Holocene climate and oceanography of the coastal Western United States and California Current System

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Abstract

Examination of climatic and oceanographic changes through the Holocene (11.75 ka-present) allows for an improved understanding and contextualization of modern climate change. Climate records of the Holocene can be utilized as a "baseline" from which to compare modern climate and can also provide insights into how environments experience and recover from change. However, individual studies on Holocene climate in the literature tend to focus on a distinct geographic location, a specific proxy record, or a certain aspect of climate (e.g., upwelling or precipitation), resulting in localized, record-specific trends rather than a comprehensive view of climate variability through the Holocene. Here we synthesize the major oceanographic and terrestrial changes that have occurred in the Western United States (bounded by 30°N to 52°N and 115°W to 130°W) through the most recent 11.75 ka and explore the impacts of these changes on marine and terrestrial ecosystems and human populations. We present a novel spatiotemporal analysis of Holocene marine and terrestrial temperature, hydroclimate, and fire activity across the early, mid, and late Holocene using a coded analysis of over fifty published studies. Following coded analysis of temperature, hydroclimate, and fire activity in the paper, we include a broader literature review of environmental change through the Holocene, including an examination the impacts of multi-millennial climate trends on ecological communities. We find that the early Holocene is characterized by warming relative to pre-Holocene conditions, including warm sea surface conditions, a warm and dry Pacific Northwest, a warm and wet Southwest, and overall spatial and temporal stability. In the mid Holocene, these patterns reverse; this interval is characterized by cool sea surface temperatures, a cool and wet Pacific Northwest and warm and dry Southwest. The late Holocene is the most variable interval, both spatially and temporally, and a novel spatial trend appears in terrestrial climate with warmer coastal areas and cooler inland areas. Human communities interacted with the environment throughout the entire Holocene, as evidenced in archeological and paleoenvironmental records, yet the recent era of colonization (1850-present) represents an unprecedented environmental interval in many records. Broadly, our analysis shows linkages between terrestrial and oceanographic conditions, distinct environmental phases through time, and emphasizes the importance of local factors in controlling climate through the dynamic Holocene.

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1 Introduction

1.1 Overview of Holocene Climate

In contrast to past intervals of glacial/interglacial variability, the Holocene has largely been regarded as a climatically stable interval. However, local and global changes in Holocene climate merit further investigation. Meta-analysis of global temperatures and patterns through the Holocene show a globally warm period from 11 to 5 ka, termed the Holocene Climatic Optimum, largely driven by a concurrent peak in summer solar insolation in the Northern Hemisphere (Mayewski et al., 2004; Wanner et al., 2008; Renssen et al., 2012; Marcott et al., 2013; Bader et al., 2020). Following this period of global warmth, competing lines of evidence show divergent global temperature regimes in the last 5 ky (some records show global warming and others global cooling); this phenomenon is termed the Holocene Conundrum (Wanner et al., 2008; Marcott et al., 2013; Liu et al., 2014; Marsicek et al., 2018; Bader et al., 2020). Currently available global reconstructions typically under-sample temperature records from the North Pacific and Western North America, motivating the need for further analysis of Holocene change over time in this region (Marcott et al., 2013; Kaufman et al., 2020; Praetorius et al., 2020; Walczak et al., 2020).

Holocene climate variability on various timescales has been attributed to multiple climate forcing mechanisms, including: changes in solar insolation, volcanic activity, land-use change, variations in atmospheric greenhouse gas concentrations, and climate feedbacks (Crowley, 2000; Bradley, 2003; Atwood et al., 2016). Specifically, Northern Hemisphere summer insolation was at a Holocene maximum and winter insolation was at a Holocene minimum at 9 ka, with important implications for global and regional climate (Renssen et al., 2012; Marcott et al., 2013; Marsicek et al., 2018; Swain et al., 2018; Routson et al., 2019; Bader et al., 2020; Kaufman et al., 2020). In the early Holocene, peak summer insolation and continued melting of Northern Hemisphere ice sheets are dominant drivers of North American climate; following the collapse of the Laurentide Ice Sheet, the impact of ice sheet feedbacks on climate is reduced (Viau et al., 2006; Renssen et al., 2012; Bader et al., 2020). In North America broadly, mean summer temperatures increased from the last glacial maximum (26-19 ka) (Clark et al., 2009; Waelbroeck et al., 2009) until between 6 and 3 ka by ~4^{O}C and subsequently decreased (Viau et al., 2006). Across the continent, millennial-scale climate variability on the order of 0.2^{O}C occurs across the entire Holocene (Viau et al., 2006). Analysis of global and continental records show a high degree of temporal and spatial climate variability highlighting the need to assess region-specific changes through time. Understanding regional Holocene variability is particularly relevant to contextualize biotic and environmental responses to anthropogenic climate change.

1.2 Modern climate and oceanography of Western North America

Western North America currently experiences impacts of drought, fire, heatwaves, and fisheries, agriculture, and ecological shifts due to climate change (e.g., Ainsworth et al., 2011; Mann and Gleick, 2015; Westerling et al., 2011; Wise, 2016). Quantifying climatic and environmental changes over time in this region is of particular importance as it hosts a large modern human population, a multitude of natural resources, and highly biodiverse and productive ecosystems. By investigating climate and environmental change through the Holocene, we can better

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In the modern system, the interaction between the Aleutian Low pressure system, the North Pacific High pressure system, and the Continental Thermal Low pressure system drive temperature and hydrographic gradients (Fig. 1). Modern terrestrial climate of the Western United States varies latitudinally with cooler temperatures and wintertime precipitation in the PNW and warmer temperatures, general aridity, and relatively reduced precipitation in the SW (Fig. 1) (e.g., Sheppard et al., 2002; Adams and Comrie, 1997; Barlow et al., 1998). Hydroclimate variability is typically characterized by a north–south dipole pattern of precipitation anomalies with opposing signs and less often by a west-east pattern (e.g., Wise, 2016, 2010). Atmospheric rivers are a major source of hydrologic input and variability in this region (e.g., Dettinger et al., 2011). Drought is a recurrent and salient feature of climate in the West, particularly in the context of anthropogenic climate change (Fig. 1) (e.g. Cook, 2004; Wise, 2016). Wildfire is also a dominant feature of the landscape of the Western United States; climate, vegetation/fuel availability, and human activity interact as drivers of fire activity (e.g., Marlon et al., 2012; Westerling et al., 2003, 2011; Higuera et al., 2021; Dennison et al., 2014; Shuman et al., 2022). Variability in precipitation, air temperature, and fire regime exert strong control over plant and animal communities (e.g., Beaty and Taylor, 2009; Clark et al., 2012; Marlon et al., 2006; Shuman et al., 2018; Dingemans et al., 2014).

Marine and terrestrial climates are linked in this region; westerly winds influenced by North Pacific ocean-atmosphere dynamics result in high correlation between North Pacific sea surface temperatures (SST) and coastal air temperatures (e.g., LaDochy et al., 2007; Barron and Anderson, 2011). The westerly winds generated by the Aleutian Low pressure system and North Pacific High pressure system fuel the California Current System (CCS), which flows southward from ~50° N to ~15°N (Fig. 1) (e.g., Checkley and Barth, 2009; Hickey, 1979). The CCS is characterized by strong seasonal wind-driven upwelling that drives high surface productivity along Western North America (e.g., Siedlecki et al., 2015; Hickey, 1979; Checkley and Barth, 2009). Respiration, remineralization, and decomposition lead to high organic carbon export and oxygen-depleted (CO_2-rich) bottom waters (e.g., Checkley and Barth, 2009; Chelton et al., 1982; Siedlecki et al., 2015). The interaction of the equatorward California Current, the poleward Davidson Current, and the sub-surface, poleward California Undercurrent drive oceanographic conditions south of Point Conception (Bray et al., 1999). Seasonal, annual, and decadal events, including the Pacific Decadal Oscillation (PDO), North Pacific Gyre Oscillation, and El Niño Southern Oscillation (ENSO) play a significant role in driving Eastern North Pacific SST and productivity across multiple timescales (e.g., Chavez et al., 2003; Batchelder and Powell, 2002; Di Lorenzo et al., 2008; Lluch-Cota et al., 2001; Mantua et al., 2002). Changes

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in marine currents, upwelling regime, and temperature impact primary production, with cascading implications for the entire marine food web (Barron et al., 2003b; Yati et al., 2020).

Climate and environmental change through time impact human communities that have been present in Western North America throughout the Holocene. Evidence from over 40 archeological sites in North America shows humans were likely present before, during, and after the Last Glacial Maximum (26.5-19 ka) (Becerra-Valdivia and Higham, 2020). Additional evidence for human presence and societal expansion within the geographic and temporal range of this review includes archaeological evidence from shell middens as well as Indigenous oral histories (e.g., Braje et al., 2012; Erlandson et al., 2007, 2009; Kennett et al., 2007; McKechnie, 2015; Rick, 2011; Becerra-Valdivia and Higham, 2020). Previous work has investigated linkages between climate and human communities on a local scale through the Holocene (e.g., Braje et al., 2012; Erlandson et al., 2007; Glassow et al., 2012; Kennett et al., 2007; McKechnie, 2015; Rick, 2011).

Here, we conduct a spatiotemporal analysis of temperature, hydroclimate, and fire activity between the early, mid, and late Holocene and synthesize previously published records of both marine and terrestrial systems from the Western United States and California Current System (Appendices A-C), resulting in the most comprehensive multi-proxy Holocene climate reconstruction for this region to date. This review addresses the following linked research questions: How do temperature, hydroclimate, and fire activity vary between the early, mid, and late Holocene in the Western United States? How do marine and terrestrial environments interact in this region during the Holocene? How do climate and oceanographic changes impact ecological communities in the Holocene?

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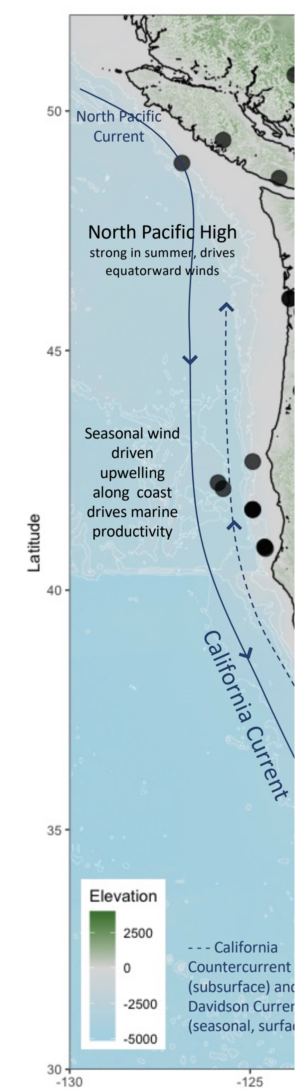

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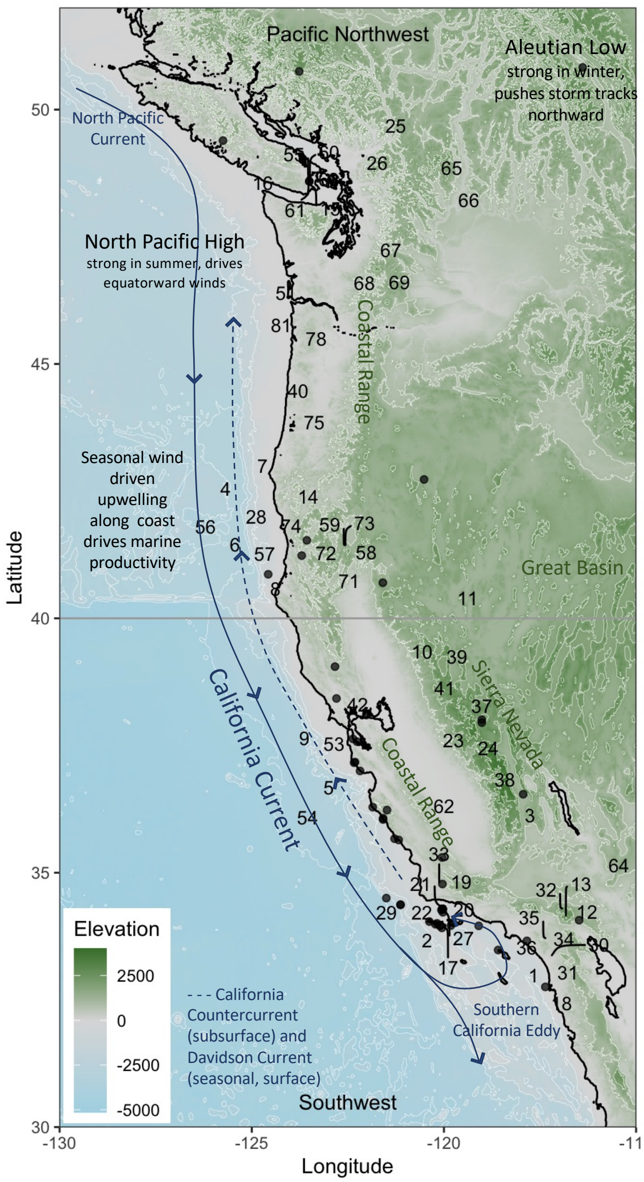

Figure 1: Map of locations of all studies reviewed in the paper with simplified schematic of modern oceanographic and hydrographic conditions. Sites used in spatiotemporal analysis are numbered, numbers correspond to papers

listed in Appendix A. Sites used in literature review are included as black dots. Gray horizontal line shows delineation between Pacific Northwest and Southwest for the purposes of this study.

