-3 and 90% for LEDC10-1 (Kirby et al., 2007, 2013). The sediment cores were transported from the California State University, Fullerton Paleoclimatology Laboratory to the University of California, Los Angeles in 2018 where they were stored in the MacDonald Biogeography Laboratory Cold Room at 4 °C and subsampled for charcoal and x-ray fluorescence (XRF) elemental geochemical analyses.

3.2 Composite Core

Cores LEGC03-3 and LEDC10-1 were combined to construct a single composite record. To assess how the overlapping portions of LEGC03-3 and LEDC10-1 cross-correlated, I used stratigraphic profiles of percent organic matter estimated via loss on ignition (LOI) at 550 °C as a method of cross-correlation (LOI data reported in Kirby et al. (2007, 2018)). Percent organic matter reflects a combination of allochthonous and autochthonous sources in lake systems (Dean, 1974; Heiri et al., 2001). Autochthonous lake organic matter is the amount which is derived from in situ lake productivity, and reflects properties such as water temperature, water column turbidity, and/or nutrient availability (Dean, 1981; Benson et al., 1998; Kirby et al., 2005). This constitutes the primary source of organic matter in Lake Elsinore (Anderson, 2001). As such, I use the similarity in percent total organic matter between LEGC03-3 and LEDC10-1 as a tie point for cross-correlating sediment depth and age data for the development of a composite core.

After computing a cross-correlation coefficient of 0.65 ($p < 0.05$) for the best match in stratigraphy, the record for total organic matter for the coinciding portion of the cores, LEGC03-3 was transposed on core LEDC10-1 by noting LEGC03-3 depths and equivalent LEDC10-1 depths. I chose to transpose LEGC03-3 over LEDC10-1 due to LEDC10-1 having better ^{14}C dated chronological control and a higher sediment recovery percentage. As a result, all LEGC03-3 data was transferred down 39 cm, thus allowing the correlating portions of LEGC03-3 and LEDC10-1 to coincide in depth. For the corresponding overlapping sediment samples, all data were averaged; where sediment existed for only one core, the data for that core's depth were used for analysis in the composite core.

3.3 Chronology

Age control for LEGC03-3 was established using several dating methods, including: presence of non-native pollen types, changes in elemental lead concentrations, ^{137}Cs activity, and accelerator mass spectrometry radiocarbon (AMS ^{14}C) dating (as reported in Kirby et al., 2018, 2019). Due to lack of datable macrofossil organic matter, 18 bulk organic sediment samples were used for AMS ^{14}C dating for LEGC03-3 (Kirby et al., 2007). Radiocarbon samples for LEGC03-3 were measured at the University of California, Irvine W. M. Keck Carbon Cycle Accelerator Mass Spectrometry Laboratory (Kirby et al., 2019). Core LEGC03-3 ages were cross-correlated with eight ^{14}C dates measured on core LEGC03-2 and five ages from LESS02-11 which were previously determined by Kirby et al. (2007, 2010), including the surface age (2003 AD, -0.053 kcal BP), elemental Pb (1975 AD, -0.025 kcal BP), ^{137}Cs (1963 AD, -0.013 kcal BP), and exotic pollen markers (*Eucalyptus*, 1910 AD, 0.040 kcal BP; *Erodium*, 1800 AD, 0.15 kcal BP) (Kirby et al., 2019).

LEDC10-1 chronology comes from 28 AMS ^{14}C dates of terrestrial macrofossils including charcoal, gastropods, seeds, and/or wood (Kirby et al., 2018). All ^{14}C samples for LEDC10-1 were treated and measured at the Lawrence Livermore National Laboratory or the University of California, Irvine W. M. Keck Carbon Cycle Accelerator Mass Spectrometry Laboratory (Kirby et al., 2018).

Table 1. Age control data for LEGC03-3, LEGC03-2, and LESS02-11. Acquired from Kirby et al. (2019).

Core ID	Depth Interval	Core LEGC03-3 Equivalent	UCIAMS ID	$\delta^{13}C$ (‰)	^{14}C AGE (BP)	±	Material Dated
LESS02-11ab	0	0	NA	NA	NA	0	Intact Surface (2003 AD)
LESS02-11ab	31	31	NA	NA	NA	5	Elemental Pb (1970 AD)
LESS02-11ab	46	46	NA	NA	NA	0	137Cs (1963 AD)
LEGC03-3*	105-106	105.5	8263	-20.7	860	25	Bulk organics
LESS02-11ab	110	110	NA	NA	NA	10	Exoctic Pollen (Eucalyptus) (1910 AD)
LESS02-11ab	150	150	NA	NA	NA	20	Exotic Pollen (Erodium) (1800 AD)
LEGC03-3*	162-163	162.5	8264	-20.4	650	20	Bulk organics
LEGC03-3*	195-196	195.5	8265	-17.9	1,180	20	Bulk organics
LEGC03-3	264-265	264.5	8266	-17.5	1,115	25	Bulk organics
LEGC03-2	298-299	299.5	8260	-17.8	2,290	20	Bulk organics
LEGC03-3	324-325	324.5	8267	-18.4	2,270	30	Bulk organics
LEGC03-3	395-396	395.5	8268	-20.3	2,610	20	Bulk organics
LEGC03-2	405-406	396.5	6832	-21.0	2,075	25	Bulk organics
LEGC03-2	405-406	396.5	6695	-14.2	2,060	35	Bulk organics
LEGC03-2	432-433	421.93	8261	-16.2	2,915	25	Bulk organics
LEGC03-3	469-470	469.5	8270	-17.6	3,160	25	Bulk organics
LEGC03-2	556-557	533.79	8262	-15.2	4,385	30	Bulk organics
LEGC03-3	536-537	536.5	8271	-19.2	3,125	20	Bulk organics
LEGC03-3	610-611	610.5	8272	-16.1	5,160	30	Bulk organics
LEGC03-2	624-625	614.17	6833	-15.8	4,605	25	Bulk organics
LEGC03-3*	635-636	635.5	8274	-18.4	4,955	30	Bulk organics
LEGC03-3*	683-684	683.5	8275	-18.1	4,945	30	Bulk organics
LEGC03-3	713-714	713.5	8277	-17.6	6,025	35	Bulk organics
LEGC03-3	759-760	759.5	8278	-17.3	5,820	30	Bulk organics
LEGC03-3	800-801	800.5	8279	-18.1	5,540	40	Bulk organics
LEGC03-2	850-851	818.69	6834	-14.4	6,825	30	Bulk organics
LEGC03-2	947-948	899	6835	-17.7	7,350	30	Bulk organics
LEGC03-3	924-925	924.5	8280	-19.4	7,910	50	Bulk organics
LEGC03-3	986-987	986.5	8283	-14.9	8,465	40	Bulk organics
LEGC03-3	1048-1049	1048.5	8284	-17.0	8,225	40	Bulk organics
LEGC03-3	1071-1072	1071.5	8286	-18.0	7,965	40	Bulk organics

Calib 4.4.2, Stuiver et al. (1993)
(*not used in age model)

Table 2. Age data from LEDC10-1. Acquired from Kirby et al. (2018).

LEDC10-1 Depth Range (cm)	Average Depth (cm)	ID	$\delta^{13}C$(‰)*	^{14}C Age (BP)	±	2σ Range	Age (cal a BP)	Material Dated
1274-1275	1274.5	‡N93630	-25	8,655	35	9,541-9,684	9,613	Gastropods
1274-1275	1274.5	‡N93631	-25	8,710	35	9,548-9,780	9,664	Gastropods
1396-1398	1397.0	‡94679	-25	10,155 (9,450 Res. Corrected #)	46	11,685-12,030	11,858	Bulk
1508-1510	1509.0	‡94680	-22.9	10,950 (10,240 Res. Corrected #)	46	12,648-12,964	12,806	Bulk
1540-1542	1541.0	‡94681	-25	11,650 (10,940 Res. Corrected #)	46	13,334-13,691	13,513	Bulk
1618-1620	1619.0	‡94682	-24.6	12,200 (11,490 Res. Corrected #)	46	13,887-14,202	14,045	Bulk
1683-1685	1684.0	‡N95444	-25	12,140	280	13,437-15,067	14,252	Mixed Discrete
1710-1711	1710.5	‡N95445	-25	12,460	120	14,091-15,090	14,591	Mixed Discrete
1723-1725	1724.0	§134836	-25	12,190	290	13,470-15,155	14,313	Mixed Discrete (0.035mgC)
1738-1739	1738.5	‡N95446	-25	13,420	230	15,390-16,932	16,161	Mixed Discrete
1747-1748	1747.5	‡N94003	-25	13,260	35	15,578-16,699	16,139	Charcoal
1778-1779	1778.5	‡N94004	-25	13,775	35	16,734-17,049	16,892	Wood
1823-1824	1823.5	‡N94005	-25	14,360	30	17,154-17,790	17,472	Charcoal
1823-1824	1823.5	‡N94243	-25	14,310	30	17,082-17,706	17,394	Charcoal
1870-1872	1871.0	§134837	-25	14,740	200	17,460-18,424	17,942	Charcoal; Charred Grass (0.073mgC)
1997-1999	1998.0	‡N94006	-25	16,580	40	19,461-19,936	19,699	Seeds
2019-2020	2019.5	‡N94007	-25	16,880	40	19,832-20,321	20,077	Seeds
2081-2082	2081.5	‡N94008	-25	17,980	180	20,911-22,128	21,520	Wood
2198-2199	2198.5	‡N94010	-25	19,630	40	23,134-23,779	23,457	Seeds
2280-2282	2281.0	§134839	-23.4	20,870	90	24,881-25,516	25,199	Small Twig
2292-2293	2292.5	§134840	-24.1	21,370	90	25,510-25,899	25,700	Charcoal
2344-2345	2344.5	‡N94245	-25	21,025	40	24,940-25,556	25,248	Charcoal
2344-2345	2344.5	‡N94011	-25	21,120	70	24,834-25,494	25,164	Charcoal
2384-2386	2385.0	§118908	-25	22,010	80	26,078-26,843	26,460	Charcoal
2425-2427	2426.0	§134841	-23.9	21,760	210	25,650-26,481	26,061	Small Charcoal (0.16mgC)
2438-2453	***2445.5***	UCLA	na	***29,200****	***2,000***	na		***IRSL method***
2500-2517	***2508.5***	UCLA	na	***31,300****	***2,200***	na		***IRSL method***
2830-2832	2831.0	§118909	-25	25,940	110	30,419-31,016	30,720	Charcoal
2860-2861	2860.5	‡150331	-25	26,550	90	30,970-31,262	31,116	Wood
2860-2861	2860.5	‡150337	-25	26,270	80	30,758-31,179	30,969	Wood