2 Methodology

For the purposes of this paper we follow the standard convention formally recognized by the International Commission on Stratigraphy (Walker et al., 2018): early Holocene (Greenlandian, 11.75-8.2 ka), mid Holocene (Northgrippian, 8.2-4.2 ka), and late Holocene (Meghalayan, 4.2-0 ka). We do include interpretations that span across these sub-epoch time intervals. We constrain our study to the geographic region bounded by 30°N to 52°N and 115°W to 130°W as this region has an abundance and variety of long-term records through the Holocene.

2.1 Spatiotemporal Analysis

To conduct a spatiotemporal analysis of environmental change in this region we identified studies using rigorous criteria, coded the results of previous studies through time, and visualized the results in a series of maps (Figs. 2,3). Records were initially identified using the following topics as search terms: marine temperature, ocean circulation, marine productivity, terrestrial hydroclimate, drought, floods, terrestrial temperature, fire, marine ecology, and terrestrial ecology. For inclusion in the spatiotemporal analysis, previously published studies must be located within the defined geographic region (30°N to 52°N and 115°W to 130°W), have a published age model, must span at least 3000 years of the Holocene and must present a clearly identified and described climatic pattern or patterns for an entire Holocene interval. Results from each paper were binned into time intervals: early, mid, and late Holocene, and coded using the following categories: hydroclimate (wet or dry), temperature (warm or cold), and fire activity (high or low).

Results were coded using keywords from the original authors' description of climate conditions at each point in time: temperature keywords: warm, cold, cool; hydroclimate keywords: wet, dry, moisture, arid(ity), pluvial, fluvial, precipitation; fire keywords: high, low, activity, frequency, return interval, intensity. We generated a database that contains paper (author, date), latitude, longitude (of all sites within each paper), region (PNW or SW), archive type, type of chronology, number of age dates used in age model, and coded results for each category (hydroclimate, temperature, fire activity) in each interval (early, mid, late). The spatiotemporal analysis includes results from 46 papers at 75 sites (Appendix A).

A wide range of archive types are represented here: dendrochronology, speleothem, lacustrine sediments, marine sediments, and other records including geomorphology, animal midden, and lichen archives. Interpretations in original papers are based on a variety of well-established proxies: alkenones, carbon and nitrogen isotopes of bulk sediments, charcoal, diatom and silicoflagellate assemblage, foraminiferal assemblage, geomorphology, hydrogen isotopes from leaf wax, oxygen and carbon isotopes of nearshore marine organisms, oxygen and carbon isotopes of biogenic and non-biogenic calcite, macrofossil abundance, pollen assemblage, radiocarbon dating, sedimentology, including grain size analysis, lithology, organic content, carbon content analysis, and tree ring/tree stump analysis.

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This paper makes no attempt to evaluate the effectiveness of each proxy or to re-examine the primary data; rather, interpretations of data from original work are maintained. For example, changes in SST may be inferred from alkenones, foraminiferal assemblages, or foraminiferal isotope records in previously published studies, but all are represented as temperature in the coded database. It is important to note that some proxies are seasonally biased and thus represent only a portion of an overall climate/ecological trend. We utilize the term "fire activity" to be inclusive of multiple paleofire proxy types including fire return intervals, CHAR, charcoal accumulation, and others. Some papers contributed multiple data points to this step. For example, some records included interpretations of multiple processes (e.g., temperature and hydroclimate) and some include interpretations across multiple time intervals (early, mid, late). Yet, papers that only included one interpretation in one interval are also included.

Results of coded analysis are plotted in space through the three time intervals (early, mid, late Holocene) (Figs. 2,3). Temperature (marine and terrestrial), hydroclimate, and fire activity are plotted separately (Figs. 2, 3). Base maps with elevation are generated using the R package marmap (Pante and Simon-Bouhet, 2013) accessing bathymetric and elevation data from the NOAA ETOPO1 global relief model (Amante and Eakins, 2009).

Following the spatial and temporal analysis, we highlight a subset of regionally representative time series records from the PNW (Fig. 4) and SW (Fig. 5). We prioritized continuous records, and records that span at least two intervals of the Holocene (Kaufman et al., 2020). Further, we selected records that represent temperature, hydroclimate, and fire activity for each region (PNW and SW). For these purposes, data was accessed through original papers, supplemental information, or through the NOAA Paleoclimate Database (Appendix C).

2.2 Literature Review

Following coded analysis of temperature, hydroclimate, and fire activity in the paper, we include a broader literature review of environmental change through the Holocene and a discussion of the impacts of climate changes to ecological communities (Appendix B). For inclusion in this step of the review, previous studies must be within the geographic range of the study and include a published age model. Papers identified in this step are discussed in text in the manuscript. The literature review includes 107 papers from 148 sites.

2.4 Chronological uncertainty

For this review, we rely on previously published chronologies. Each paper included here has 2-120 age dates (Appendix B). The mean number of age dates per record is 16.6 and the median is 12 (Appendix B). The most common methods of age dating were radiocarbon of organic material (68 sites) and radiocarbon of carbonate (46); tephrochronology, dendrochronology, oxygen isotope stratigraphy, varve chronology and others were less common (Appendix B). To accommodate age uncertainty and differences in age model development between papers, all interpretations utilized in the coded analysis and map visualizations (Figs. 2-3) must have been reported by original authors as a consistent trend across a full interval of the Holocene (> 3k). Thus, by identifying climatic codes at a

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In the second step of the systematic review process, we identified papers that met a second set of criteria, coded results through time, and conducted a spatial and temporal analysis of the synthesis. This criteria included all studies at least 3000 years of the Holocene, and in which the au ... [11]

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Following the spatial and temporal analysis, we highlight a subset of regionally representative time series records from the PNW (Fig. 4) and SW (Fig. 5). We prioritized records with high temporal resolution, continuous records, and records that span at least two intervals of the Holocen ... [12]

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multi-millennial scale, we reduce error due to variability in age model development between papers. In text and in the broader literature review, the timing of events uses the original authors published age dates. We encourage readers to reference Appendix B for additional information about age control. Importantly, timing of events such as the 8.2 ka event, Medieval Climate Anomaly, Little Ice Age, and Era of Colonization are based on the original author's interpretations.

3 Results and discussion

3.1 Early Holocene (11.75-8.2 ka)

Thirty-three papers encompassing 59 sites fit the criteria for inclusion in the spatiotemporal analysis. Archives included lake sediments (40 sites), marine sediments (15 sites), and two others (geomorphology, dendrochronology) (Appendix A, B).

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3.1.1 Regional Synthesis and Marine-terrestrial Interactions

Spatial analysis of coded hydroclimate, temperature, and fire history indicate that the early Holocene was generally characterized by a dry and warm PNW and a wet and warm SW (Fig. 2). These trends are also observed in time series data from both regions (Figs. 4, 5). In the PNW, sea surface temperatures were warm, winters were dry, and fire activity was high (Fig. 4). In the SW, sea surface temperatures were warm, terrestrial temperatures were cold, fire activity was low, and hydroclimate was generally wet (Fig. 5).

Generalized warming in the early Holocene relative to pre-Holocene conditions follows two abrupt Northern Hemisphere climate transitions, characterized by rapid warming during the Bølling–Allerød (14.7-12.9 ka) and rapid cooling associated with the Younger Dryas (12.9-11.7 ka) (Barron et al., 2003b; McGann, 2015). Sea surface temperatures were warm across the entire coastal CCS during the early Holocene (Fig. 2), likely driven by high summer insolation (insolation maximum at 9 ka) and warming following deglaciation. Despite warm SST across the region, terrestrial hydroclimate and temperatures varied latitudinally, indicating regional differences in marine-terrestrial climate linkages and impacts of the summer insolation maximum (Fig. 3). In the PNW, warm SSTs co-occurred with warm and dry terrestrial conditions (Heusser, 1998; Barron et al., 2003b; Steinman et al., 2016), while in the SW, wet conditions were driven by a combination of more intense winter precipitation associated with reduced winter insolation and the evolution of the North American Monsoon (NAM) and the resultant increase in summertime precipitation in the early Holocene relative to pre-Holocene (Fig. 2) (Bird and Kirby, 2006; Kirby et al., 2015; Metcalfe, 2015).

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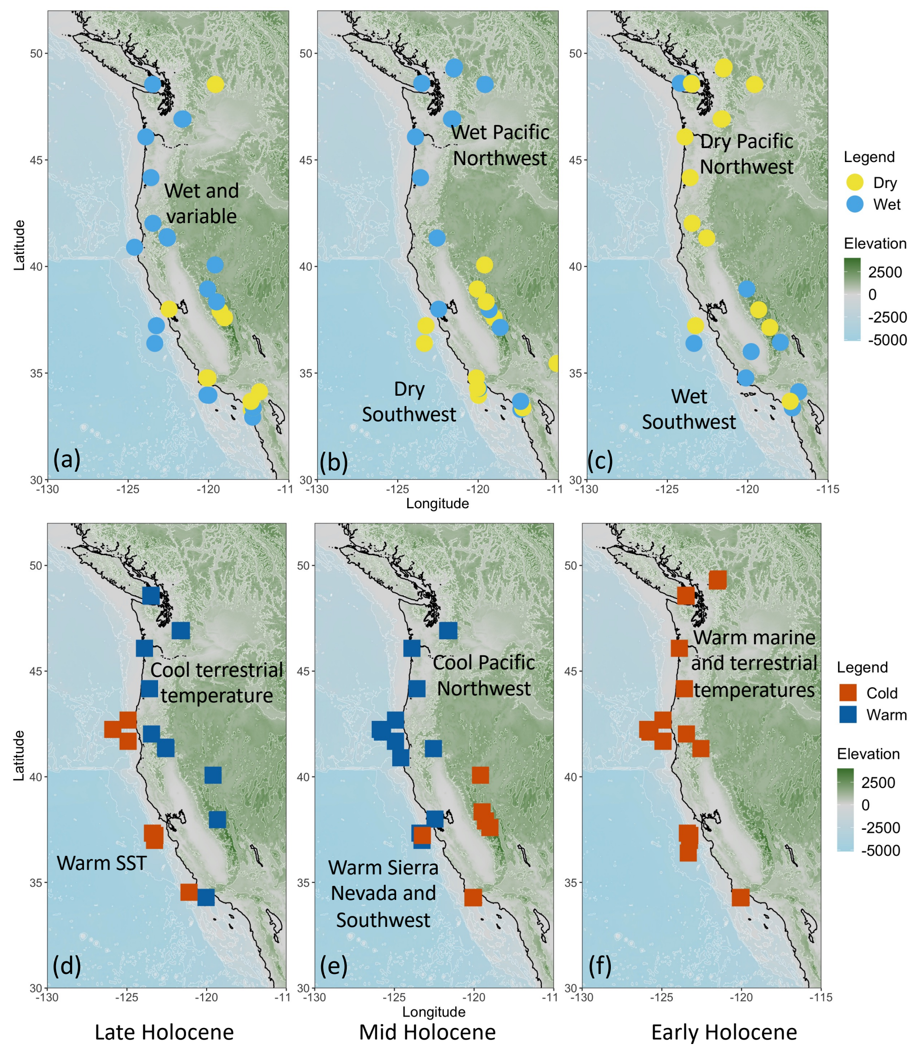

Figure 2: Top panel shows hydroclimate records in early (11.7 - 8.2 ka, (c)), mid (8.2 - 4.2 ka, (b)), and late (4.2 - 0 ka, (a)) Holocene: yellow dots represent dry and light blue represents wet. Bottom panel shows temperature records

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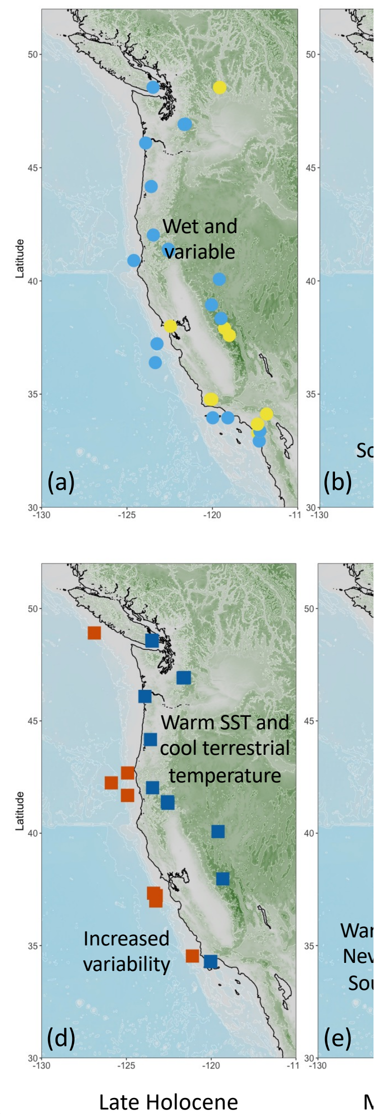

from early (f), mid (e), and late (d) Holocene: dark blue squares represent cold temperatures and orange represents warm temperatures.