* $\delta^{13}C$ values are the assumed values according to Stuiver and Polach (1977) when given without decimal places.
† CALIB 6.0.1 Program (Stuiver and Reimer, 1986)
‡ LLNL AMS Results

3.4 Macroscopic Charcoal

Local fire history for the Elsinore cores was reconstructed with high-resolution macroscopic charcoal analysis. Charcoal processing followed modified procedures described by Whitlock & Larsen (2001), Myrbo et al. (2005), and Schlachter & Horn (2010). To identify and quantify macroscopic charcoal particles, 1 cm^3 sediment samples taken at consecutive 1 cm intervals were treated with 40 mL of 6% hydrogen peroxide (H_2O_2) in an Erlenmeyer flask to bleach and partially digest organic matter, placed in a drying oven at 50 °C for 24 hours, filtered through a 125 μm sieve, transferred to Petri dishes using distilled water (dH_2O), added a drop of 0.5% sodium hexametaphosphate as a deflocculant, and dehydrated at 50 °C. Following completion of processing, macroscopic charcoal particles were counted under a light microscope at 20x magnification. Charcoal abundances were divided by the sample volume to obtain concentration values (particles cm^{-3}). Charcoal concentrations were then converted to charcoal accumulation rate (CHAR; particles cm^{-2} yr^{-1}) values, measuring the number of charcoal fragments deposited per cm^2 per year.

The long-term fire history reconstruction was compared to previously reported environmental proxies from Lake Elsinore such as percent organic matter, calcium carbonate, and sand. The record was also compared to other paleoclimatic and paleoenvironmental records from California and southwestern North America, records of Pacific sea surface temperatures, and reconstructed orbital and radiative forcings.

3.5 XRF and Sedimentology

Elemental composition of the sediments was analyzed using a portable Vanta XRF Analyzer. Barring core gaps and sample depths excluded due to poor sediment preservation, XRF measurements were taken at continuous 1 cm intervals along a split core surface lined with plastic wrap. Twenty-eight detected and quantified elements were measured and recorded as parts per million (ppm). However, here I only report calcium (Ca) concentrations which is used as a proxy for environmental factors such as lake productivity (Chawchai et al., 2016; Croudace et al., 2019).

4. Results

4.1 Composite Core

LEGC03-3 and LEDC10-1 were combined via cross-correlation on percent organic matter to create a composite core and chronology. The cores were cross-correlated by percent organic matter at 966.5 to 1,068.5 cm from LEGC03-3 and 1,005.5 to 1,107.5 cm from LEDC10-1 (Figure 4). On average, a 1-2% difference of loss-on-ignition between LEGC03-3 and LEDC10-1 was found at these depths. This negligible difference may be accounted for by discrepancies in loss-on-ignition processing such that the method does not account for losses of CO_2 from carbonates in calcareous soils, losses of water bound in clay minerals (Ball, 1964), and losses of inorganic carbon that may occur at temperatures between 425 and 520 °C (Heiri et al., 2001). The centimeter-scale coherency adds confidence to our interpretation that the Lake Elsinore composite core records fine-scale event stratigraphy when transferred to the age-depth model.

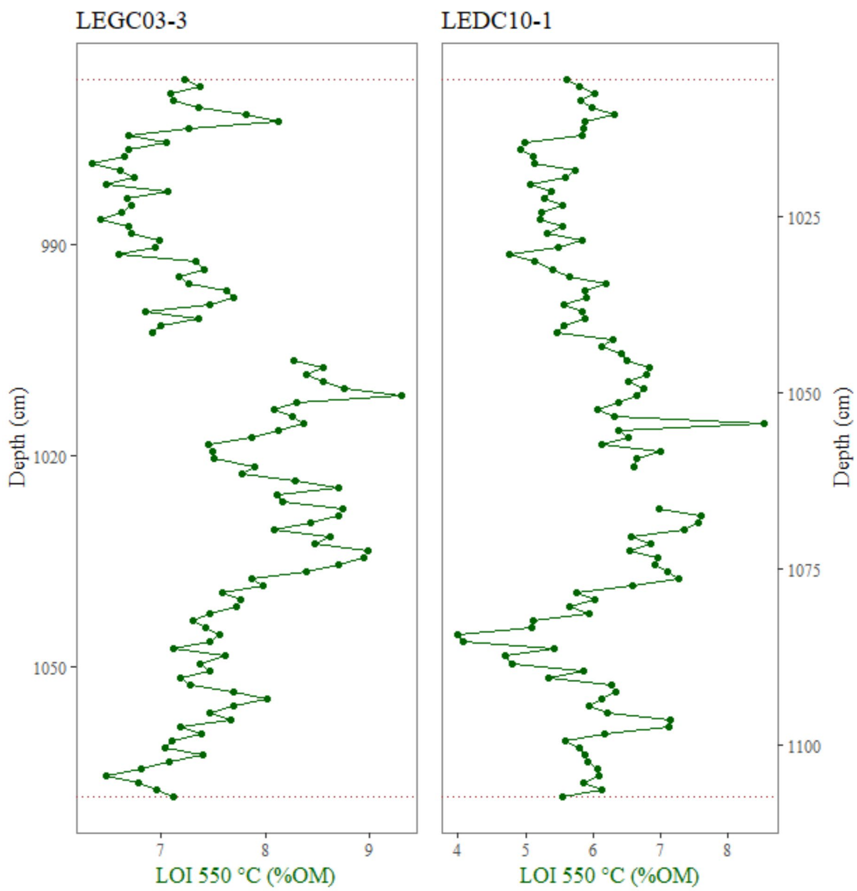

Figure 4. Comparison illustrating centimeter-scale percent organic matter data for cores LEGC03-3 and LEDC10-1. The data within the brown dashed lines show the cross-correlation between the basal segment of LEGC03-3 (966.5-1,068.5 cm) and the uppermost portion of LEDC10-1 (1,005.5-1,107.5 cm).

4.2 Chronology

Lake Elsinore chronology for cores LEGC03-3 and LEDC10-1 were acquired and modified from Kirby et al. (2018, 2019) to create a single, composite age record. Fifty-three radiocarbon dates, five dates from the surface, elemental Pb, ^{137}Cs, and exotic pollen markers (Table 1 and 2) were input into the rbacon age-depth modeling package in RStudio (Blaauw & Christen, 2011) and used to determine sediment chronology. Given the results of the age-depth model, an estimated basal date of 32,950 cal yr BP was extrapolated from the average sediment accretion rate following the last ^{14}C dated sample at 2,860.5 cm. Age results for the composite core span 32,950 cal yr BP to 1994 AD (Figure 5).

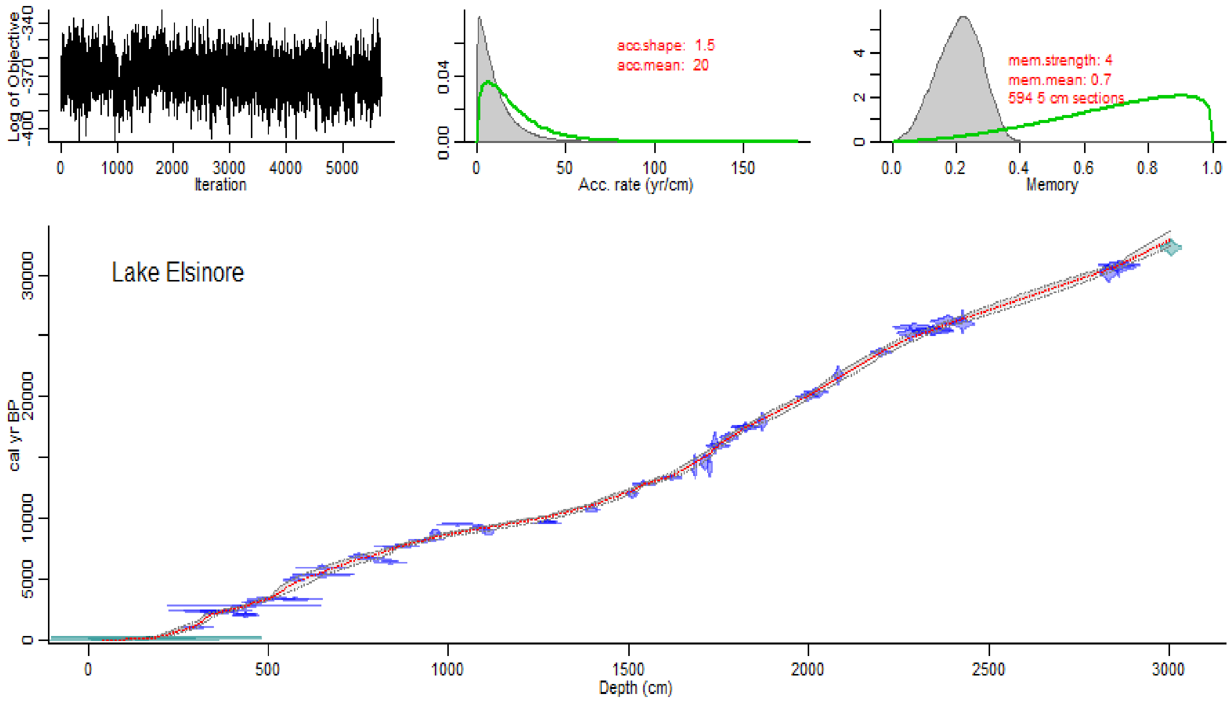

Figure 5. Age-depth model created in RStudio using the rbacon package for Lake Elsinore's composite core. The composite record spans 32,950 cal yr BP to 1994 AD.