3.1.2 Terrestrial climate

In the PNW, multiple records show warm and dry conditions in the early Holocene (Figs. 2c, 2f) (Mohr et al., 2000; Hallett et al., 2003; Briles et al., 2005; Malamud-Roam et al., 2006; Marlon et al., 2006; Gavin et al., 2007; Long et al., 2011; Steinman et al., 2019). Drier than modern conditions existed in locations dominated by winter precipitation (largely PNW) (Fig. 2c) (McGann, 2011; Hermann et al., 2018; Leidelmeijer et al., 2021). An East-West precipitation gradient was established with warm and dry conditions in the East and wet conditions in the West (Brown and Hebda, 2002), fire activity was high at multiple locations (Hallett et al., 2003; Marlon et al., 2006; Gavin et al., 2007; Steinman et al., 2019), and the amount of biomass burning and the extent of tree cover increased during this time (Figs. 2, 3) (Marlon et al., 2006; Gavin et al., 2007). The early Holocene increase in fire activity in the PNW relative to pre-Holocene conditions may have been caused by warmer/drier conditions resulting from amplified seasonality due to increased summer insolation relative to pre-Holocene (Walsh et al., 2017; Steinman et al., 2019). In some locations (i.e., Scanlon and Castor Lake), fire frequency increased relative to glacial, but remained lower relative to the mid or late Holocene (Walsh et al., 2017). Few records show wet conditions in the PNW during the early Holocene (McQuoid and Hobson, 2001).

In California's Central Valley and Sierra Nevada, the early Holocene was wet with low or variable fire frequency (Figs. 2, 3) (Benson et al., 2002; Bacon et al., 2006; Negrini et al., 2006; Hallett and Anderson, 2010). Fuel abundance exerted a stronger control on fire than regional climate (Hallett and Anderson, 2010). In the Eastern Sierra Nevada (i.e., Lower Gaylor Lake and Barrett Lake near Mono Lake), low biomass (sparse pine dominated forests and chaparral shrubs) reinforced by low snowpack persistence due to the summer insolation maximum, led to low fire frequency (Hallett and Anderson, 2010). In the Lake Tahoe Basin, precipitation was high in the early Holocene and fire frequency was low in the very early Holocene (11-9 ka) and transitioned to higher fire frequency than modern from 9 ka through mid Holocene (Lindstrom, 1990; Benson et al., 2002; Beaty and Taylor, 2009).

In comparison to the arid PNW, early Holocene conditions in the SW were largely wetter than modern (Fig. 2). Lacustrine records from across the SW show heavy precipitation in the early Holocene (Bird and Kirby, 2006; Kirby et al., 2007, 2010, 2012, 2014, 2015; Bird et al., 2010; Du et al., 2018). Wet conditions at this time were driven by both winter precipitation and the North American Monsoon (Bird and Kirby, 2006; Kirby et al., 2007; Marcott et al., 2013; Hermann et al., 2018). Prior to 8 ka, the trajectory of the North American Monsoon was shifted west of its modern-day impact due to warm SST in the Gulf of California and the northern shift of the North Pacific High, resulting in some precipitation in Southern California (Barron et al., 2012). Yet monsoonal precipitation alone cannot explain the wet conditions of the early Holocene (Kirby et al., 2007, 2012; Barron et al., 2012). The early Holocene winter insolation minimum led to an increase in winter precipitation in Southern California (Bird and Kirby, 2006; Kirby et al., 2007; Marcott et al., 2013; Hermann et al., 2018). Atmospheric river-like storms may have

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played a key role in contributing to wet conditions at this time. (Kirby et al., 2005, 2007, 2012; Bird et al., 2010). High moisture/precipitation is shown in both inland (desert) and coastal sites, including increased runoff into the Santa Barbara Basin from 9 to 8.5 ka and a pluvial episode synchronous across multiple sites in Southern California from 9.1 to 8.25 ka (Kirby et al., 2007, 2010, 2012, 2014; Du et al., 2018). In contrast, lake sediment records from Southern California that resolve summer evaporation show high evaporation and multiple intervals of drought in the early Holocene; high winter precipitation and high summer evaporation may explain the differences between multiple records in this region (Kirby et al., 2019).

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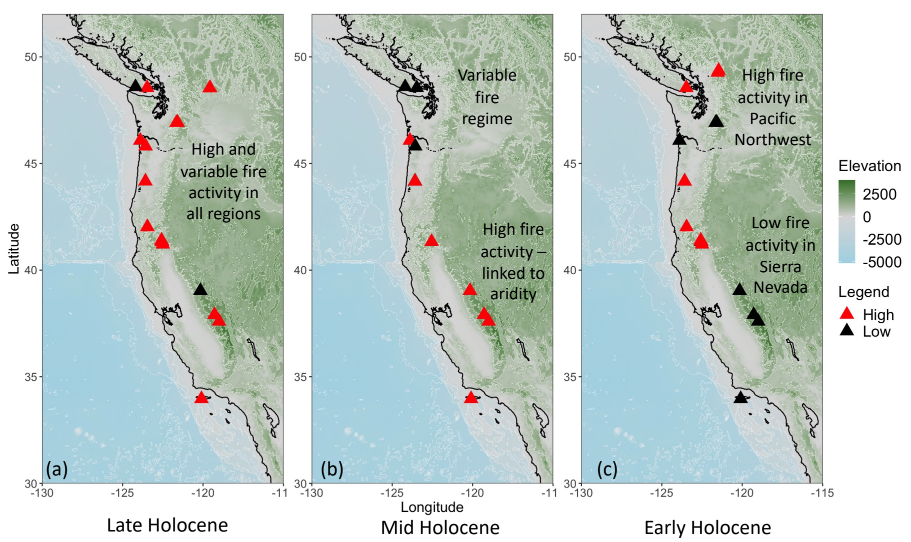

Figure 3: Fire activity as reconstructed by charcoal records through the early (11.7 - 8.2 ka, (c)), mid (8.2 - 4.2 ka, (b)), and late (4.2 - 0 ka, (a)) Holocene; red indicates high fire activity, green indicates low fire activity. Multiple metrics for fire activity are used; interpretations of original authors are preserved.

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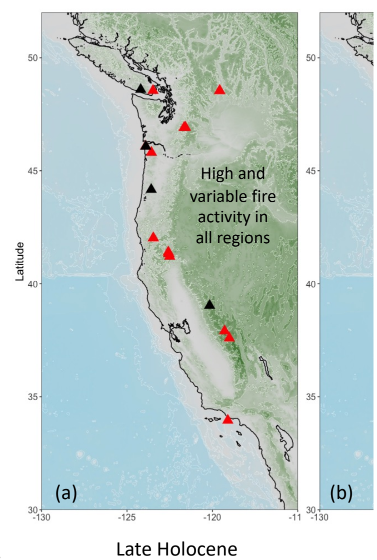

3.1.3 Marine conditions

Offshore of Southern Oregon through Central California, the early Holocene was characterized by warm SSTs resulting from subtropical waters transported by currents comparable to the modern-day Davidson Current (Figs. 1, 2) (Mix et al., 1999; Barron et al., 2003b; Barron and Bukry, 2007a). In this area, the oceanographic regime was characterized by overall warm conditions, moderate to high export productivity, ventilation of deeper waters, and the development of the oxygen minimum zone (Barron et al., 2003b; McGann, 2011; Addison et al., 2017). During this time, the California Current was weaker than present allowing a strong northward Davidson-like current (Barron and Bukry, 2007a). Though upwelling was weaker than modern in the early Holocene, records from offshore

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Oregon show moderate marine productivity and multiple records indicate an increase in coastal upwelling beginning at 9 ka (Gardner et al., 1988; Barron et al., 2003b; Addison et al., 2017; Barron et al., 2017). Offshore Southern California (in Santa Barbara Basin), high productivity and overall warm SSTs occurred during the early Holocene (Kennett et al., 2007; Fisler and Hendy, 2008). Records extending from Northern California south to the Baja California (Sur) peninsula indicate that in many locations, the onset of poorly oxygenated conditions in subsurface and intermediate waters occurred in the early Holocene, indicating changes in surface water productivity, intermediate water ventilation, or changes in the strength or source of North Pacific Intermediate Water relative to pre-Holocene conditions (Kennett and Ingram, 1995; Mix et al., 1999; Roark et al., 2003; Moffitt et al., 2014).

3.1.4 8.2 ka Event

The end of the early Holocene is marked by a large-scale Northern Hemisphere cooling event initiated by an abrupt drainage of glacial lakes Agassiz and Ojibway into the North Atlantic that weakened Atlantic Meridional Overturning Circulation (Barber et al., 1999; Thomas et al., 2007; Matero et al., 2017; Estrella-Martínez et al., 2019; Voarintsoa et al., 2019). Though a globally well described event, relatively few records (fewer than 10 records reviewed in this paper) from the Northeastern Pacific and Western United States record impacts of the 8.2 ka event. In central California (White Moon Cave), speleothem records show increased effective moisture at 8.2 ka which is attributed to intensification of the Pacific storm track that is synchronous on Eastern and Western sides of the Pacific (Oster et al., 2017). A lake record from Dry Lake in the SW (San Bernardino Mountains) shows a cooler, dryer and enhanced erosional period during the 8.2 ka event (Bird and Kirby, 2006). Marine records from off the coast of Northern California (near the California-Oregon border) show a cold event at 8.2 ka, but this is not noted in other nearby marine records (Barron et al., 2003b). We infer that the 8.2 ka event has a limited impact in this region, apart from the teleconnected impact of changes to the Pacific storm track impacting local hydroclimate.

3.1.5 Ecological responses to change

In the early Holocene, terrestrial plant communities generally indicate warm conditions, but show a process of succession out of glacial-associated ecosystems (Heusser, 1998). In the PNW, expansion of alder (*Alnus*) and ferns (*Pteridium*) began at the start of the Holocene, and Douglas fir (*Pseudotsuga menziessii*), western hemlock, grasses (*Poaceae*), and bracken fern (*Pteridium*) forests emerged by the end of the interval (Heusser, 1983; Pellatt et al., 2001). Southern Oregon cave records demonstrate taxonomic stability in plant communities through the early Holocene with communities dominated by pine (*Pinus*) and sagebrushes (*Amaranthaceae*, *Artemisia*) (Beck et al., 2018). In the Klamath mountains, pine and oak (*Quercus*) dominated the pollen record during the warm dry early Holocene; similarly, pine, oak, and juniper dominated the record in the Siskiyou Mountains (Mohr et al., 2000; Briles et al., 2005). In Northern California, pollen assemblages indicate warm winters, including an expansion of coastal redwoods, and declining alder (*Alnus*) forests (Barron et al., 2003b; Lyle et al., 2012). The increasing upwelling during the Holocene led to enhanced coastal fog and as a result, increasing dominance of coastal redwood (*Sequoia sempervirens*) (Gardner et al., 1988; Barron et al., 2003b; McGann, 2015; Addison et al., 2017). In Central California, increases in redwoods, oaks, *Nepenthes densiflora*, and *Asteraceae* indicate warmer and wetter

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conditions relative to glacial (McGann, 2015). In Southern California, the early Holocene maintained a forest ecosystem distinct from the modern with more pines and conifers than in the late Holocene and modern (Heusser, 1978).

In marine systems off the coast of Northern California (Farallon Escarpment and offshore of the Russian River) transitions in planktic and benthic fauna occurred during the early Holocene as environmental conditions transitioned out of the glacial (Gardner et al., 1988; McGann, 2011). From 11.75 to 10 ka marine sediment records show low abundance of the upwelling-associated diatoms *Thalassionema nitzschioides* and *Thalassionema longissimi,* and dominance of a cool, subpolar foraminiferal assemblage (Gardner et al., 1988). By 10.5-9 ka, carbonate productivity and total carbon (organic and carbonate-bound carbon) peaked and warm water morphotypes of foraminifera were dominant across two Northern California marine sediment records during this spike in productivity (Gardner et al., 1988; McGann, 2011). In coastal systems, kelp forests were present along the entire coastline from the SW to the PNW and increased in both size and range during the early Holocene (Erlandson et al., 2007; Graham et al., 2010). In deeper waters, the gradual development of the oxygen minimum zone in the early Holocene led to a transformation of seafloor ecosystems to a low oxygen-adapted assemblage (Cannariato and Kennett, 1999; Moffitt et al., 2014; McGann, 2015). Off the coast of Point Conception, seafloor fauna (e.g., benthic foraminifera) were variable in the early Holocene, with the establishment of the modern fauna by 9ka (McGann, 2015).

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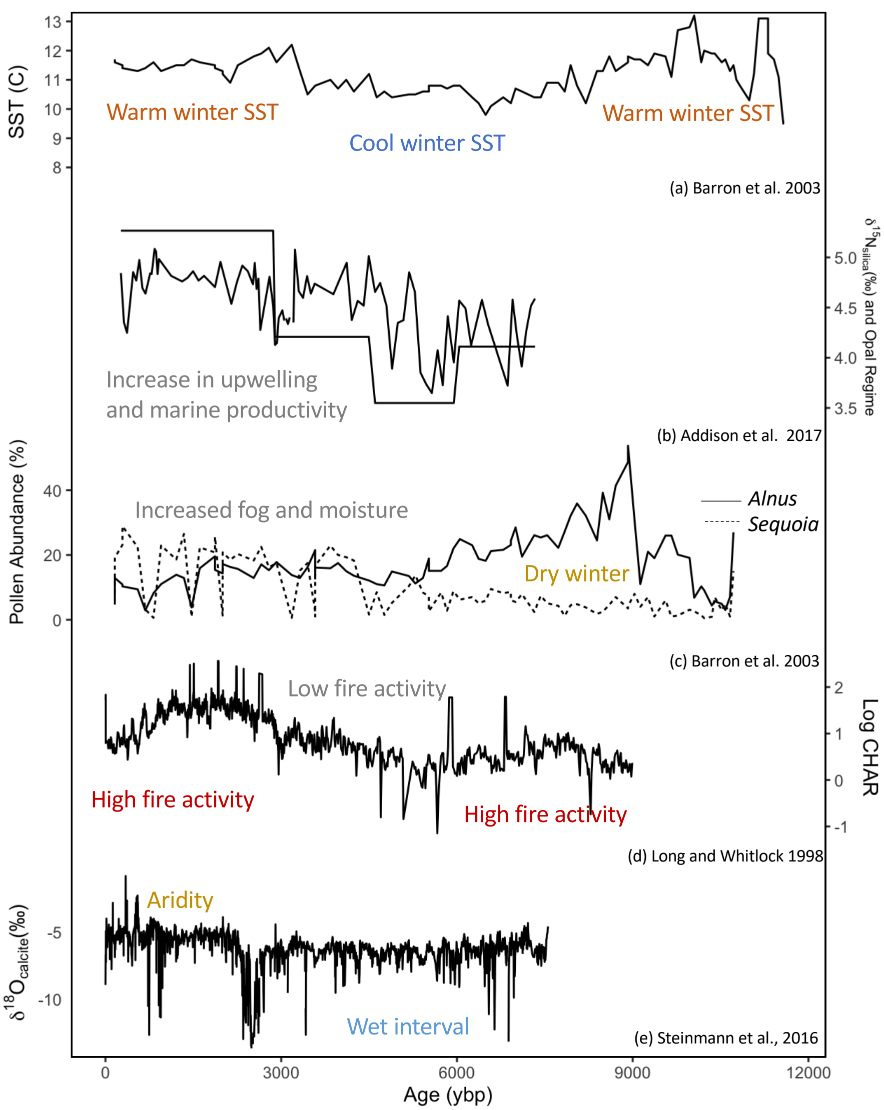

Figure 4: Representative datasets from the Pacific Northwest. Panels from top to bottom Alkenone sea surface temperature from core ODP1019 ((a), Barron et al. 2003). Bulk sediment δ15N and opal regime index from core

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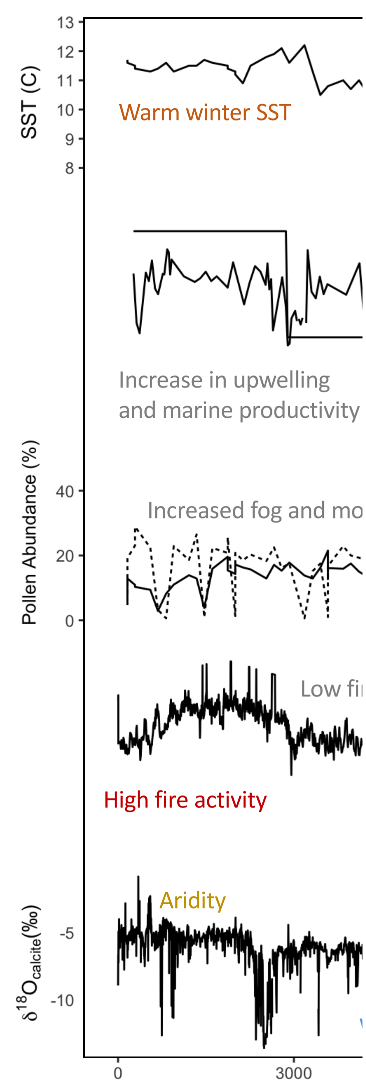
Evidence for human presence and settlement along the North American Pacific coast throughout the Holocene is well documented in Indigenous ethno-history and archaeological records, yet these records are geographically disparate (Erlandson et al., 2007; McKechnie, 2015; Edinborough et al., 2017). In the PNW, archeological evidence for human presence is documented prior to the start of the Holocene (Kaufman et al., 2016; Beck et al., 2018; Becerra-Valdivia and Higham, 2020). One hypothesis for human migration across this region suggests that the southward migration of people just prior to the Holocene was correlated with the availability of marine resources, specifically the expansion of kelp forests may have been linked to the expansion of available coastal resources and thus human migration (Erlandson et al., 2007). Abundant early Holocene archaeological records from the Channel Islands show evidence of a diversified maritime economy, consumption of shellfish, marine mammals, and fin fish, yet a relatively small population size relative to later in the Holocene (Erlandson et al., 2007, 2009; Braje et al., 2012). Additional localized studies of human responses to environmental and ecological variability on the Channel Islands capture snapshots of human-environment interaction in the early Holocene, but do not capture the full time interval and thus are not included here. ... [13]



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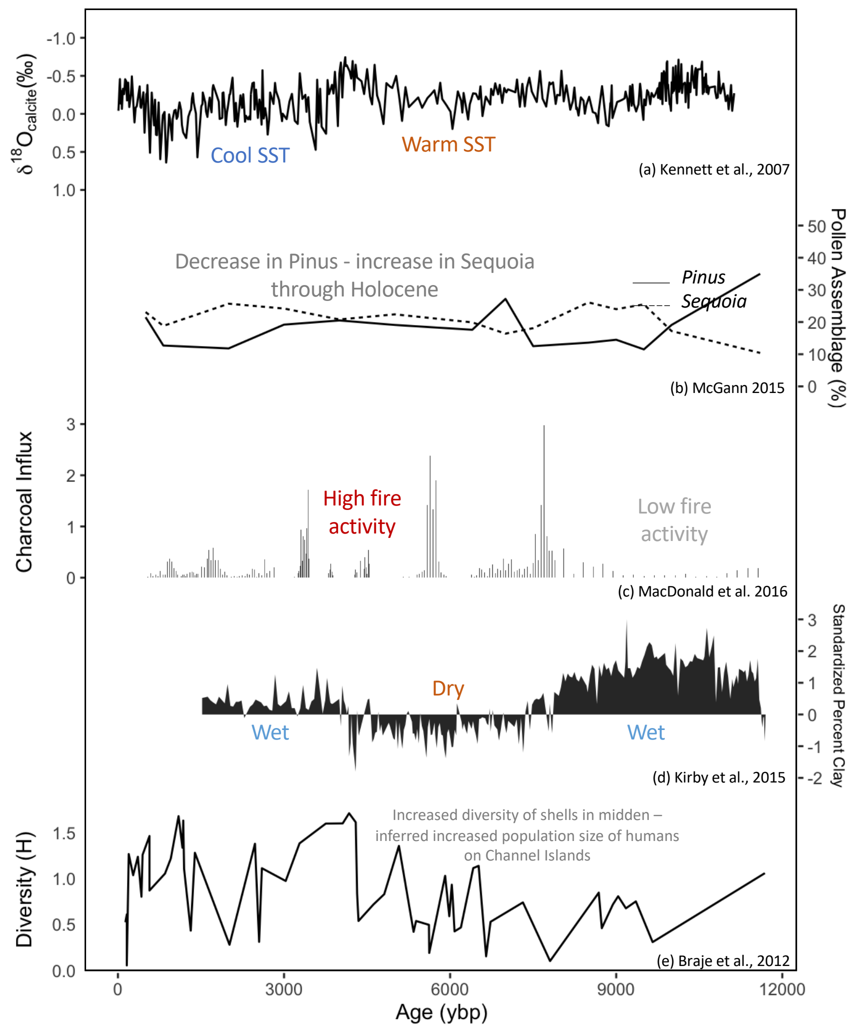
TN062-O550 ((b), Addison et al. 2017). Relative abundance of pollen: solid line is *Alnus* (alder) and dashed line is *Sequoia* (coastal redwood) from core ODP1019 ((c), Barron et al 2003). Log charcoal accumulation rate at Little Lake ((d), Long and Whitlock 1998). Lake sediment bulk calcite $\delta^{18}O$ from Cleland Lake, Washington ((e), Steinman et al. 2016).



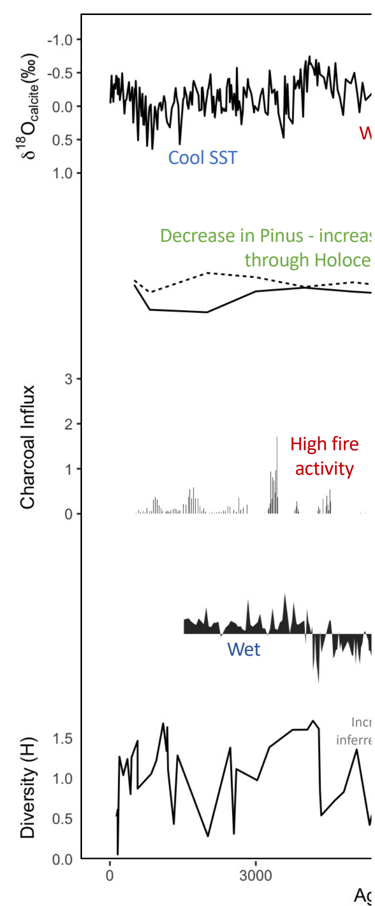


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Figure 5: Representative datasets from the Southwest. Oxygen isotope record from planktonic foraminifera G. bulloides from Santa Barbara Basin core ODP 893 ((a), Kennett et al. 2007). Pollen assemblage (%) of Pinus and

Sequoia from Central California marine sediment core ((b), McGann 2015). Charcoal influx to Kirman Lake in the Sierra Nevada mountains ((c), Macdonald et al., 2016). Standardized percent clay as a proxy for relative lake status for Silver Lake ((d), Kirby et al., 2015). Diversity of shells from shell midden sites on Channel Islands, grey lines are average 6-12 ka (0.69) and 0-6 ka (0.98) ((e), Braje et al. 2012).

3.2 Mid-Holocene (8.2-4.2 ka)

Thirty-three papers encompassing 58 sites met the criteria for spatiotemporal analysis in the mid Holocene and were coded and plotted in Figs. 2 and 3. Archives included lake sediments (36 sites), marine sediments (18 sites), and three others (terrestrial midden, dendrochronology, and geomorphology) (Appendix A, B).

3.2.1 Regional Synthesis and Marine-terrestrial Interactions

Spatial analysis of coded hydroclimate, temperature, and fire history indicates that the mid Holocene was characterized by a wet and cool PNW and a dry and warm SW relative to modern conditions (Fig. 2). Fire activity was high in the Sierra Nevada mountains and variable and transitional in the PNW (Fig. 3). Time series analyses supports these findings: offshore of the PNW, sea surface temperatures were cool, upwelling activity was moderate and terrestrial PNW winters were wet, fire activity was low and variable, and the overall hydroclimate was wet relative to the early Holocene (Fig. 4). In the SW, sea surface temperatures were warm, fire activity was high, hydroclimate was generally dry (Fig. 5).

Hydroclimate and temperature trends functionally reversed in the mid Holocene relative to the early Holocene, and the mid Holocene was a time of transition and variability in many records (Figs. 4, 5). In the PNW, SST transitions from warm to cool temperatures coeval with a shift from warm and dry to cool and wet terrestrial conditions. These coincident transitions suggest that the mechanisms for marine-terrestrial climate linkages persisted through the early and mid Holocene, namely a negative correlation between marine temperatures and terrestrial moisture/precipitation (Fig. 2). Yet nuanced changes occurring on shorter timescales may play an important role in determining hydroclimate of the region. A previously published review of hydroclimate records in Western North America (PNW, Northern Rockies and most of California) at 6 ka shows aridity in areas that are dominated by winter precipitation, including multi-decadal to centuries-long 'mega droughts' due to reduced winter water vapor transport (Hermann et al., 2018). However, our findings reveal that when evaluated at a broader timescale (8.2-4.2 ka), the mid Holocene PNW is cool and wet (Fig. 2). We posit two hypotheses to reconcile these differences. First, we propose that the coastal PNW was wet and cool whereas interior areas may have been dry (Hermann et al., 2018). Alternatively, in the PNW, this time period may have been characterized by seasonal hydroclimate extremes, multiple records identify high winter precipitation and warm summers with high evaporation (Marlon et al., 2006; Whitlock et al., 2008; Steinman et al., 2016), thus exhibiting both wet and dry phases on short timescales. As such, seasonally resolved proxies are particularly advantageous to fully capture climate in the past.

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The shift in SW terrestrial hydroclimate from wet in the early Holocene to dry in the mid Holocene (Fig. 2) may be due to several processes. A southward shift in NAM occurred between 9 and 6 ka, resulting in Mexico, rather than California, receiving a higher amount of precipitation (Barron et al., 2012; Metcalfe, 2015). Further, pluvial episodes driven by atmospheric river-type storms are rare in the mid Holocene, with the exception of one pluvial episode from 7.0-6.4 ka that is synchronous across several Southern California records (Kirby et al., 2012). Both phenomena (atmospheric rivers and NAM) are linked to changes in Eastern Tropical Pacific SSTs, rather than adjacent marine conditions in the California Current System (Fisler and Hendy, 2008; Kirby et al., 2012; Metcalfe, 2015). Thus, the lack of precipitation led to overall aridity in the Southwest in the mid Holocene and may not have been driven by local changes in SST of adjacent marine systems (Fig. 2).

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3.2.2 Terrestrial climate

Between 8.2 to 4.2 ka, terrestrial conditions were generally cool and wet in the PNW and warm and dry in the SW, while marine systems were generally cool (Fig. 2), yet the mid Holocene was a time of transition and variability in terrestrial climate. A transition to cooler, wetter conditions during the mid Holocene occurred across several sites in the PNW (Nederbragt and Thurow, 2001; Marlon et al., 2006; Long et al., 2011; Walsh et al., 2017). For example, lake sediment records from North-central Washington (Scanlon and Castor Lake) demonstrate the variability in mid Holocene hydroclimate including low lake stand at 7 ka and high lake stand at 5 ka (Steinman et al., 2019).