4.3 Macroscopic Charcoal

The macroscopic CHAR record at Lake Elsinore reveals substantial changes in fire activity throughout the past 32,950 cal yr BP (Figure 6). Total CHAR ranged between 0 and 146.5 particles cm^{-2} yr^{-1} and averaged 3.13 particles cm^{-2} yr^{-1}. The largest peaks in charcoal occur during late MIS 2 and MIS 1 at 13,143, 13,090, 12,967-12,880, 136, 116, and -38 cal yr BP. CHAR data show that charcoal influx to Lake Elsinore remained consistently low during late MIS 3 and Early MIS 2 from 32,950 to 25,000 cal yr BP with CHAR averaging at 0.5675 particles per cm^{-2} yr^{-1}. Short, low amplitude increases (4.2 to 13.09 particles cm^{-2} yr^{-1}) occur at 30,313, 29,695, 27,320, 26,829, and 25,445 cal yr BP. Intervals with the longest sustained maximum CHARs occurred during the late Bølling Allerød to Younger Dryas transition from 12,967 to 12,880 cal yr BP with values ranging from 21.33 to 86.77 particles cm^{-2} yr^{-1}. Charcoal deposition was quiescent during the Early Holocene. During the Middle Holocene, from 7,000 to 3,500 cal yr BP charcoal deposition becomes increasingly variable with peak CHAR values from 4,807 to 4,795 cal yr BP. From 1050-500 cal yr BP, average CHAR values reach 9.52 particles per cm^{-2} yr^{-1} with highest values seen during the beginning and end of the period. From 500 to 200 cal yr BP, high CHAR values are seen followed by lower values. In the Late Holocene, charcoal deposition rapidly fluctuates and nears values seen during the late Bølling Allerød.

4.4 XRF, Core Sedimentology, and Proxy Interpretations

Results for loss-on-ignition and percent sand for LEGC03-3 were initially detailed in Kirby et al. (2007, 2010, 2013, 2018). Here, I provide a composite record with the modified age-depth model for cores LEGC03-3 and LEDC10-1 of loss-on-ignition and percent sand (Figure 6). This updated record does not invalidate interpretations from the previous studies, but rather modifies the approximate dates of sedimentary descriptions from Kirby et al. (2007, 2010, 2013, 2018).

Total organic matter values from 32,950 cal yr BP to 1994 AD range from 0.76% to 43.75% (Figure 6). Greatest organic matter content occurs during MIS 2 between ~25,000 to 23,000 cal yr BP, to a lesser extent during late MIS 3 between 31,000 to 30,000 cal yr BP, and from 20,000 to 18,000 cal yr BP. From the beginning of MIS 1 and onwards, organic matter values gradually decrease and are uniformly low averaging 8.58%.

As temperature decreases, the solubility of calcium carbonate increases. Therefore, lower total carbonate values suggest colder lake water temperatures whereas higher carbonate values may indicate warmer lake water temperatures (He, 1992). In addition, if lake levels are high, Lake Elsinore can overflow and the open lake conditions and throughflow of water will lead to decreased evaporative concentrations of Ca. Total carbonate content is used as a proxy for relative lake level and water temperature as a shallower lake will heat more than a deep one (Kirby et al., 2013). Total carbonate values fluctuate from 0 to 34.8% (Figure 6). Carbonate content is consistently low during late MIS 3 to MIS 2 between 32,950 and 14,600 cal yr BP; however, it increases dramatically during late MIS 2 after 14,600 cal yr BP and into MIS 1. The Holocene carbonate values show high amplitude variability, with carbonate content ranging from 3.25 to 34.8% and averaging 10.35%.

Warm water temperatures and lake regression can produce Ca saturation, whereas during wetter and colder periods, Ca is diluted in the sediment due to the formation of a deeper lake (Kylander et al., 2011; Croudace et al., 2019) and throughflow of water in the case of Elsinore. I interpreted times of high Ca and $CaCO_3$ to reflect more shallow and warm lake conditions. Calcium as inferred by XRF, ranged between 0 to 22,031 PPM and averaged 19,989.02 PPM (Figure 6). From 22,500-14,600 cal yr BP, Ca concentrations remained stably low in comparison to the entire record. Highest peaks and variability in Ca can be found during MIS 1. During this period, high values in Ca coincide with peaks in charcoal.

Low percent sand values are used to infer intervals of diminished runoff and thus drier climates and vice versa for high percent sand values (Kirby et al., 2010, 2013, 2014). Percent sand content ranges from 0 to 77.84% with an average of 5.7% (Figure 6). A notable and anomalous peak in sand content occurs between 27,600 and 25,700 cal yr BP. However, Kirby et al. (2018) do not interpret this as a period of enhanced run-off, but rather a period of drought wherein the lake's mud depth boundary likely migrated basinward.

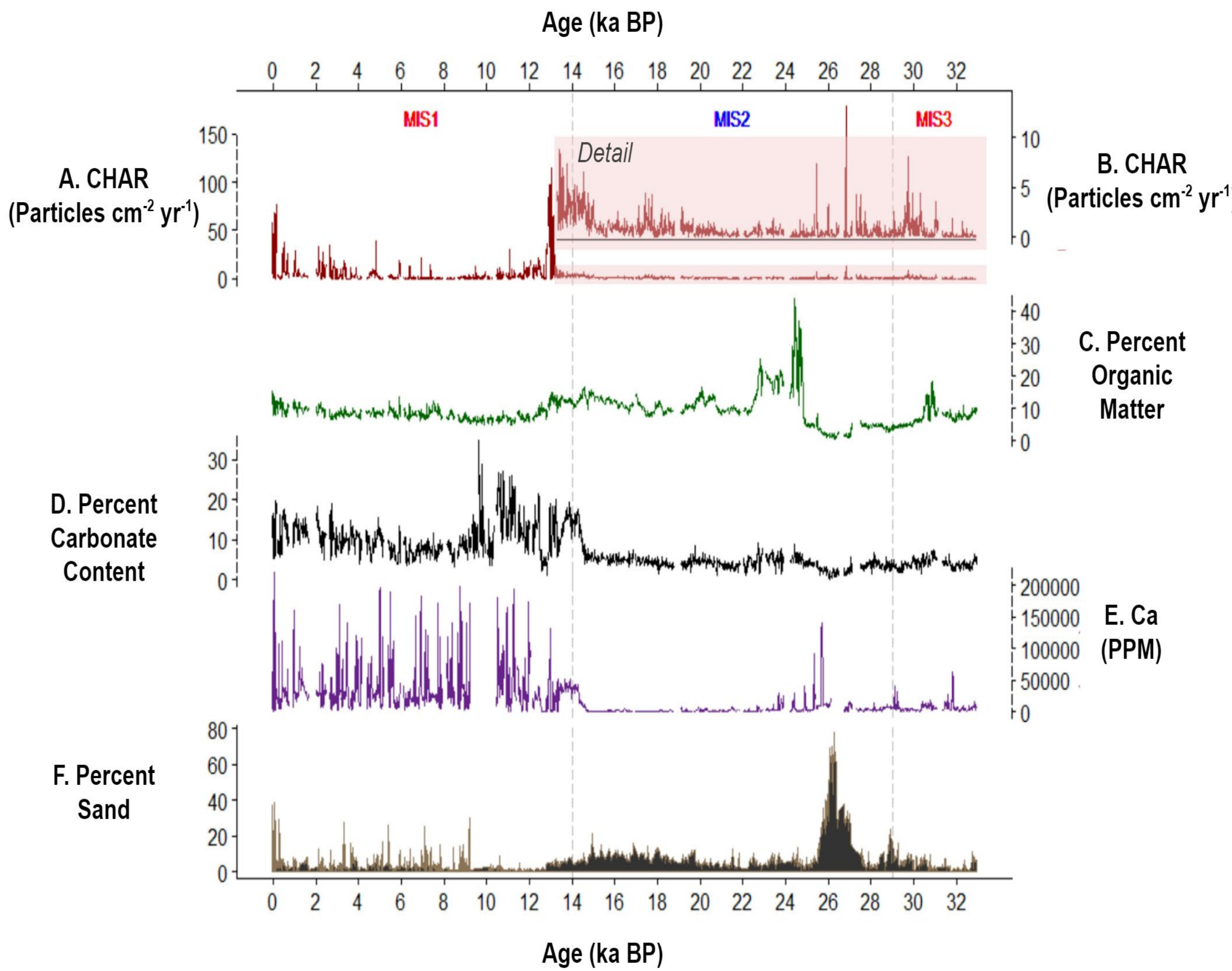

Figure 6. Lake Elsinore paleoclimate data. (A) Charcoal accumulation rate (B) Charcoal accumulation rate in detail from 32,950-13,205 cal yr BP, (C) Percent organic matter, (D) Percent carbonate content (Kirby et al., 2007, 2010, 2013, 2018), (E) Trace element calcium (Ca), and (F) Percent sand (Kirby et al., 2010, 2013, 2018). MIS bounds are noted by the dashed grey lines.