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Fire records from the PNW indicate a transition in hydroclimate and vegetation (Fig. 3). Fire activity increased on Vancouver Island, in the Oregon coast range, and in the Klamath and Siskiyou mountains through this interval (Brown and Hebda, 2002; Briles et al., 2005; Whitlock et al., 2008; Long et al., 2011). In Oregon and the Northern Rocky Mountains, the combination of cooler, wetter conditions increased fuels and hot, dry summers led to more severe and larger fires relative to the early Holocene (Marlon et al., 2006; Whitlock et al., 2008). In coastal areas, increases in fire activity were linked to increased summer drought over time (Briles et al., 2005; Whitlock et al., 2008). Yet, in other nearby regions, fire activity was variable: on Mount Rainier, fire activity increased from 8 to 6.6 ka and decreased from 6.6 to 4 ka (Walsh et al., 2017), in Northern Washington, fire frequency decreased at the start of the mid Holocene with the development of cooler, wetter summers, yet increased again at 4.5 ka (Gavin et al., 2007).

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In the mid Holocene, the Sierra Nevada was dry relative to the early and late Holocene (Lindstrom, 1990; Benson et al., 2002; Hallett and Anderson, 2010; MacDonald et al., 2016). A northerly shift in the Intertropical Convergence Zone (ITCZ) in the mid Holocene led to reduced winter precipitation (including snowpack), which led to drier summers and increased fire frequency relative to early Holocene (Hallett and Anderson, 2010). Previous work investigating paired marine-terrestrial records from the Sierra Nevada (Kirman Lake) and Eastern Tropical Pacific highlight the connection between SST cooling (in the Eastern Tropical Pacific) and increased aridity (MacDonald et al., 2016). The marine-terrestrial link driving precipitation patterns was strongest throughout the mid Holocene, particularly from ~ 8 to 3 ka (MacDonald et al., 2016). The combination of aridity and increased biomass, led to

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control of fire by climate in the Sierra Nevada Mountains (Fig. 3) (Hallett and Anderson, 2010). Increased fire activity was synchronous with warming in the Eastern Sierra beginning at 5 ka (Hallett and Anderson, 2010). Additionally, high fire frequency in Lake Tahoe Basin in the mid Holocene (peak at 6.5 ka) was synchronous with high fire frequency in Northern California and Oregon and is attributed to warm dry climate in the Lake Tahoe Basin at this time (Beaty and Taylor, 2009).

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In the SW, the mid Holocene is characterized by generalized arid conditions. Lake records from the Mojave Desert (Silver Lake, California) indicate a distinct dry period from ~4.2-7.8ka (Kirby et al., 2015). Vegetation traces (macrofossils and pollen) from packrat middens in the Mojave Desert indicate increased aridity compared to modern with a particularly arid period from 6.8 to 5.0 ka (Spaulding, 1991). Pollen records from marine sediments offshore Central California identify a “mid Holocene dry period” from 8-6.4 ka (McGann, 2015). On the Channel Islands, hydroclimate conditions shifted from dry to wet at ~6.9 ka, coincident with an increase in fire activity (Anderson et al., 2010). Despite aridity in the desert SW, marine sediment records from Santa Barbara Basin show extreme precipitation events with increased flooding occurring between 7.3-6.6 ka and 5.5-3.0 ka (Du et al., 2018). Finally, lake sediment records from Lake Elsinore show multiple pluvial episodes and lower relative evaporation in the mid Holocene (Kirby et al., 2019).

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3.2.3 Marine conditions

In the mid Holocene, records indicate that off the coast of Oregon and California, sea surface temperatures were cool, while the Santa Barbara Basin was warm (Fig. 2) (Mix et al., 1999; Fisler and Hendy, 2008; Barron and Anderson, 2011; Barron et al., 2019). Generally, the North Pacific was experiencing negative PDO or La Niña-like conditions, with a weak/west-shifted winter Aleutian Low and strong/northward summer North Pacific High (Barron and Anderson, 2011). A dominant feature of mid Holocene Eastern North Pacific oceanography was an increase in coastal upwelling. Marine sediment records from offshore of Northern California (40.9°N, 124.6°W) suggests a two-fold increase in upwelling and coastal fog beginning at 5.4 ka and a decrease in SST at 5 ka (Barron et al., 2003b; Addison et al., 2017). Coastal upwelling off California was enhanced during the summer and fall but suppressed during the spring as a result of a strong North Pacific High driven by orbital forcing (Diffenbaugh et al., 2003; Diffenbaugh and Ashfaq, 2007; Barron and Anderson, 2011). The increase in upwelling is due to a strengthening of the California Current and is documented as far south as Point Conception but is not documented in Santa Barbara Basin (Barron and Bukry, 2007a). Despite a cooling trend seen in multiple records from off the coast of Oregon and Northern California, records from offshore Central California (Farallon Escarpment) show a slight warming trend through time, but at a decreased rate relative to the early Holocene, a decrease in carbonate productivity and total carbon export, relative to the early Holocene and continued low oxygen at depth (McGann, 2011). Warming conditions through the mid Holocene observed offshore Central California conflict with studies from further north showing a cooling trend, but compare favorably with records of warming from farther south (McGann, 2011).

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Sea surface temperatures during the mid Holocene were generally warm in Santa Barbara Basin and periodically punctuated by short cool periods at 8.2, 7.6, 5.0, and, 4.2 ka (Fisler and Hendy, 2008) and an interval of cold, high productivity from 5.8-6.3 ka (Kennett et al., 2007). Additional evidence from Santa Barbara Basin shows that the mid Holocene was warmer and more variable than the early Holocene which may have been due to increased decadal scale variability (Friddell et al., 2003; Fisler and Hendy, 2008). SSTs in Santa Barbara Basin initially rose by 3-4^{O}C followed by an abrupt increase of > 2^{O}C in less than 40 years at 7.5 ka (Friddell et al., 2003). Nearshore conditions on the Channel Islands were variable with an interval of cooler than modern SST during 6.3-5.3 ka preceded and followed by intervals of warmer than modern SSTs (Glassow et al., 2012). Circulation and ventilation of relatively young North Pacific Intermediate Water into Santa Barbara Basin was stable through the mid Holocene (Roark et al., 2003). When compared to global records, SST trends from the North Pacific (generalized warming in the North Pacific from 7 ka to present) are inversely correlated with the SST in the North Atlantic (Kim et al., 2004).

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3.2.4 Ecological responses to climate change

In the PNW, ecosystems responded to increases in moisture in the mid Holocene. The establishment of rainforest taxa in Northern Cascades forest occurred during wet conditions and a variable fire regime in the mid Holocene (Hallett et al., 2003). Lake sediment records from near Mount Rainier show a shift to cooler, wetter conditions and a transition to mesic forests, indicating an increase in effective moisture (Walsh et al., 2017). In British Columbia, mild winters led to an increase in oaks, hemlock, and grasses during this interval (Pellatt et al., 2001). In Northern Washington, lodgepole pine-dominated forest transitioned to a forest with abundant western white pines and Douglas-fir trees (Gavin et al., 2003, 2007). Near the end of the mid Holocene (~4.5 ka), fire frequency once again increased, despite the development of the modern western hemlock and redcedar forest that typically indicate cooler, wetter climate and mild summers (Gavin et al., 2003, 2007). In contrast, one record from the Saanich Inlet (British Columbia) shows that oak and Douglas fir increased during this time (Heusser, 1983, p.19). In Northern California, terrestrial systems shifted from dominance by pine to an increased presence of *Sequoia* coastal redwoods, indicating an increase in coastal fog (Barron et al., 2017)

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Farther south, pollen records from Santa Barbara Basin show numerous changes in terrestrial ecosystems during this interval, including a decrease in *Pinus* and conifers; a general decrease in all trees leads to a temporary peak in herbaceous plants (*Asteraceae*) (at 5 ka) followed by a transition to a chaparral, coastal sage scrub dominated ecosystem and an increase in oaks (Heusser, 1978, 1998). A brief period of dry conditions from 8-6.4 ka led to an increase in herbs (*Asteraceae*) and pines with a coincident decrease in oaks and tanoak (*N. densiflora*) in Central California (McGann, 2015). In Southern California, salt marsh fauna peaks at 6 ka and riparian community plants generally decrease through the Holocene, indicating changes that are linked to drying trends in the SW in the mid Holocene (Heusser, 1978).

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In marine systems offshore Northern California, the increase in upwelling through the mid Holocene impacted both planktic and benthic ecosystems. For example, *T. nitzschioides* dominate the diatom/silicoflagellate assemblage,

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which indicates a shallow thermocline, high productivity within the California Current, and increased upwelling (Gardner et al., 1988; Barron et al., 2017). In Santa Barbara Basin, an increase in warm water planktics and a *Neogloboquadrina incompta* dominated assemblage indicates a stable, warm, and stratified water column (Fisler and Hendy, 2008). The establishment of the modern low oxygen zone continues in this interval, with important implications for seafloor ecosystems including the development of a novel community between 7-5 ka, associated with sulfide-rich, anoxic chemosynthetic seafloor ecosystems in Santa Barbara Basin (Moffitt et al., 2015).

3.3 Late Holocene (4.2 ka-present)

Thirty-four papers encompassing 57 sites met the criteria for spatiotemporal analysis in the Late Holocene and were coded and plotted in Figs. 2 and 3. Archives included lake sediments (41 sites), marine sediments (14 sites), and two others (dendrochronology and lichenometry) (Appendix A, B).

3.3.1 Regional Synthesis and Marine-terrestrial Interactions

Analysis of coded hydroclimate, temperature, and fire history shows that the late Holocene was characterized by a wet PNW and wet and variable SW relative to the early and mid Holocene (Fig. 2). Marine temperatures were warm while terrestrial temperatures were cool and variable across both regions (Fig. 2). Fire activity was high and varied across both regions (Fig. 3). In the PNW, SSTs were warm, upwelling activity was high, coastal fog and moisture increased, fire activity was high, and the overall hydroclimate was variable (Fig. 4). In the SW, SSTs were variable, fire activity was high and variable, hydroclimate was generally wet, and human-environment interactions increased as populations in this region grew (Fig. 5). Although for some records, temporal resolution increases towards the present, increased variability relative to the early and mid Holocene is persistent across multiple proxy types and temporal scale of record.

In comparison to the early and mid Holocene, the late Holocene shows greater variability in hydroclimate, temperature, and fire history both within and among records. Marine-terrestrial linkages in the late Holocene also show high variability and an increase in dominance of decadal to annual phenomena (Fig. 2). Coastal upwelling and precipitation are linked; intervals of stronger upwelling are linked to wetter conditions, and reduced upwelling is tied to aridity. In the late Holocene, upwelling and precipitation increased in magnitude and variability (Ingram, 1998; Addison et al., 2017). Changes in PDO exerted control on terrestrial hydroclimate; a period of negative PDO at 1.1-0.7 ka, with cooler North Pacific SST and higher upwelling, is coeval with prolonged drought in Western North America (MacDonald and Case, 2005). Southwestern droughts in late Holocene co-occur with cooler than average SST in Santa Barbara Basin. Similarly, nearshore records from Central California show high SST variability coincident with drought during the interval from 0.7-0.5 ka (Fig. 2) (Jones and Kennett, 1999; Barron et al., 2010). Late Holocene changes to PDO and ENSO progressed northward, with enhanced ENSO/PDO effects beginning at 4 ka in Southern California and 3.4 ka in Northern California (Barron and Anderson, 2011; Arellano-Torres et al., 2019). Further, the late Holocene exhibited alternating wet and dry cycles that may be linked oscillation of precipitation sources between tropical and North Pacific-sourced water (Feakins et al., 2014; Kirby et al., 2014).

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Similar to the early Holocene, much of the evidence of human activity and interaction with the environment during the mid Holocene is centered at the Channel Islands due to exceptional preservation of shell middens. In the mid Holocene, human population on the Channel Islands increased resulting in enhanced marine harvesting pressure after 6 ka, as indicated by an increase in shell midden diversity (Fig. 5) (Braje et al., 2012). Increased reliance on marine resources for food may have also been due to severe arid conditions (6.3 – 5.0 ka) that reduced terrestrial resources and availability of drinking water. This environmental shift facilitated an increase in fisheries as well as coastal shellfish harvesting (Kennett and Kennett, 2000; Kennett et al., 2007). Further, evidence of exchange between people on the Channel Islands with people in the Great Basin increased during this time and by the mid Holocene, semi-permanent villages were established on the Channel Islands (Kennett and Kennett, 2000; Kennett et al., 2007). As in the early Holocene, records of human community occupation and interactions with the environment are widespread in the mid Holocene, yet most represent snapshots in time and thus, are not included in the review.

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High variability within and between records (Figs. 2, 3) is a dominant trend across both the PNW and SW in the late Holocene.