5. Discussion

5.1 Holocene Fire Activity and Earlier MISs

Lake Elsinore's high-resolution charcoal record reveals substantial changes in fire activity over the past 32,950 cal yr BP. Generally, the greatest charcoal deposition occurred during periods of rapid climate change and during the relatively warm and dry period of the Holocene (MIS 1). To place the changes in fire activity over time in conjunction with prevailing climatic conditions and insolation changes, I compare biomass burning at Lake Elsinore during the MIS stages (late MIS 3 to MIS 1; late MIS 3: 32,950-29,000 cal yr BP; MIS 2: 29,000-14,000 cal yr BP; MIS 1: <14,000 cal yr BP; boundaries as reported in Lisiecki & Raymo, 2005, Figure 7).

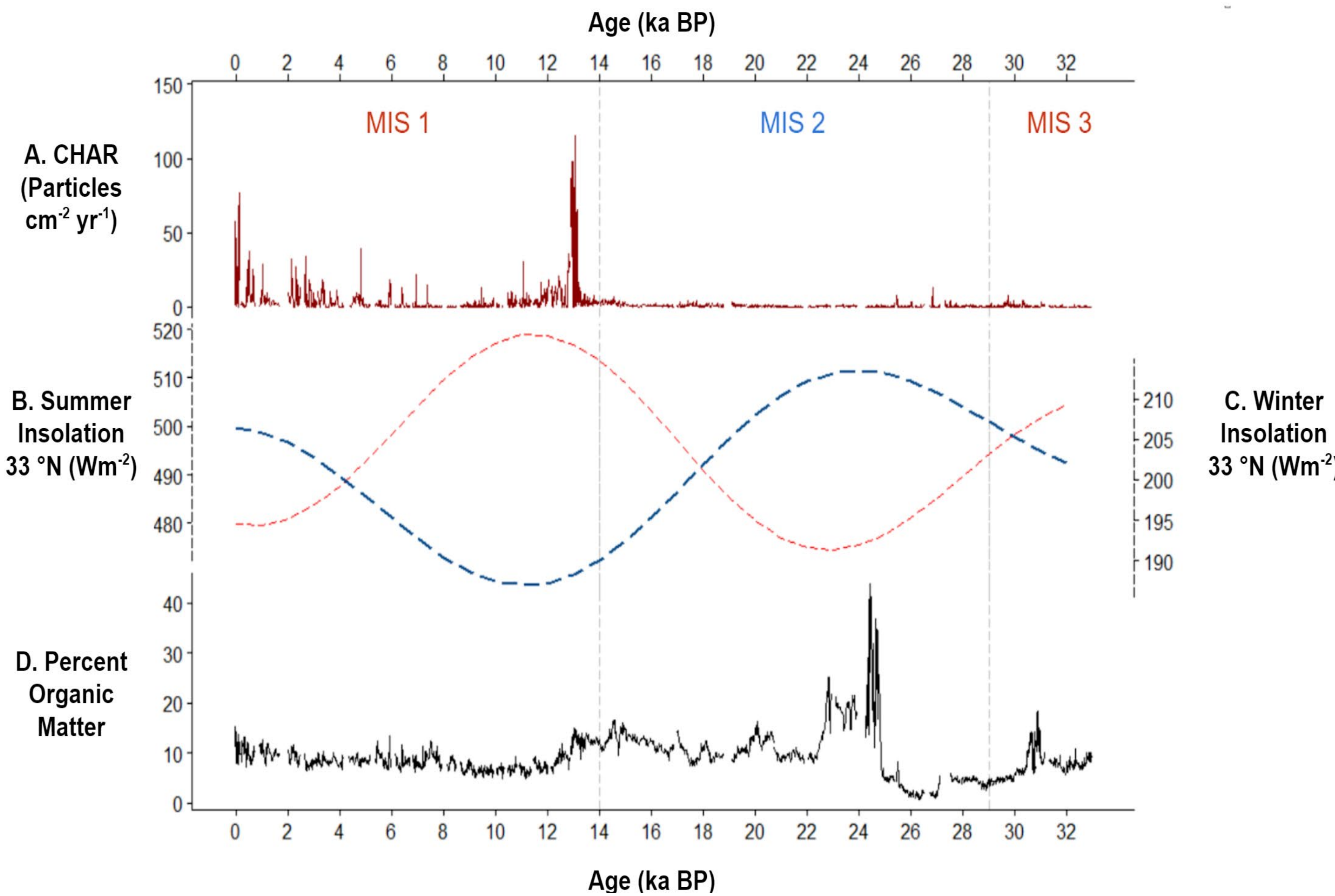

Figure 7. Data plotted by age and with MIS boundaries noted. (A) Lake Elsinore charcoal accumulation rate, (B) Summer insolation at 33 °N latitude (Laskar, 2004), (C) Winter insolation at 33 °N latitude (Laskar, 2004), and (D) Lake Elsinore percent organic matter (Kirby et al., 2007, 2010, 2013, 2018).

The Elsinore charcoal record exhibits increased fire activity and variability within interglacials than during glacials. Despite the high-amplitude variability in charcoal influx at Lake Elsinore during late MIS 3 interstadial, charcoal influx rates were modest when compared to the most recent past of the Holocene, but higher than most of the MIS 2 stadial. MIS 3 was likely warmer than MIS 2, but cooler and moister than MIS 1 (Glover, 2016; Glover et al., 2020). The highest charcoal deposition during late MIS 3 occurred as summer insolation gradually declined and winter insolation rose at approximately 30,000 cal yr BP. Globally, biomass burning was lower during the global Last Glacial Maximum (LGM: 26,000-19,500 cal yr BP) than the Holocene (Daniau et al., 2010; Clark et al., 2012). Therefore, although there are fluctuations in fire activity during late MIS 3 at Lake Elsinore, average CHAR values are smaller in comparison to MIS 1.

The southwestern United States experienced a climate that was wetter than present during the LGM, as inferred by proxies (Kirby et al., 2013). Southern California received an influx of Pacific moisture by 22,000 cal yr BP, creating wet conditions (Oster et al., 2015). Although there was enhanced precipitation, minimal fire activity occurred at Lake Elsinore during the LGM as the global climate was generally cooler. Low charcoal, percent sand, and low organics at Lake Elsinore reflect cooler conditions. Prevailing climate conditions likely influenced ecosystem dynamics and were not conducive to reductions in terrestrial biomass nor high fire activity. The early MIS 2 mega-drought documented at Lake Elsinore (Kirby et al., 2018) and subsequent moisture influx at 22,000 cal yr BP (Oster et al., 2015) suggest that Southern California had a complex and dynamic hydrological regime during the Last Ice Age.

Extreme influx of charcoal deposition occurred at Lake Elsinore during the MIS 2/1 transition as summer insolation reached its highest peak during the MIS 2/1 transition at ca.

14,000 cal yr BP. Changes in obliquity and perihelion caused Northern Hemisphere summer insolation levels to be 4 to 8% greater than present-day during the late glacial and Early Holocene (Berger, 1978; Laskar et al., 2004; Clark et al., 2012). Greater than present summer insolation led to increases in the onshore flow of moisture from the Gulf of California which, in turn, increased the magnitude and spatial extent of NAM (i.e., summer monsoons) in the coastal southwest (Tubbs, 1972; Thompson et al., 1993; Liu et al., 2003). Increased lightning storms likely enabled the increase in fire activity as fuel loads were enhanced given moisture increases.

Insolation changes govern MIS 1 (i.e., Holocene) scale hydrologic variability in Southern California (Kirby et al., 2007). Sporadic fire activity is recorded during the Early Holocene, likely in part due to higher than modern summer insolation during the Early Holocene (Laskar et al., 2004). Precipitation during the Early Holocene likely had a strong component of summer NAM rain. However, even summer precipitation might have been low as it was not until ~8,000 cal yr BP that the Bermuda High displaced north due to the decay of the Laurentide Ice Sheet, thus allowing a greater proportion of insolation to contribute to warming (MacDonald et al., 2016) and generating enhanced NAM summer precipitation (Metcalfe et al., 2015). Kirby et al. (2007) found evidence of a wetter Early Holocene at Lake Elsinore as a result of proxy-interpretation with low total organic matter and total carbonate indicating high lake levels and a decrease in lake productivity. Lower winter insolation in the Early Holocene likely increased the frequency of winter storms at Lake Elsinore, as it was apparent from modern-lake level precipitation analyses that slight increases in winter storm activity produced a significant impact on the lake's water-level depth (Hudson, 1978; Kirby et al., 2007).

Transitioning from the Middle to Late Holocene, was a period of changing large-scale control on fire activity as summer insolation increased and winter insolation decreased. The

Elsinore record shows high variability during the Late Holocene and peak fire activity is recorded at ca. 1027-990, 511-476, 414-406, 136-130, and -38 cal yr BP. The Late Holocene is known to be a period characterized by hydrologic variability within the region, typified by periodic decadal-scale droughts with extended wet periods (Cook et al., 2004; MacDonald et al., 2007; Meko et al., 2007). Kirby et al. (2019) found evidence for eight centennial droughts with no apparent pluvials at Lake Elsinore from 3,050 to 550 cal yr BP. Periodic droughts impacting the low-elevation site, stocked with considerable biomass that likely accumulated during wet periods, led to more increased fire activity than during the Middle Holocene.

Peaks in fire activity, occurring around 1,027-990 cal yr BP in the Elsinore record, could be related to general warm and arid conditions associated with the Medieval Climate Anomaly (MCA; 1,050-500 cal yr BP). Alterations in California's hydroclimatology during the MCA are thought in part due to relative stability in terms of solar output, prolonged La Niña conditions (Seager et al., (2005a)), a persistent North Atlantic Oscillation mode (Trouet V et al., (2009)), and minimal volcanic activity (Mann et al., 2005). Other arid phases and higher temperatures during the MCA extended over California and the Southwest (Woodhouse et al., 2010; Heusser et al., 2015). Similarly, to Lake Elsinore, charcoal records and fire scars support evidence for high fire activity during the MCA (Mohr et al., 2000; Swetnam et al., 2009; Colombaroli & Gavin, 2010). Fire activity increased during the Late Holocene and modern levels are high relative to the entire Holocene. Though I focus predominantly on climate and ecosystem dynamics, one cannot rule out the role of human intervention in modulating past fire activity.

Discerning the role of climatic responses from human impact in fire histories is difficult as anthropogenic biomass burning cannot be easily differentiated from natural fire in paleoecological records (Whitlock et al., 2010). It is possible that increasing human populations and changes in land use also played a role in altering fire activity near Lake Elsinore at least since the Mid-to-Late Holocene since human presence has been documented since this time at Lake Elsinore (Grenda, 1997) and throughout the U.S. Southwest, *Juniperus* was a preferred fuel for Native American cooking fires (Lanner, 1981).

5.2 Fire Activity and Changing Local Hydroclimate

To examine how Lake Elsinore's fire activity relates to other changes recorded in the cores, I compared the high-resolution fire history record to elemental geochemistry and previously reported high-resolution proxies at Lake Elsinore from the MIS 3/2 transition onwards. I also compare these changes to sea surface temperature (SST) reconstructions. Variations in SSTs in the tropical and North Pacific affect coastal and interior southwest US paleohydrocliamtes at sub-decadal to millennial timescales (Kirby et al., 2010; Barron et al., 2012) and drive fire regimes in the Northern Hemisphere (Swetnam & Betancourt, 1990; Kitzberger et al., 2001). In coastal southwest North America, El Niño fires are more widespread than La Niña fires (Norman et al., 2003), as La Niña climate states produce, on average, less precipitation (Cayan et al., 1999; Castello & Shelton, 2004).

Sand and carbonate content from the Elsinore record indicates a gradual drying trend from the most recent glacial into the Early Holocene (Figure 6) (Kirby et al., 2013). Sand content is highest during the Oldest Dryas, a period characterized by a climate wetter than today (19,000-14,700 cal yr BP; Kirby et al., 2018), and carbonate content ranges from absent to low during this time. The cold, wet climate was likely unconducive to extreme fire events during this time. Moving into the Bølling Allerød, sand content decreases, likely in response to enhanced aridity and reduced precipitation inflow. Carbonate content increases from the Oldest Dryas; however, a drastic decrease in carbonate content at ~13,100 cal yr BP coincides with one of the major peaks in fire activity. With increasing aridity, fire activity gradually increases and CHAR maxima are reached during the Bølling Allerød to Younger Dryas transition. The beginning of the Younger Dryas, with its inferred drying climate as supported by a decrease in sand content and increases in carbonate reflecting a warmer, shallow lake, supports high fire activity that gradually declines moving into the Early Holocene. The combined proxies indicate a distinct hydroclimate shift from a cold, wet glacial environment to a largely arid precipitation regime during the Holocene. The shifts in climate were conducive to a high frequency and intensity fire regime.

At Lake Elsinore, sand content and Ca concentration become increasingly variable during the Holocene, likely reflecting hydrologic variability and increasing temperatures. Numerous paleoclimate records from Southern California, such as a glacial record from the Dry Lake area (Owen et al., 2003), a littoral record from Lake Elsinore (Kirby et al., 2005), and a marsh record from San Joaquin Marsh (Davis, 1992) support the interpretation that the early Holocene was wetter than today. Moving into the Mid-Holocene, there is increased sand content at Lake Elsinore and at Silver Lake, California (Kirby et al., 2015) between ~7,500 to 4,000 cal yr BP reflecting enhanced aridity and generally low lake levels. Warming leads to increased fire activity as it promotes increased storm intensity and lightning conditions (Price, 2009) and likely accelerated fuel drying during droughts (Meehl et al., 2007).

The Late Holocene was a time of high amplitude, rapid climate change at Lake Elsinore. The lake's CHAR record over the past 3,000 cal yr BP reveals large oscillations in fire frequency and/or intensity. A possible mechanism for the change in fire regime could be shorter-term, higher-amplitude hydrologic variability induced by increasingly variable ENSO after 3,000 years (Conroy et al., 2008; MacDonald et al., 2016). However, based on the prior Elsinore chronology, Kirby et al. (2010) found that by comparing the Elsinore data to two ENSO reconstructions, ENSO variability was likely not the predominant forcing of Holocene climate in Southern California. However, shifts between El Niño and La Niña drive drought severity and the accumulation of fuels during a fire season or years (Grissino-Mayer & Swetnam, 2000). Decades of pluvials and fuel accumulation are often associated with significant fires when they are interrupted by droughts that reduce available fuel accumulation and moisture (Swetnam & Betancourt, 1998). Therefore, ENSO variability may play a role in fire regimes at Lake Elsinore during the Late Holocene.

5.3 The 12.9 "Cosmic" Event and the Late Glacial-Interglacial Transition (LGIT; 15,000 to 10,000 cal yr BP)

Lake Elsinore's most dynamic and extreme charcoal influx and environmental change occurs during the Bølling Allerød to the Younger Dryas chronozone (Figure 8). During this time, atmospheric CO_2 and percent area deglaciated in North America increased in a stepwise fashion (Monnin et al., 2004; Dyke, 2004). Variability in CO_2 affects vegetation productivity (Ward & Strain., 1999) and possibly fuel loads (Marlon et al., 2009). Enhanced fire activity from several sites in North America at the start of the Younger Dryas chronozone were thought to be partly caused by extraterrestrial impact events (Firestone et al., 2007; Thackeray et al., 2019).

The hypothesized comet impacts (Firestone et al., 2007; Thackeray et al., 2019) are closely similar in timing, but based on my current chronology, may have occurred approximately 190 years after the widespread increase in fire activity beginning at 13,090 cal yr BP observed at Lake Elsinore. If the chronology is correct, increased fire activity during this period in the Lake Elsinore record more likely closely coincides with the Intra-Allerød cold period (IACP)--an abrupt and short-term climate reversal recorded in the NGRIP $\delta^{18}O$ ice-core record (Figure 8). The IACP is associated with a rapid oscillation in North Atlantic temperatures that may have affected atmospheric circulation patterns across the continent promoting the likelihood of drought, frost damage on some tree species, and fire activity (Marlon et al., 2009). In addition, it must be remembered that the peak in charcoal at 13,090 cal yr BP occurs in connection with generally high charcoal values associated with the summer insolation maximum occurring over the MIS 2 to MIS 1 transition (Figure 8). At this time, neither hypothesis can be firmly rejected as the chronological control remains too imprecise.

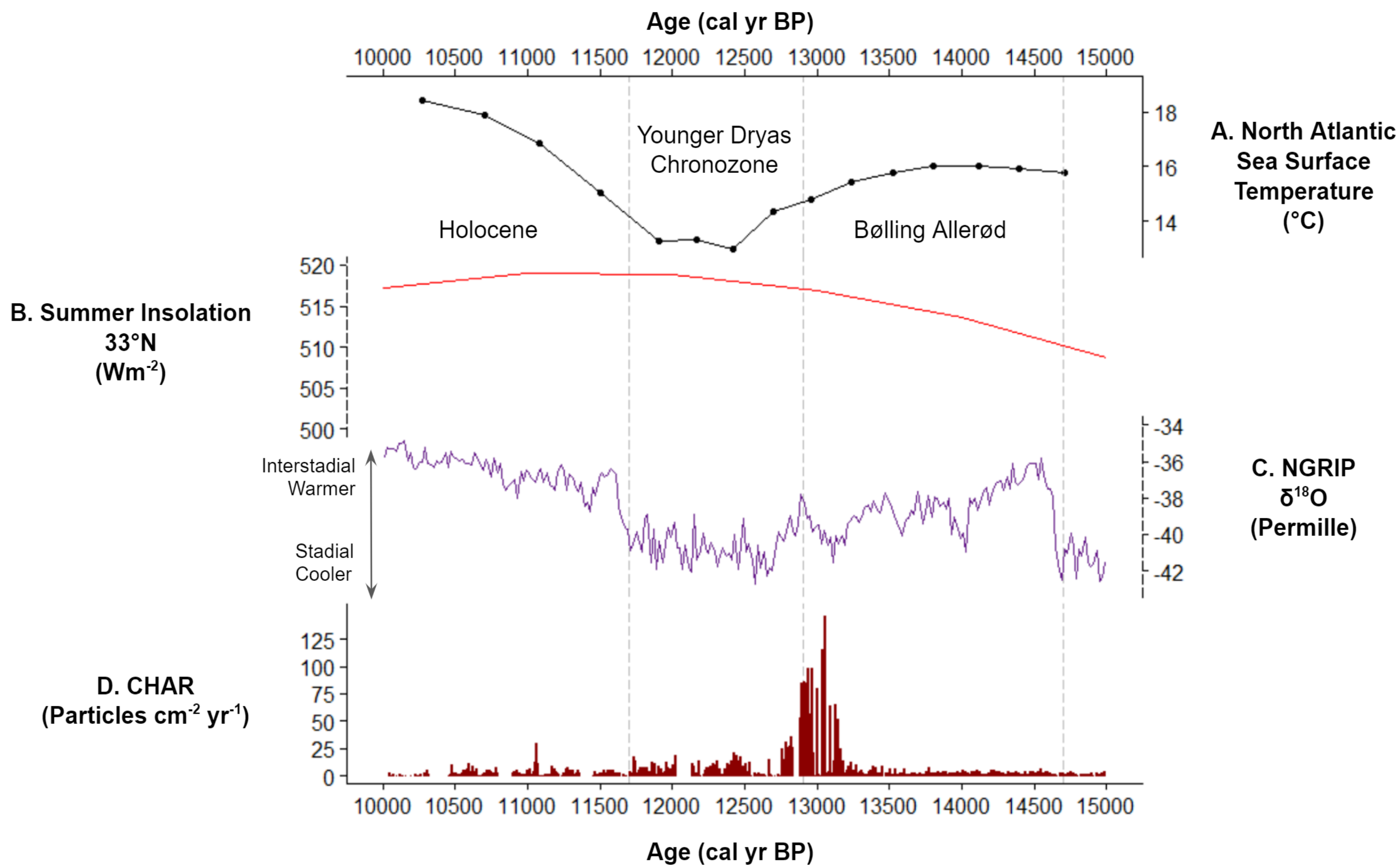

Figure 8. Lake Elsinore charcoal data compared to other paleoproxies and sea surface temperatures during the late glacial-interglacial transition. (A) North Atlantic Sea Surface Temperatures °C (Bard, 2002), (B) Summer insolation at 33 °N latitude, the approximate latitude of the study site (Laskar, 2004), (C) NGRIP $\delta^{18}O$ shifts, a proxy for North Atlantic Sea Surface Temperatures (Rasmussen et al., 2014), (D) Lake Elsinore charcoal accumulation rate. Vertical dashed lines mark the temporal extent of well-known climatic periods.