3.3.2 Terrestrial climate

Hydroclimate varies spatially and temporally through the late Holocene with the highest and most variable fire activity relative to the early or mid Holocene (Figs. 2, 3). In the PNW, multiple records show a cool and wet climate, with pronounced wet periods (Mohr et al., 2000; Nederbragt and Thurow, 2001; Reyes and Clague, 2004; Briles et al., 2005; Malamud-Roam et al., 2006). However, trends of increasing aridity towards the present and intervals of drought are also documented (Steinman et al., 2016, 2019; Walsh et al., 2017; Shuman et al., 2018). In the San Francisco Bay region, hydroclimate was also variable, with intervals of aridity documented at 3.0-2.5 ka and 1.7-0.73 ka (Byrne et al., 2001; McGann, 2008)**.**

In the PNW, fire activity was high and variable in the late Holocene, despite intra-regional differences in hydroclimate and vegetation. Fire activity on Mount Rainier was highest in the past 4 ka relative to the rest of the Holocene, and conditions became increasingly dry throughout the late Holocene (Steinman et al., 2016, 2019; Walsh et al., 2017). Vegetation records show a surprising dominance of flora associated with cooler, wetter conditions despite the highest number of fire episodes and shortest fire return intervals during this period (Walsh et al., 2017). In North Cascades National Park in Northern Washington, high variability in fire frequency and lower synchrony among forest fire events occurred even within the same forest; a decrease in fire frequency from 3.5-2.4 ka corresponded with a cool, humid climate, while high fire frequency from 2.4-1.3 ka suggests more frequent prolonged summer drought (Hallett et al., 2003; Gavin et al., 2007). In this region, the present-day fire regime was established by 1.3 ka (Hallett et al., 2003; Gavin et al., 2007). In the Oregon coast range, changes in vegetation led to a decrease in fire activity beginning at 2.75 ka (Gavin et al., 2007). The increase in fire frequency and variability in the PNW may have been due to changes in forest composition, changes in temperature and precipitation, increased ENSO frequency leading to increased summer drought, or due to increases in human population and thus, human-induced fire (Walsh et al., 2017). Despite an increase in precipitation and a decrease in temperature, charcoal accumulation rates from the Oregon Coast Range and Northern California (Klamath-Siskiyou Mountains) suggest that fires became larger and more severe in this region, with high variability during the latter part of the Holocene, likely due to increases in woody vegetation to fuel forest fires (Marlon et al., 2006, 2013; Whitlock et al., 2008).

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Spatial and temporal variability in climate and fire history occurred across the Sierra Nevada mountains (Figs. 2, 3). In the Eastern Sierras, hydroclimate varied throughout the late Holocene; Mono Lake water level fluctuated through this time (3.7 ka- highest in last 7 ka, 1.8 ka low stand, multiple rapid fluctuations in last 1.2 ka), Owens Lake exhibited three intervals of wetter and cooler climate at 3.6 ka, 0.8 ka, and 0.35 ka (Bacon et al., 2018), and increased precipitation through the late Holocene at Pyramid Lake led to rising lake levels (Benson et al., 2002). Strong fire synchrony occurred in the Sierra Nevada since 2.5 ka which is linked to periods of drought (Hallett and Anderson, 2010). In the Lake Tahoe Basin, changes in vegetation from open forest to mesic forest drive a decline in

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fire frequency from the Mid-Holocene to modern, with a particularly low fire interval from 4.0 to 3.5 ka (Beaty and Taylor, 2009). Records from the Sierra Nevada show glacial advancement linked to cooling beginning 3.9 ka (Konrad and Clark, 1998).

In Central and Southern California, multiple wet and dry phases occurred through the late Holocene (Fig. 2) (Feakins et al., 2014; Kirby et al., 2014). In coastal Central California, marine records show that winter precipitation increased in the late Holocene (McGann, 2011). Several lake records from Southern California (Lower Bear Lake, Lake Elsinore, Tulare Lake, and Owens Lake) all indicate a return to wetter conditions beginning between 4.0-3.35 ka (Kirby et al., 2010, 2014). Records from coastal lagoons on Santa Rosa Island and in Southern California show multi-centennial fluctuations between wet and dry conditions (Davis, 1992; Anderson and Byrd, 1998; Cole and Wahl, 2000; Anderson et al., 2010). Similarly, records from Southern California indicate multiple wet and dry intervals that be linked to alternation of precipitation source water between more tropical and more North Pacific source water (Dingemans et al., 2014; Feakins et al., 2014; Kirby et al., 2014, 2019). A dry period between 2.5 to 2.0 ka is synchronous across multiple records from Southern California (Dingemans et al., 2014; Kirby et al., 2014, 2019; Platzman and Lund, 2019), and persistent droughts and elevated aridity are dominant across the Western US from 1.1 to 0.7 ka (Cook, 2004). In the Mojave Desert (Silver Lake, California) conditions returned to ephemeral, wet lake conditions beginning at 3.8 ka after a mid Holocene period of aridity (Fig. 5) (Kirby et al., 2015). Yet other records show increased aridity in the Mojave Desert compared to the mid Holocene (Spaulding, 1991).

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Across the study region, extreme events (rainfall, drought, flooding) become a dominant feature across multiple records over the past 2 ka (Cook, 2004; Malamud-Roam et al., 2006; Rasmussen et al., 2006; Kirby et al., 2015). A pronounced megadrought occurred in Western North America from 1.1 - 0.7 ka, that was previously linked to cool SST over the Eastern Tropical North Pacific (Cook, 2004). More variable conditions have been attributed to changes in insolation as well as shorter term processes including ENSO and PDO (Cook, 2004; Kirby et al., 2007, 2010; Barron and Anderson, 2011). Gradual decreases in summer insolation and increases in winter insolation contribute to maximum drying in the late Holocene relative to the early Holocene (Kirby et al., 2007). Enhanced PDO and ENSO variability in the last 4 ka contribute to increased terrestrial hydroclimate and temperature variability (Kirby et al., 2010; Barron and Anderson, 2011).

Human control of the fire regime led to land use and ecosystem changes across the Western US during this interval. In Washington, an increase in human artifacts in the subalpine zone beginning at 3.6 ka, combined with a change in climate and thus ranges of game species, provide some evidence for increased presence of people in subalpine terrain and potentially an increase in human-caused fire (Walsh et al., 2017). Across California, late Holocene increases in chaparral, grassland, and sage scrub ecosystems were reinforced by intentional burning and prescribed burning played an important role in structuring ecosystems (Heusser, 1978; Anderson et al., 2010, 2013; Cowart and Byrne, 2013; Crawford et al., 2015; Lightfoot and Cuthrell, 2015; Klimaszewski-Patterson et al., 2021).

3.3.3 Marine Conditions

In the late Holocene, SST increased off the coast of Oregon and California and SST decreased in the Santa Barbara Basin relative to the mid Holocene (Figs. 2, 4, 5) (Barron et al., 2003a; Kennett et al., 2007; Barron and Anderson, 2011). Late Holocene marine conditions show increased variability in SST, intensification of the California Current, and increased upwelling relative to the mid Holocene (Fig. 3) (Barron and Bukry, 2007a; Barron and Anderson, 2011). While global records suggest a shift in climate characteristics at 4.2 ka, several California and Oregon records experience a delayed mid to late Holocene shift (Barron and Bukry, 2007a; Addison et al., 2017; Barron et al., 2017). Modern seasonality within the California Current (strong spring-summer upwelling with cool SSTs, and relaxation with warmer SSTs during fall) was established between 3.5 and 3.2 ka (Barron and Bukry, 2007a). Diatom-based productivity increased at 2.9 ka offshore of Northern California and changes in relative abundance of diatom and pollen species suggest significantly increased upwelling and productivity at this time (Addison et al., 2017). Additional evidence from offshore of Northern California shows cooler SSTs occurred from ~3.6 and 2.8 ka, accompanied by increased precipitation, an abrupt warming of winter SSTs at 2.8ka, and an intensification of spring upwelling beginning 2.6 ka (Barron et al., 2017). Since 2.6 ka, PDO-like warm-cool oscillations have dominated the SST regime (Barron et al., 2017).

Further south, off the coast of Santa Cruz, California, upwelling and productivity increased steadily through the late Holocene (Barron et al., 2019). Additional records from offshore Central California indicate the late Holocene marked the onset of warm modern offshore conditions with high productivity (total and organic carbon export) relative to the mid and early Holocene (McGann, 2011; Barron et al., 2019). Marine oxygenation off the coast of Central California declined through the late Holocene (McGann, 2011). Nearshore records from Central California show that SST was 1^{O}C cooler than modern from 2-0.7 ka (Jones and Kennett, 1999).

In Southern California, late Holocene SST cooling with high SST variability (in Santa Barbara Basin) began at ~4 ka (Fig. 5) (Kennett et al., 2007; Fisler and Hendy, 2008). High amplitude changes in salinity due to variability of input of freshwater into the basin are documented within Santa Barbara Basin (Kennett et al., 2007). Brief cold events occurred in Santa Barbara Basin at ~4.2-3.8, 1.5-1.2, and 0.8-0.3 ka and correspond to glacial advances in the Sierras (Fisler and Hendy, 2008). Variable oceanographic conditions in the late Holocene may be due to increasing ENSO variability in the tropical Pacific (Barron and Bukry, 2007b). Intensification of the California Current and increased East-West seasonal gradients (driving increased winds that enhance upwelling) are documented offshore Northern California (Barron et al., 2003b; Barron and Bukry, 2007b, b) and across the Southern California Borderlands. Nearshore records from Santa Cruz Island show persistently cold SSTs and persistent upwelling on the western coast of Santa Cruz Island in late Holocene compared to a wider range of nearshore conditions on the south side of the island (Flores, 2017). In deeper waters, a drastic change in the age of North Pacific Intermediate Water in Santa Barbara Basin (shift to older water and lower bioturbation) at 2 ka with a subsequent stable age of water entering from 2 ka to present suggests changes in the North Pacific Intermediate Water circulation pattern (Roark et al., 2003). This shift is concurrent with a decrease in Greenland temperature and increase in ice accumulation rate

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suggesting trends in Santa Barbara Basin relate to larger atmospheric circulation patterns (Roark et al., 2003). Further, the oxygen minimum zone persists in intermediate waters off the coast of Southern California, but is reduced in intensity relative to the mid Holocene (Balestra et al., 2018; Wang et al., 2020). Importantly, most records from this region are within the Southern California Bight and shoreward of the California Current. Further work is needed to understand the southern portion of the California Current and the impact of ENSO and PDO through this time interval (Arellano-Torres et al., 2019).

3.3.4 Ecological responses to change

Forested ecosystems in the PNW and Northern California transitioned to modern temperate, cool, wet, highly fire-adapted systems with increased fir and pine (Heusser, 1983; Mohr et al., 2000; Pellatt et al., 2001; Barron et al., 2003b, 2019; Briles et al., 2005; Anderson et al., 2013) while SW systems became increasingly dominated by chaparral and sage scrub ecosystems (particularly since ~2.5 ka) (Heusser, 1978; Anderson and Byrd, 1998; Cole and Wahl, 2000; Anderson et al., 2010; Dingemans et al., 2014). In the Siskiyou mountains, a shift in hydroclimate to wet, cool conditions at 2.1 ka led to the development of the modern forest dominated by firs (*Abies*) and cypress (*Pseudotsuga*) and moderated by a modern fire regime (Briles et al., 2005). In parallel with increases in hydroclimate and temperature variability, in Northern California the amplitude and frequency of changes between pine and alder intensified in the late Holocene and coastal scrub expanded (Fig. 4) (Barron et al., 2003b; Anderson et al., 2013). In Central California, changes to forest assemblages occurred gradually through time, trending towards decreased dominance of pine in the modern (Fig. 5) (McGann, 2015; Barron et al., 2019). Finally, in Southern California, ecological change varied locally, with transitions in pollen regimes indicating increased moisture occurring around 2 ka in multiple records (Anderson and Byrd, 1998; Cole and Wahl, 2000; Dingemans et al., 2014).

Marine ecosystems reflect the establishment of modern levels of coastal upwelling and productivity in the late Holocene (Addison et al., 2017; Barron et al., 2017). Offshore Northern California, the gyre-associated diatom species *Pseudoeunntia doliolus* increased threefold indicating the onset of modern oceanographic conditions in this region (Barron et al., 2003b). Offshore Central California, upwelling evolved gradually over time and the upwelling-indicator diatom species *T. nitzschioides* gradually increased through this interval (Barron et al., 2019). In Santa Barbara Basin, late Holocene cooling led to an increase in the abundance of cold-associated (*N. pachyderma*) and upwelling-associated (*Globigerina quinqueloba)* planktic foraminifera (Fisler and Hendy, 2008). Oxygen deficient zones were well established by the late Holocene and persisted throughout the interval, structuring seafloor and pelagic ecosystems (Ohkushi et al., 2013; Moffitt et al., 2014, 2015; Palmer et al., 2022). As human populations increased throughout the late Holocene, human harvesting pressure on marine ecosystems increased, including an expansion of consumption of finfish and pinnipeds and a diversification of taxa in middens (Erlandson et al., 2009; Rick, 2011; Braje et al., 2012).