5.4 Regional Comparison of Fire History

Well-dated, high-resolution terrestrial charcoal records spanning MIS 3 through MIS 1 are relatively uncommon in Southern California. The limited sites included in this comparison represent a spatially diverse assemblage, timescales, elevational gradient, and climatically complex ecoregions. Consequently, similarities and dissimilarities in the fine-scale temporal and spatial variability in fire activity are likely a result of not only large-scale controls of climate, but also mesoscale climate, vegetation (Whitlock et al., 2008), and site conditions (e.g., lake versus marsh, basin size, and closed versus open basin). There are considerable differences in the patterns shown by individual charcoal-based reconstructions since late MIS 3 through MIS 1. Nevertheless, general trends in fire activity reveal that high charcoal influx occurred during the Bølling Allerød to Younger Dryas transition and during the Late Holocene.

5.4.1 MIS 3/2 Transition Fire Activity

Fire activity was low for most of the late MIS 3 to Early MIS 2 transition; likely a consequence of the glacial mega-drought and the cold, dry period sustained during the Last Glacial Maximum. Baldwin Lake, a high-elevation (2,040 m) lake, sited approximately 84 km northeast of Lake Elsinore shows an increase in xeric flora that coincides with the glacial mega-drought inferred at Lake Elsinore from 27,600 cal yr BP to 25,700 cal yr BP. This suggests a similar ecological response to the drought across elevational gradients near Lake Elsinore (Glover, 2016; Kirby et al., 2018). Similarly to Lake Elsinore, fire activity was generally suppressed at Baldwin Lake throughout the last glacial (28,000-14,000 cal yr BP) likely due to forest contraction during the arid phase. In general, overall CHAR values at Lake Elsinore exceed CHAR values at Baldwin Lake, thus suggesting more fire activity, or charcoal inflow from runoff at the lower elevation site.

5.4.2 MIS 2/1 Transition Fire Activity

Local high frequency fires are interpreted in the Elsinore record from the Bølling Allerød to the Younger Dryas transition. A sediment record from Arlington Canyon, which lies off Southern California's coast on the Northern Channel Islands, lacks evidence for a single high-intensity fire. However, the most abundant sedimentary charcoal influx occurs at approximately 14,000 and 12,500 cal yr BP. Onshore pollen records and nearby offshore marine cores document large shifts from *Pinus*-dominated to *Quercus*-dominated pollen assemblages at 14,000 cal yr BP (Hardiman et al., 2016). During this time at Lake Elsinore, high biomass burning suggests fires of greater spatial extent and/or intensity to past fire regimes and the area experiences similar vegetation shifts to those seen at Arlington Canyon. Moreover, a synthesis of 35 paleofire records throughout North America identified steep increases in biomass burning around 13,900, 13,200, and 11,700 cal yr BP (Marlon et al., 2009). The MIS 2/1 transition was a period of rapid environmental changes and dynamic fire regimes.

5.4.3 Late MIS 1 Fire Activity

Generally, biomass burning was greater at Lake Elsinore during the Late Holocene than the preceding MIS 2 and 3. The Elsinore record of fire frequency, intensity, and variability was highest during the Late Holocene and fire regimes were also high in other sites in Southern California (Anderson et al., 2010). Increases in fire activity during the Late Holocene are thought to be partly influenced by humans and increased climatic variability.

6. Conclusion

The fire history reconstruction presented here offers vital insights into the fire, climate, and ecosystem dynamics from Southern California. Lake Elsinore's sedimentary charcoal record spanning 32,950 cal yr BP to 1994 AD shows increased fire variability, frequency, and intensity as temperatures warmed from MIS 3 to the Holocene. Generally, biomass burning was greater during interglacials than during glacials. With a few exceptions, namely the MIS 2/1 transition, the Elsinore fire record shows low biomass burning during the glacial and deglaciation and higher, more variable biomass burning during the Mid-to-Late Holocene. Greatest charcoal influx occurs during the Bølling Allerød to Younger Dryas transition. Mechanisms causing large charcoal influxes and thus extreme fire activity cannot be supported nor rejected as the chronological control remains too imprecise. Though it is likely that increases in fire activity during this period were a consequence of abrupt and extreme climatic changes. Fire frequency and intensity increased from the early Holocene to the Late Holocene. By comparing the Elsinore charcoal record to other paleofire reconstructions across Southern California, we demonstrate that fire frequency, intensity, and variability has increased in Southern California during the Late Holocene. The Late Holocene has had relatively high fire activity, perhaps influenced by ocean sea surface temperatures, also reflecting Native American ignition, and increased human land-use. The results lead us to conclude that the fire regime in the area may be extremely sensitive to future climate change due to increasing greenhouse gases. With the pervasive threat of increased fire variability and intensity due to global warming in the remainder of the 21st century, it is imperative to study past fire, climate, and ecosystem dynamics to inform present and future fire dynamics in these increasingly vulnerable ecosystems.

7. References

Alley, R. B., & Clark, P. U. (1999). The deglaciation of the northern hemisphere: a global perspective. *Annual Review of Earth and Planetary Sciences*, *27*(1), 149-182.

Anderson, R.S, & Koehler, P. A. (2003). Modern pollen and vegetation relationships in the mountains of southern California, USA. *Grana*, *42*(3), 129-146.

Anderson, R. S., Starratt, S., Jass, R. M. B., & Pinter, N. (2010). Fire and vegetation history on Santa Rosa Island, Channel Islands, and long-term environmental change in southern California. *Journal of Quaternary Science*, *25*(5), 782-797.

Ball, D. F. (1964). Loss-on-ignition as an estimate of organic matter and organic carbon in non-calcareous soils. *Journal of soil science*, *15*(1), 84-92.

Barron, J. A., & Anderson, L. (2011). Enhanced Late Holocene ENSO/PDO expression along the margins of the eastern North Pacific. *Quaternary International*, *235*(1-2), 3-12.

Barry, R.G. and Chorley, R.J. (2009). Atmosphere, weather and climate. Routledge.

Berger, A. (1978). Long-term variations of daily insolation and Quaternary climatic changes. *Journal of the atmospheric sciences*, *35*(12), 2362-2367.

Beuhler, M. (2003). Potential impacts of global warming on water resources in southern California. *Water Science and Technology*, *47*(7-8), 165-168.

Blaauw, M., & Christen, J. A. (2011). Flexible paleoclimate age-depth models using an autoregressive gamma process. *Bayesian analysis*, *6*(3), 457-474.

Braconnot, P., Otto-Bliesner, B., Harrison, S., Joussaume, S., Peterchmitt, J. Y., Abe-Ouchi, A., ... & Kageyama, M. (2007). Results of PMIP2 coupled simulations of the Mid-Holocene and Last Glacial Maximum–Part 1: experiments and large-scale features. *Climate of the Past*, *3*(2), 261-277.

CAL FIRE. (2020). California Department of Forestry and Fire Protection. Retrieved from https://www.fire.ca.gov/.

Castello, A. F., & Shelton, M. L. (2004). Winter precipitation on the US Pacific coast and El Nino–Southern Oscillation events. *International Journal of Climatology: A Journal of the Royal Meteorological Society*, *24*(4), 481-497.

Cayan, D. R., Redmond, K. T., & Riddle, L. G. (1999). ENSO and hydrologic extremes in the western United States. *Journal of Climate*, *12*(9), 2881-2893.

Chawchai, S., Kylander, M. E., Chabangborn, A., Löwemark, L., & Wohlfarth, B. (2016). Testing commonly used X-ray fluorescence core scanning-based proxies for organic-rich lake sediments and peat. *Boreas*, *45*(1), 180-189.

Clark, P. U., Shakun, J. D., Baker, P. A., Bartlein, P. J., Brewer, S., Brook, E., ... & Marchitto, T. M. (2012). Global climate evolution during the last deglaciation. *Proceedings of the National Academy of Sciences*, *109*(19), E1134-E1142.

Colombaroli, D., & Gavin, D. G. (2010). Highly episodic fire and erosion regime over the past 2,000 y in the Siskiyou Mountains, Oregon. *Proceedings of the National Academy of Sciences*, *107*(44), 18909-18914.

Cook, E. R., Woodhouse, C. A., Eakin, C. M., Meko, D. M., & Stahle, D. W. (2004). Long-term aridity changes in the western United States. *Science*, *306*(5698), 1015-1018.

Conroy, J. L., Overpeck, J. T., Cole, J. E., Shanahan, T. M., & Steinitz-Kannan, M. (2008). Holocene changes in eastern tropical Pacific climate inferred from a Galápagos lake sediment record. *Quaternary Science Reviews*, *27*(11-12), 1166-1180.