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3.3.5 Human-environment interactions¶
Human-environment interactions are well documented in the late Holocene relative to previous time intervals both due to the increase in human population and the preservation bias in archaeological records and recency bias in oral histories. In multiple locations, a late Holocene drought was a destabilizing factor for societies. In the SW, a 26-year-long drought that occurred 0.8 ka is linked to social destabilization and abandonment of well-established Ancestral Puebloan villages (deMenocal, 2001). In northern California, the abandonment of shell mounds following four millennia of occupation (5 to ~1.2 ka) co-occurs with drought in this region revealing potential societal impacts of drought (Ingram, 1998). Human control of the fire regime led to land use and ecosystem changes across the Western US during this interval. In Washington, an increase in human artifacts in the subalpine zone beginning at 3.6 ka, combined with a change in climate and thus ranges of game species, provide some evidence for increased presence of people in subalpine terrain and potentially an increase in human-caused fire (Walsh et al., 2017). Across California, late Holocene increases in chaparral, grassland, and sage scrub ecosystems were reinforced by intentional burning and prescribed burning played an important role in structuring ecosystems (Heusser, 1978; Anderson et al., 2010, 2013; Cowart and Byrne, 2013; Lightfoot and Cuthrell, 2015; Klimaszewski-Patterson et al., 2021).¶
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Human interactions with the marine environment were critical factors in structuring societies, and conversely, changes in ocean conditions impacted users of coastal resources. In Central California, marine resources including shellfish and fish, were harvested throughout the late Holocene (Jones and Kennett, 1999). Occurrence of drought from 0.5-0.3 ka led to an increase in fish bone presence in middens, indicating enhanced use of fisheries as a resource during a time of drought, despite a documented decrease in marine productivity and high-amplitude marine seasonality coeval with the interval of drought (Jones and Kennett, 1999). Indigenous coastal populations were highly reliant on marine resources (largely *Mytilus californianus*) and even inland occupants of Central California traveled to the coast seasonally to harvest mussels (Jones et al., 2008). On the Channel Islands, human population and sociopolitical complexity increased in the late Holocene (Rick, 2011; Braje et al., 2012). As populations increased, diet breadth expanded and human harvesting pressure on marine ... [14]

3.4 Medieval Climate Anomaly and Little Ice Age

Specific investigation of the Medieval Climate Anomaly (MCA) and the Little Ice Age (LIA) are included in some of the papers reviewed here. Generally, the MCA was an anomalously warm event that is linked to pronounced drought conditions throughout the Western United States. Alternatively, the LIA was a brief period of cooling predominantly identified in Northern Hemisphere records (Cook, 2004). Evidence of dry conditions during the MCA is indicated in a breadth of records: from Mono Lake and Owens Lake in the Eastern Sierra Nevada (Stine, 1990; Bacon et al., 2018), freshwater input into San Francisco Bay, Abbot Lake and Zaca Lake in coastal Central California (Dingemans et al., 2014; Hiner et al., 2016; Platzman and Lund, 2019), Central California pollen history (McGann, 2015), flood events in Santa Barbara Basin (Schimmelmann et al., 2013; Du et al., 2018), tree stump dating in the Sierra Nevada (Stine, 1994), and a synthesis of tree-ring records (Cook, 2004). Dry conditions were likely caused by anomalously warm terrestrial temperatures and are linked to cool SSTs over the Eastern Tropical Pacific (Cook, 2004) and in the adjacent Santa Barbara Basin (Kennett and Kennett, 2000; Fisler and Hendy, 2008; Barron et al., 2010; Asmerom et al., 2013). Fire activity increased in the MCA in the Eastern Sierra and Lake Tahoe Basin, which may be due to warm summer enhanced growth and decreased snowpack, but in Western North America more broadly, fire activity was reduced during the MCA and LIA relative to the past 3 ka (Beaty and Taylor, 2009; Hallett and Anderson, 2010). The LIA was characterized by warm SSTs in Southern California, wetter conditions in the Sierra Nevada and Southern California, and minimum fire frequency in Western North America (Reyes and Clague, 2004; Whitlock et al., 2008; Barron et al., 2010; Feakins et al., 2014; Kirby et al., 2019).

3.5 Era of Colonization

Humans have been interacting with the environment in Western North America throughout the entirety of the Holocene. Indigenous peoples exerted control of fire and interacted with, managed, and cultivated marine and terrestrial plants and animals throughout the Holocene (e.g., Minnis, 2004; Braje et al., 2012; McKechnie, 2015; Taylor et al., 2016; Edinborough et al., 2017; Beck et al., 2018; Platzman and Lund, 2019; Ellis et al., 2021; Klimaszewski-Patterson et al., 2021). As populations of Indigenous North Americans increased throughout the Holocene, human-environment interactions including marine and terrestrial resource use and prescribed fire increased (Heusser, 1978; Anderson et al., 2010, 2013; Cowart and Byrne, 2013; Crawford et al., 2015; Lightfoot and Cuthrell, 2015; Klimaszewski-Patterson et al., 2021). Additionally, climate changes impacted communities throughout the Holocene; intervals of climate stability are correlated with consistent resource use, while intervals of climate instability and drought are related to migration, changing resource use, and conflict (Grenda and Benitez, 1997; Ingram, 1998; Jones and Kennett, 1999; Kennett and Kennett, 2000; deMenocal, 2001; Kennett et al., 2007). While human-environment interactions and Indigenous land stewardship were environmental and ecological drivers throughout the Holocene, the onset of colonization, genocide of Indigenous people, land-use change, urbanization, industrialization, and anthropogenic climate change are evident in many records examined here and represent an unprecedented environmental regime in multiple records (Ellis et al., 2021).

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Impacts of land-use change and human control of fire at the time of colonization precede changes due to urbanization and anthropogenic climate change (Crawford et al., 2015; Waters et al., 2016). Changes in the view and management of fire shaped the landscape and climate in the last several hundred years, beginning with a measurable increase in fire (relative to Indigenous prescribed burning) following settler colonization and a subsequent measurable decrease in fire in the last 100 years due to fire suppression (Gavin et al., 2007; Anderson et al., 2010, 2013; Dingemans et al., 2014; Crawford et al., 2015; Taylor et al., 2016; Walsh et al., 2017; Platzman and Lund, 2019). Prior to 1860, fire activity in the Sierra Nevada was positively correlated with temperature, but in the last 150 years (after 1860 CE) fires are linked to human activity and socio-ecological change, rather than temperature or moisture (Anderson et al., 2013; Taylor et al., 2016). In the Sierra Nevada the highest fire activity in the last 400 years occurred following Spanish colonialism and the lowest fire activity occurred with the onset of fire suppression beginning in 1904 CE (Taylor et al., 2016). In the Klamath Mountains, fire activity increased as Native American population increased in the last 1.5 ka and then abruptly decreased with the onset of colonization (Crawford et al., 2015). In coastal Central California recent increases in fire beginning in the mid nineteenth century are attributed to burning of logging slash (Cowart and Byrne, 2013).

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Increases in extractive processes and land-use conversions for ranching and agriculture have also contributed to changing fire regimes over the last several hundred years and also led to changes in hydrology and landscape geomorphology (Heusser, 1983; Byrne et al., 2001; Cowart and Byrne, 2013; Platzman and Lund, 2019). Pollen records in British Columbia show the impacts of colonization, logging, farming, and urbanization on local terrestrial ecosystems (Heusser, 1983). Influx of freshwater to the San Francisco Bay decreased dramatically relative to the late Holocene at 1930 CE due to diversion of upstream water flow (Byrne et al., 2001). The extractive processes of the Gold Rush Era (beginning at 1850) in Northern California led to increased sedimentation and heavy metal pollution in the San Francisco Bay Delta; post-colonization lead (Pb) levels are unprecedented throughout the rest of the Holocene and concentrations of Sr, Ti, Cu, Ni, and Zn also increased following colonization (Fard et al., 2021). The onset of logging and ranching caused landscape conversion including transition of redwood forest to grasses and oak landscapes in coastal Central California (Cowart and Byrne, 2013). Further, the introduction of non-native species is well documented across the region (Anderson and Byrd, 1998; Cole and Wahl, 2000; Anderson et al., 2010, 2013; Dingemans et al., 2014). The impact of both a changing fire regime and land use change resulted in shifts in terrestrial ecosystems (Cowart and Byrne, 2013; Dingemans et al., 2014; Platzman and Lund, 2019).

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Human impacts on nearshore marine ecosystems are documented throughout the Holocene. Yet widespread and detectable impacts of land use change and anthropogenic climate change on marine systems do not appear until the last several hundred years, following colonization and the Industrial Revolution, respectively. Land use change and the conversion of land to rangeland and cultivated agricultural land beginning around 1800 CE led to the collapse of benthic marine ecosystems and may have contributed to a decrease in oxygenation across the Southern California Bight (Christensen et al., 1994; Tomasovych and Kidwell, 2017; Wang et al., 2017; Palmer et al., 2020). Impacts of anthropogenic climate change on marine systems in this region include species range shifts caused by rising SSTs

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and geochemical and structural changes to organisms due to ocean acidification; these changes represent a divergence from scales of past variability (Field et al., 2006; Pak et al., 2016; Osborne et al., 2020). Human activity, including intentional use and alteration of marine and terrestrial systems, has been a feature of Western North America throughout the Holocene that is detectable in multiple archives (lake sediments, marine sediments, archaeological records), yet colonization, urbanization, and industrialization led to a novel environmental interval.

4 Conclusions

Understanding Holocene climate and oceanographic patterns in the Western United States and California Current System is critical for contextualizing and predicting modern changes. Relative to pre-Holocene conditions, the early Holocene was dry and warm in the PNW and wet and warm in the SW; sea surface temperature was warm along the coast (Fig. 2). The mid Holocene was characterized by a wet, cool PNW and dry, warm SW with generalized cool SST, except for Santa Barbara Basin (Fig. 2). The late Holocene is the most variable interval with a general pattern of warm marine conditions and cool terrestrial conditions (Fig. 2). Control of fire regime shifts throughout the Holocene; in the early Holocene, fire activity is linked to changes in vegetation following the deglacial, but in multiple locations shifts to control by climate in the mid Holocene and in most records is highest and most variable in the late Holocene (Fig. 3). While human-environment interactions persist throughout the Holocene and impact the climate, landscape, and ecosystems of Western North America, the impacts of settler colonization, urbanization, and industrialization in recent centuries are documented broadly and, in some cases, represent divergences from scales of expected variability as recorded throughout the rest of the Holocene.

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Multiple factors combine and interact to drive climate changes through the Holocene including orbital forcing, ice sheet dynamics, solar forcing, annual to decadal phenomena, and marine-terrestrial interactions. Orbital forcing, including the Northern Hemisphere summer insolation peak in the early Holocene, drives climate change on millennial timescales. Annual to decadal phenomena such as ENSO and PDO become dominant drivers of climate in the late Holocene and lead to increased temporal variability. The relationship between marine and terrestrial systems evolves through time; notably, continental conditions in the Pacific Northwest and Southwest respond differently to changes in marine conditions. In the PNW broadly, marine temperatures are inversely correlated with precipitation. In the early Holocene, warm SSTs in the PNW coeval with warm, dry inland conditions, in the mid Holocene, the trend reverses. Yet, the increase in upwelling as a dominant oceanographic feature throughout the Holocene complicates this relationship, as upwelling in the PNW is positively correlated with precipitation yet characterized by cool SSTs. Thus, in the late Holocene, the interaction between an enhanced upwelling regime yet generalized warm SST patterns may both play a role in influencing terrestrial hydroclimate. In contrast, in the SW, marine temperatures are generally positively correlated with precipitation; warm intervals (such as the early Holocene) coeval with wet intervals and periods of drought coeval with cool SSTs offshore Southern California. In addition to marine-terrestrial interactions on regional scales, changes in source and strength of precipitation sources impact hydroclimate of the region; for example, changes in the intensity or geographic extent of the North American

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Monsoon and occurrence of atmospheric-river storms are both linked to processes in the Eastern Tropical North Pacific and have implications for hydroclimate across the region studied here. Future studies should fill in geographic gaps in sampling of the region and continue to distinguish between trends across temporal scales including seasonal, annual, and decadal, based on proxy type and preservation.

Although general trends can be identified across broad regions (PNW and SW), local factors play a key role in determining the exact conditions for a particular location. Additionally, age control challenges and proxy sensitivity issues (including seasonality) complicate Holocene climate reconstruction. Complete synchrony between records across a full time period for marine conditions, for terrestrial climate, or for fire activity is functionally absent; multiple anomalous or contradictory records exist (Figs. 2, 3). For example, fire activity in adjacent lake basins show different trends and nearshore vs. offshore records of marine conditions present apparently competing evidence (Fig. 3). Marine sediment records from Santa Barbara Basin are often utilized as records of the entire North Pacific, but here we find that trends in Santa Barbara Basin are not always synchronous with other records in this region (Fig. 2). We posit that these instances do not present competing evidence, but rather that local factors are critical in determining local climate. This is of critical importance for interpreting present and future climate change. This synthesis of climate and oceanographic processes and resultant impacts on ecosystems provides a window into understanding modern patterns of climate and climate change in the Western United States and Northeast Pacific and amplifies the need for future research investigating marine-terrestrial interactions, local and regional scale processes, and integrated physical-ecological-human systems.

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Appendices

Appendix A

Appendix A shows the results of the coded spatiotemporal analysis of previously published records.