Croudace, I. W., Löwemark, L., Tjallingii, R., & Zolitschka, B. (2019). High resolution XRF core scanners: A key tool for the environmental and palaeoclimate sciences.

Daniau, A. L., Harrison, S. P., & Bartlein, P. J. (2010). Fire regimes during the Last Glacial. *Quaternary Science Reviews*, *29*(21-22), 2918-2930.

Dansgaard, W., Johnsen, S. J., Clausen, H. B., Dahl-Jensen, D., Gundestrup, N. S., Hammer, C. U., ... & Bond, G. (1993). Evidence for general instability of past climate from a 250-kyr ice-core record. *Nature*, *364*(6434), 218.

Davis, O. K. (1992). Rapid climatic change in coastal southern California inferred from pollen analysis of San Joaquin Marsh. *Quaternary Research*, *37*(1), 89-100.

Dean, W. E. (1974). Determination of carbonate and organic matter in calcareous sediments and sedimentary rocks by loss on ignition; comparison with other methods. *Journal of Sedimentary Research*, *44*(1), 242-248.

Dyke, A. S. (2004). An outline of North American deglaciation with emphasis on central and northern Canada. In *Developments in Quaternary Sciences* (Vol. 2, pp. 373-424). Elsevier.

Ejarque, A., Anderson, R. S., Simms, A. R., & Gentry, B. J. (2015). Prehistoric fires and the shaping of colonial transported landscapes in southern California: A paleoenvironmental study at Dune Pond, Santa Barbara County. *Quaternary Science Reviews*, *112*, 181-196.

Engel R. 1959. Geology of the Lake Elsinore quadrangle, California. Calif. Div. Mines Bull. 146: 52.

Firestone, R. B., West, A., Kennett, J. P., Becker, L., Bunch, T. E., Revay, Z. S., ... & Dickenson, O. J. (2007). Evidence for an extraterrestrial impact 12,900 years ago that contributed to the megafaunal extinctions and the Younger Dryas cooling. *Proceedings of the National Academy of Sciences*, *104*(41), 16016-16021.

Gavin, D. G., Hallett, D. J., Hu, F. S., Lertzman, K. P., Prichard, S. J., Brown, K. J., ... &

Peterson, D. L. (2007). Forest fire and climate change in western North America: insights from sediment charcoal records. *Frontiers in Ecology and the Environment*, *5*(9), 499-506.

Gershunov, A., & Barnett, T. P. (1998). Interdecadal modulation of ENSO teleconnections. *Bulletin of the American Meteorological Society*, *79*(12), 2715-2726.

Glover, K. C. (2016). *Southern California climate and vegetation over the past 125,000 years from lake sequences in the San Bernardino Mountains* (Doctoral dissertation, University of California, Los Angeles).

Glover, K. C., Chaney, A., Kirby, M. E., Patterson, W. P., & MacDonald, G. M. (2020). Southern California Vegetation, Wildfire, and Erosion Had Nonlinear Responses to Climatic Forcing During Marine Isotope Stages 5–2 (120–15 ka). *Paleoceanography and Paleoclimatology*, *35*(2), e2019PA003628.

Grenda, D. R. (1997). Site structure, settlement systems, and social organization at Lake Elsinore, California.

Grissino Mayer, H. D., & Swetnam, T. W. (2000). Century scale climate forcing of fire regimes in the American Southwest. *The Holocene*, *10*(2), 213-220.

Hardiman, M., Scott, A. C., Pinter, N., Anderson, R. S., Ejarque, A., Carter-Champion, A., & Staff, R. A. (2016). Fire history on the California Channel Islands spanning human arrival in the Americas. *Philosophical Transactions of the Royal Society B: Biological Sciences*, *371*(1696), 20150167.

Heiri, O., Lotter, A. F., & Lemcke, G. (2001). Loss on ignition as a method for estimating organic and carbonate content in sediments: reproducibility and comparability of results. Journal of paleolimnology, 25(1), 101-110.

Heusser, L. E., Kirby, M. E., & Nichols, J. E. (2015). Pollen-based evidence of extreme drought during the last Glacial (32.6–9.0 ka) in coastal southern California. *Quaternary Science Reviews*, *126*, 242-253.

Heyerdahl, E. K., Brubaker, L. B., & Agee, J. K. (2002). Annual and decadal climate forcing of historical fire regimes in the interior Pacific Northwest, USA. *The Holocene*, *12*(5), 597-604.

Hudson, T. (1978). Lake Elsinore Valley: its story. *Mayhall Print Shop, Lake Elsinore*.

Hull, A. G., & Nicholson, C. (1992). Seismotectonics of the northern Elsinore fault zone, southern California. *Bulletin of the Seismological Society of America*, *82*(2), 800-818.

IPCC, W. (2013). IPCC, 2013: summary for policymakers. *Climate change*.

Jennings, A. E., Hald, M., Smith, M., & Andrews, J. T. (2006). Freshwater forcing from the Greenland Ice Sheet during the Younger Dryas: evidence from southeastern Greenland shelf cores. *Quaternary Science Reviews*, *25*(3-4), 282-298.

Jones, T. L. (1992). Settlement trends along the California coast. *Essays on the prehistory of maritime California*, *10*, 1-37.

Keeley, J. E. (2005). Fire as a threat to biodiversity in fire-type shrublands. *Planning for biodiversity: bringing research and management together. USDA Forest Service General Technical Report PSW-GTR-195*, 97-106.

Keeley, J. E. (2009). Fire intensity, fire severity and burn severity: a brief review and suggested usage. *International Journal of Wildland Fire*, *18*(1), 116-126.

Kirby, M. E., Feakins, S. J., Bonuso, N., Fantozzi, J. M., & Hiner, C. A. (2013). Latest pleistocene to holocene hydroclimates from Lake Elsinore, California. *Quaternary Science Reviews*, *76*, 1-15.

Kirby, M. E., Heusser, L., Scholz, C., Ramezan, R., Anderson, M. A., Markle, B., ... & Price, B. (2018). A late Wisconsin (32–10k cal a BP) history of pluvials, droughts and vegetation in the Pacific south-west United States (Lake Elsinore, CA). *Journal of Quaternary Science*, *33*(2), 238-254.

Kirby, M. E., Lund, S. P., Anderson, M. A., & Bird, B. W. (2007). Insolation forcing of Holocene climate change in Southern California: a sediment study from Lake Elsinore. *Journal of Paleolimnology*, *38*(3), 395-417.

Kirby, M. E., Lund, S. P., Patterson, W. P., Anderson, M. A., Bird, B. W., Ivanovici, L., ... & Nielsen, S. (2010). A Holocene record of Pacific decadal oscillation (PDO)-related hydrologic variability in southern California (Lake Elsinore, CA). *Journal of Paleolimnology*, *44*(3), 819-839.

Kirby, M. E. C., Patterson, W. P., Lachniet, M., Noblet, J., Anderson, M., Avila, J., & Nichols, K. (2019). Pacific Southwest United States Holocene droughts and pluvials inferred from sediment 18O (calcite) and grain size data (Lake Elsinore, CA). *Frontiers in Earth Science*, *7*, 74.

Kitzberger, T., Swetnam, T. W., & Veblen, T. T. (2001). Inter-hemispheric synchrony of forest fires and the El Niño-Southern Oscillation. *Global Ecology and Biogeography*, *10*(3), 315-326.

Kylander, M. E., Ampel, L., Wohlfarth, B., & Veres, D. (2011). High-resolution X-ray fluorescence core scanning analysis of Les Echets (France) sedimentary sequence: new insights from chemical proxies. *Journal of Quaternary Science*, *26*(1), 109-117.

Lanner, R. M. (1981). *The piñon pine: a natural and cultural history*. University of Nevada Press.

Laskar, J., Robutel, P., Joutel, F., Gastineau, M., Correia, A. C. M., & Levrard, B. (2004). A long-term numerical solution for the insolation quantities of the Earth. *Astronomy & Astrophysics*, *428*(1), 261-285.

Lawson, R., & Anderson, M. A. (2007). Stratification and mixing in Lake Elsinore, California: An assessment of axial flow pumps for improving water quality in a shallow eutrophic lake. *Water research*, *41*(19), 4457-4467.

Lisiecki, L. E., & Raymo, M. E. (2005). A Pliocene-Pleistocene stack of 57 globally distributed benthic δ18O records. *Paleoceanography*, *20*(1).

Liu, Z., Otto-Bliesner, B., Kutzbach, J., Li, L., & Shields, C. (2003). Coupled climate simulation of the evolution of global monsoons in the Holocene. *Journal of Climate*, *16*(15), 2472-2490.

Lynch H.B. 1931. Rainfall and stream run-off in Southern California since 1769. The Metropolitan Water District of Southern California, Los Angeles, California, pp. 1–31.

MacDonald, G. M., & Case, R. A. (2005). Variations in the Pacific Decadal Oscillation over the past millennium. *Geophysical Research Letters*, *32*(8).

MacDonald, G. M., Moser, K. A., Bloom, A. M., Potito, A. P., Porinchu, D. F., Holmquist, J. R., ... & Kremenetski, K. V. (2016). Prolonged California aridity linked to climate warming and Pacific sea surface temperature. *Scientific reports*, *6*, 33325.

MacHott, R. J. (2011). City of Lake Elsinore: General Plan-Certified Recirculated Program Environmental Impact Report (SCH# 2005121019).

Mack, M. C., & D'Antonio, C. M. (1998). Impacts of biological invasions on disturbance regimes. *Trends in Ecology & Evolution*, *13*(5), 195-198.

Mann J.F. Jr. 1956. The origin of Elsinore Lake Basin. Bull. Southern California Acad. Sci. 55:

72–78.

Mann, M. E., Cane, M. A., Zebiak, S. E., & Clement, A. (2005). Volcanic and solar forcing of the tropical Pacific over the past 1000 years. *Journal of Climate*, *18*(3), 447-456.

Marlon, J. R., Bartlein, P. J., Gavin, D. G., Long, C. J., Anderson, R. S., Briles, C. E., ... & Scharf, E. A. (2012). Long-term perspective on wildfires in the western USA. *Proceedings of the National Academy of Sciences*, *109*(9), E535-E543.

Marlon, J. R., Bartlein, P. J., Walsh, M. K., Harrison, S. P., Brown, K. J., Edwards, M. E., ... & Brunelle, A. (2009). Wildfire responses to abrupt climate change in North America. *Proceedings of the National Academy of Sciences*, *106*(8), 2519-2524.

Martinez, D., & Anderson, M. A. (2013). Methane production and ebullition in a shallow, artificially aerated, eutrophic temperate lake (Lake Elsinore, CA). *Science of the total environment*, *454*, 457-465.

Masi, G. J. (2005). "Orographic and large-scale influence on Southern California precipitation patterns," in *Proceedings of the Sixth Conference on Coastal Atmospheric and Oceanic Prediction and Processes*, San Diego, CA.

McManus, J. F., Francois, R., Gherardi, J. M., Keigwin, L. D., & Brown-Leger, S. (2004). Collapse and rapid resumption of Atlantic meridional circulation linked to deglacial climate changes. *Nature*, *428*(6985), 834.

Meehl, G. A., Tebaldi, C., Teng, H., & Peterson, T. C. (2007). Current and future US weather extremes and El Niño. Geophysical Research Letters, 34(20).

Meko, D. M., Woodhouse, C. A., Baisan, C. A., Knight, T., Lukas, J. J., Hughes, M. K., & Salzer, M. W. (2007). Medieval drought in the upper Colorado River Basin. *Geophysical Research Letters*, *34*(10).

Metcalfe, S. E., Barron, J. A., & Davies, S. J. (2015). The Holocene history of the North American Monsoon:'known knowns' and 'known unknowns' in understanding its spatial and temporal complexity. *Quaternary Science Reviews*, *120*, 1-27.

Millspaugh, S. H., Whitlock, C., & Bartlein, P. J. (2000). Variations in fire frequency and climate over the past 17 000 yr in central Yellowstone National Park. *Geology*, *28*(3), 211-214.

Minnich, R. A. (1988). The biogeography of fire in the San Bernardino Mountains of California: a historical study (Vol. 28). Univ of California Press.

Minnich, R.A., Barbour, M., Keeler-Wolf, T. and Schoenherr, A., 2007. Climate, paleoclimate, and paleovegetation. Terrestrial vegetation of California, pp.43-70.

Mohr, J. A., Whitlock, C., & Skinner, C. N. (2000). Postglacial vegetation and fire history, eastern Klamath Mountains, California, USA. *The Holocene*, *10*(5), 587-601.

Monnin, E., Steig, E. J., Siegenthaler, U., Kawamura, K., Schwander, J., Stauffer, B., ... & Raynaud, D. (2004). Evidence for substantial accumulation rate variability in Antarctica during the Holocene, through synchronization of CO2 in the Taylor Dome, Dome C and DML ice cores. *Earth and Planetary Science Letters*, *224*(1-2), 45-54.

Myrbo, A., Lynch, B., Curran, S., 2005. Limnological Research Center Core Facility SOP Series charcoal-sieve.pdf.

Norman, S. P., & Taylor, A. H. (2003). Tropical and north Pacific teleconnections influence fire regimes in pine-dominated forests of north-eastern California, USA. Journal of Biogeography, 30(7), 1081-1092.

Oster, J. L., Ibarra, D. E., Winnick, M. J., & Maher, K. (2015). Steering of westerly storms over western North America at the Last Glacial Maximum. *Nature Geoscience*, *8*(3), 201.

Overpeck, J., Garfin, G., Jardine, A., Busch, D. E., Cayan, D., Dettinger, M., ... & Travis, W. R. (2013). Summary for decision makers. In *Assessment of Climate Change in the Southwest United States* (pp. 1-20). Island Press, Washington, DC.

Owen, L. A., Finkel, R. C., Minnich, R. A. & Perez, A. E. 2003: Extreme southwestern margin of late Quaternary glaciation in North America: Timing and controls. Geology 31, 729–732.

Pausas, J. G., & Keeley, J. E. (2014). Abrupt climate-independent fire regime changes. *Ecosystems*, *17*(6), 1109-1120.

Power, M. J., Marlon, J. R., Bartlein, P. J., & Harrison, S. P. (2010). Fire history and the Global Charcoal Database: a new tool for hypothesis testing and data exploration. *Palaeogeography, Palaeoclimatology, Palaeoecology*, *291*(1-2), 52-59.

Power, M. J., Marlon, J., Ortiz, N., Bartlein, P. J., Harrison, S. P., Mayle, F. E., ... & Mooney, S. (2008). Changes in fire regimes since the Last Glacial Maximum: an assessment based on a global synthesis and analysis of charcoal data. *Climate dynamics*, *30*(7-8), 887-907.

Price, C. (2009). Will a drier climate result in more lightning?. Atmospheric Research, 91(2-4), 479-484.

Reynolds, R. V., & Pierson, A. H. (1941). The saw timber resource of the United States, 1630–1930. Forest Survey Release. *US Department of Agriculture, Forest Service, Washington, DC.*

Seager, R., Harnik, N., Robinson, W. A., Kushnir, Y., Ting, M., Huang, H. P., & Velez, J. (2005). Mechanisms of ENSO-forcing of hemispherically symmetric precipitation variability. *Quarterly Journal of the Royal Meteorological Society: A journal of the atmospheric sciences, applied meteorology and physical oceanography*, *131*(608), 1501-

1527.

Schlachter, K. J., & Horn, S. P. (2010). Sample preparation methods and replicability in macroscopic charcoal analysis. *Journal of Paleolimnology*, *44*(2), 701-708.

Sommers, W. T., Loehman, R. A., & Hardy, C. C. (2014). Wildland fire emissions, carbon, and climate: science overview and knowledge needs. *Forest Ecology and Management*, *317*, 1-8.

Swetnam, T. W., Baisan, C. H., Caprio, A. C., Brown, P. M., Touchan, R., Anderson, R. S., & Hallett, D. J. (2009). Multi-millennial fire history of the giant forest, Sequoia National Park, California, USA. *Fire Ecology*, *5*(3), 120.

Swetnam, T. W., & Betancourt, J. L. (1998). Mesoscale disturbance and ecological response to decadal climatic variability in the American Southwest. *Journal of Climate*, *11*(12), 3128-3147.

Thackeray, J. F., Scott, L., & Pieterse, P. (2019). The Younger Dryas interval at Wonderkrater (South Africa) in the context of a platinum anomaly.

Thompson, R. S., Whitlock, C., Bartlein, P. J., Harrison, S. P., Spaulding, W. G., Wright, H. E., … & Street-Perrott, F. A. (1993). Climatic changes in the western United States since 18,000 yr BP. *Global climates since the last glacial maximum*, 468-513.

Trouet, V., Esper, J., Graham, N. E., Baker, A., Scourse, J. D., & Frank, D. C. (2009). Persistent positive North Atlantic Oscillation mode dominated the medieval climate anomaly. *science*, *324*(5923), 78-80.

Tubbs, A. M. (1972). Summer thunderstorms over southern California. *Monthly Weather Review*, *100*(11), 799-807.

van Hoesel, A., Hoek, W. Z., Braadbaart, F., van der Plicht, J., Pennock, G. M., & Drury, M. R.

(2012). Nanodiamonds and wildfire evidence in the Usselo horizon postdate the Allerød-Younger Dryas boundary. *Proceedings of the National Academy of Sciences*, *109*(20), 7648-7653.

Vasek, F. C., & Thorne, R. F. (1977). Transmontane coniferous vegetation. *Terrestrial Vegetationof California. California Native Plant Society, Special Publication*, (9), 797-832.

Ward JK, Tissue DT, Thomas RB, Strain BR (1999) Comparative responses of model C3 and C4 plants to drought in low and elevated CO2. Glob Change Biol 5:857–867.

Westerling, A. L., Hidalgo, H. G., Cayan, D. R., & Swetnam, T. W. (2006). Warming and earlier spring increase western US forest wildfire activity. *science*, *313*(5789), 940-943.

Whitlock, C., & Bartlein, P. J. (2003). Holocene fire activity as a record of past environmental change. *Developments in Quaternary Sciences*, *1*, 479-490.

Whitlock, C., Higuera, P. E., McWethy, D. B., & Briles, C. E. (2010). Paleoecological perspectives on fire ecology: revisiting the fire-regime concept. *The Open Ecology Journal*, *3*(1).

Whitlock, C., & Larsen, C. (2001). Charcoal as a fire proxy. In *Tracking environmental change using lake sediments* (pp. 75-97). Springer, Dordrecht.

Whitlock, C., Marlon, J., Briles, C., Brunelle, A., Long, C., & Bartlein, P. (2008). Long-term relations among fire, fuel, and climate in the north-western US based on lake-sediment studies. *International Journal of Wildland Fire*, *17*(1), 72-83.

Woodhouse, C. A., Meko, D. M., MacDonald, G. M., Stahle, D. W., & Cook, E. R. (2010). A 1,200-year perspective of 21st century drought in southwestern North America. *Proceedings of the National Academy of Sciences*, *107*(50), 21283-21288.

WRCC. (2019). Climate Summary for Southern California. Retrieved from *https://wrcc.dri.edu/summary/Climsmsca.html.*

Yoon, J. H., Kravitz, B., Rasch, P. J., Simon Wang, S. Y., Gillies, R. R., & Hipps, L. (2015). Extreme fire season in California: A glimpse into the future?. *Bulletin of the American Meteorological Society*, *96*(12), S5-S9.