Number in Figure 1	Paper	Latitude	Longitude	Late Hydro	Late Temp	Late Fire	Mid Hydro	Mid Temp	Mid Fire	Early Hydro	Early Temp	Early Fire
1	Anderson and Byrd 1998	33.291667	-117.34167	dry			wet					
2	Anderson et al., 2010	33.965278	-120.097222	wet		high			high			low
3	Bacon et al., 2006	36.441174	-117.97043							wet		
4	Barron and Bukry, 2007	42.24	-125.89		warm			cold			warm	
5	Barron and Bukry, 2007	36.99	-123.268		warm			cold			warm	
6	Barron and Bukry, 2007	41.68	-124.93		warm			cold			warm	
7	Barron et al 2003	42.682	-124.93		warm			cold			warm	
8	Barron et al., 2017	40.9	-124.6	wet				cold				
9	Barron et al., 2019	37.3317	-123.3992		warm			cold			warm	
10	Beatty and Taylor 2009	39.034637	-120.1624			low			high			low
11	Benson et al 2002	40.073646	-119.5969	wet	cold		dry	warm				
12	Bird & Kirby 2006	34.120426	-116.82766							wet		
13	Bird et al., 2010	34.121045	-116.828569	dry						wet		
14	Briles et al., 2005	42.025	-123.458333	wet	cold	high				dry	warm	
15	Brown and Hebda 2002	48.547796	-123.475786	wet	cold	high			low	dry	warm	high
16	Brown and Hebda 2002	48.595278	-124.197325			low			low	wet		
17	Cole and Liu 1994	33.956389	-119.976667	wet			dry					
18	Cole and Wahl 2000	32.929595	-117.25673	wet								
19	Dingemans et al 2014	34.7666667	-120.033333	dry								
20	Du et al., 2018	34.281767	-119.963967				wet					

Number in Figure 1	Paper	Latitude	Longitude	Late Hydro	Late Temp	Late Fire	Mid Hydro	Mid Temp	Mid Fire	Early Hydro	Early Temp	Early Fire
21	Fisler and Hendy 2008	34.2875	-120.036667		cold			warm			warm	
22	Friddell et al 2003	34.271167	-120.072667					warm			warm	
23	Hallett and Anderson 2010	37.9085722	-119.2864	dry		high	dry	warm	high			low
24	Hallett and Anderson 2010	37.5957028	-119.0067	dry		high	dry	warm	high			low
25	Hallett et al., 2003	49.36	-121.466667				wet			dry	warm	high
26	Hallett et al., 2003	49.266667	-121.516667				wet			dry	warm	high
27	Kennett et al., 2007	34.2875	-120.036667		cold		dry	warm			warm	
28	Kim et al., 2004	41.682	-124.93		warm							
29	Kim et al., 2004	34.535	-121.107		warm							
30	Kirby et al 2007	33.37	-117.22	dry			dry			wet		
31	Kirby et al 2010	33.37	-117.22				dry			wet		
32	Kirby et al 2012	34.253472	-116.920249									
33	Kirby et al 2014	34.77	-120.1162	dry			dry			wet		
34	Kirby et al 2015	33.37	-117.22	wet			dry			wet		
35	Kirby et al 2019	33.6733	-117.3542	dry			wet			dry		
36	Kirby et al 2019	33.6734	-117.3641	dry			wet			dry		
37	Konrad and Clarke 1998	37.970176	-119.318354		cold		wet			dry		
38	Konrad and Clarke 1998	37.140252	-118.629612				wet			dry		
39	Lindstrom 1990	38.942579	-120.053067	wet			dry			wet		
40	Long et al., 1998	44.167778	-123.582222	wet	cold	high	wet	cold	low	dry	warm	high

Number in Figure 1	Paper	Latitude	Longitude	Late Hydro	Late Temp	Late Fire	Mid Hydro	Mid Temp	Mid Fire	Early Hydro	Early Temp	Early Fire
41	MacDonald et al 2016	38.3395	-119.4984	wet			dry	warm				
42	Malamud-Roam et al 2006	37.997233	-122.453821	dry			wet	cold				
43	Marchitto et al., 2010	25.2	-112.7					cold			cold	
44	Marlon et al. 2006	48.16	-114.36	wet	cold	high	wet	cold	high		warm	
45	Marlon et al. 2006	44.28	-110.17	wet	cold	high	wet	cold	high		warm	
46	Marlon et al. 2006	44.66	-110.62	wet	cold	high	wet	cold	high		warm	
47	Marlon et al. 2006	44.92	-110.35	wet	cold	high	wet	cold	high		warm	
48	Marlon et al. 2006	45.7	-114.99	wet	cold	high	wet	cold	high		warm	
49	Marlon et al. 2006	45.84	-113.44	wet	cold	high	wet	cold	high		warm	
50	Marlon et al. 2006	45.89	-114.26	wet	cold	high	wet	cold	high		warm	
51	Marlon et al. 2006	46.08	-123.9	wet	cold	high	wet	cold	high	dry	warm	low
52	Marlon et al. 2006	46.32	-114.65	wet	cold	high	wet	cold	high		warm	
53	McGann 2011	37.223333	-123.243333	wet	warm		dry	warm		dry	warm	
54	McGann 2015	36.392167	-123.342	wet			dry			wet	warm	
55	McQuiod and Hobson 2001	48.633333	-123.5							wet		
56	Mix et al 1999	42.117	-125.75					cold			warm	
57	Mix et al 1999	41.682	-124.93					cold			warm	
58	Mohr et al., 2000	41.333	-122.55	wet	cold	high	wet	cold	high	dry	warm	low
59	Mohr et al., 2000	41.4	-122.583	wet	cold							

Number in Figure 1	Paper	Latitude	Longitude	Late Hydro	Late Temp	Late Fire	Mid Hydro	Mid Temp	Mid Fire	Early Hydro	Early Temp	Early Fire
60	Nederbragt and Thurow 2001	48.59065	-123.503333				wet					
61	Nederbragt and Thurow 2001	48.590617	-123.503417				wet					
62	Negrini et al., 2006	36.004447	-119.785517							wet		
63	Pellatt et al., 2001	48.59065	-123.503333		cold					dry	warm	
64	Spaulding 1990	35.45	-115.1				dry					
65	Steinman et al 2019	48.5417	-119.5818	dry		high	wet			dry		
66	Steinman et al 2019	48.5394	-119.5615	dry		high	wet			dry		
67	Walsh et al. 2017	46.9231	-121.5836	wet	cold	high	wet	cold		dry		low
68	Walsh et al. 2017	46.9114	-121.6571	wet	cold	high	wet	cold		dry		low
69	Walsh et al. 2017	46.9198	-121.5886	wet	cold	high	wet	cold		dry		low
70	Whitlock et al 2008	41.21	-122.5			high						high
71	Whitlock et al 2008	41.35	-122.56			high						high
72	Whitlock et al 2008	41.4	-122.58			high						high
73	Whitlock et al 2008	42.02	-123.46			high						high
74	Whitlock et al 2008	44.16	-123.58						high			high
75	Whitlock et al 2008	45.81	-123.57			high			low			

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Appendix B

Appendix B contains a list of papers used in the literature review and the coded spatiotemporal analysis.

Abbreviations are as follows: Southwest – SW, Pacific Northwest – PNW.

	Paper	**Latitude**	**Longitude**	**Region**	**Archive**	**Proxy Type(s)**	**Age Control Methodology**	**Number of Age Dates**
1	Addison et al., 2017	40.8656	-124.573	PNW	Marine Sediment	sedimentology, carbon and nitrogen isotopes	Radiocarbon of carbonates and stratiagraphic correlation	9
2	Anderson and Byrd 1998	33.291667	-117.34167	SW	Lake Sediment	pollen assemblage	Radiocarbon of organic material	3
3	Anderson et al., 2010	33.965278	-120.097222	SW	Lake Sediment	Pollen assemblages, sedimentology, charcoal	Radiocarbon of organic material and stratiagraphic correlation	6
4	Anderson et al., 2010	33.955556	-119.095833	SW	Marine Sediment	Diatom assemblages, sedimentology	Radiocarbon of organic material and stratiagraphic correlation	6
5	Asmerom et al 2013	32.163745	-104.517682	SW	Speleothem	Oxygen and carbon isotopes, speleochronology	Uranium series	19
6	Bacon et al 2018	36.542	-117.938	SW	Geomorphology	Sedimentology	Radiocarbon of organic material	3
7	Bacon et al., 2006	36.441174	-117.97043	SW	Geomorphology	Geomorphology and stratigraphy	Radiocarbon of organic material	21
8	Barron and Anderson 2011				Review Paper	Review Paper	NA	NA
9	Barron and Bukry, 2007	42.24	-125.89	PNW	Marine Sediment	diatom assemblage, pollen assemblages, alkenones,	Radiocarbon of carbonates	3

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						sedimentology		
10	Barron and Bukry, 2007	36.99	-123.268	SW	Marine Sediment	diatom assemblage, pollen assemblages, alkenones, sedimentology	Radiocarbon of carbonates	2
11	Barron and Bukry, 2007	41.68	-124.93	PNW	Marine Sediment	diatom assemblage, pollen assemblages, alkenones, sedimentology	Radiocarbon of carbonates	20
12	Barron et al 2003	42.682	-124.93	PNW	Marine Sediment	diatom assemblage, silicoflagellate assemblage, pollen assemblage	Radiocarbon of carbonates	20
13	Barron et al., 2010	34.2875	-120.036667	SW	Marine Sediment	diatom assemblage, silicoflagellate assemblage	Radiocarbon of carbonates and varve chronology	21
14	Barron et al., 2010	34.221667	-120.028333	SW	Marine Sediment	diatom assemblage, silicoflagellate assemblage	Varve chronology	Continuous
15	Barron et al., 2012				Marine Sediment	Review Paper	NA	NA
16	Barron et al., 2017	40.9	-124.6	PNW	Marine Sediment	diatom assemblage, silicoflagellate assemblage, pollen assemblage	Radiocarbon of carbonates	12
17	Barron et al., 2019	37.3317	-123.3992	SW	Marine Sediment	diatom assemblage, silicoflagellate assemblage, pollen assemblage	Radiocarbon of carbonates	3
18	Beatty and Taylor 2009	39.034637	-120.1624	SW	Lake Sediment	charcoal	Radiocarbon of organic material	9
19	Beck et al 2018	42.730113	-120.51746	PNW	Lake Sediment	pollen assemblage, oxygen isotopes	Radiocarbon of organic material	17

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20	Benson et al 2002	40.073646	-119.5969	PNW	Lake Sediment	sedimentology, pollen assemblages	Paleomagnetism, caesium dating, radiocarbon of organics	Continuous	**Formatted:** Font: 9 pt
21	Bird & Kirby 2006	34.120426	-116.82766	SW	Lake Sediment	sedimentology, ground penetrating radar	Radiocarbon of charcoal	27	**Formatted:** Font: 9 pt
22	Bird et al., 2010	34.121045	-116.828569	SW	Lake Sediment	sedimentology	Radiocarbon of organic material	20	**Formatted:** Font: 9 pt
23	Braje et al 2012	34.038578	-120.37907	SW	Archeological record	shell assemblage, plant microfossils, charcoal	Radiocarbon of carbonates	39	**Formatted:** Font: 9 pt
24	Braje et al 2012	33.955317	-120.1062	SW	Archeological record	shell assemblage, plant microfossils, charcoal	Radiocarbon of carbonates	13	**Formatted:** Font: 9 pt
25	Braje et al 2012	34.016987	-119.765051	SW	Archeological record	shell assemblage, plant microfossils, charcoal	Radiocarbon of carbonates	6	**Formatted:** Font: 9 pt
26	Briles et al., 2005	42.025	-123.458333	PNW	Lake Sediment	pollen assemblage, charcoal	Radiocarbon of organic material and 210Pb	23	**Formatted:** Font: 9 pt
27	Brown and Hebda 2002	48.547796	-123.475786	PNW	Lake Sediment	pollen assemblage, pollen assemblages, carbon isotopes	Radiocarbon of organic material	16	**Formatted:** Font: 9 pt
28	Brown and Hebda 2002	48.595278	-124.197325	PNW	Lake Sediment	pollen assemblage, pollen assemblages, carbon isotopes	Radiocarbon of organic material	16	**Formatted:** Font: 9 pt
29	Byrne et al., 2001	38.098287	-122.02125	SW	Marine Sediment	diatom assemblage	Radiocarbon of organic material	25	**Formatted:** Font: 9 pt
30	Cannariato and Kennett 1999	34.5	-121.5	SW	Marine Sediment	foraminiferal assemblage, sedimentology	Radiocarbon of carbonates	7	**Formatted:** Font: 9 pt
31	Cannariato and Kennett 1999	34.2875	-120.036667	SW	Marine Sediment	foraminiferal assemblage, sedimentology	Radiocarbon of carbonates	17	**Formatted:** Font: 9 pt

32	Cole and Liu 1994	33.956389	-119.976667	SW	Lake Sediment	pollen assemblage, sedimentology, charcoal	Radiocarbon of organic material and pollen stratigraphy	10
33	Cole and Wahl 2000	32.929595	-117.25673	SW	Lake Sediment	pollen assemblage, charcoal	Radiocarbon of organic material	5
34	Cook et al., 2000				Review/Modeling Paper	Review/Modeling Paper	NA	NA
35	Cowart and Byrne 2013	37.173889	-122.314444	SW	Lake Sediment	pollen assemblage	Radiocarbon of organic material and charcoal	5
36	Crawford et al 2015	41.533333	-123.566667		Lake Sediment	Pollen assemblages, sedimentology, charcoal	Radiocarbon of organic material and 210Pb	31
37	Crawford et al 2015	41.233333	-123.7		Lake Sediment	Pollen assemblages, sedimentology, charcoal	Radiocarbon of organic material and 210Pb	32
38	Davis 1992	33.660482	-117.840775	SW	Marine Sediment	pollen assemblage	Radiocarbon of organic material	5
39	Dingemans et al 2014	34.76666667	-120.0333333	SW	Lake Sediment	Pollen assemblage, sedimentology, hydrogen isotopes	Radiocarbon of organic material and charcoal	16
40	Du et al., 2018	34.281767	-119.963967	SW	Marine Sediment	sedimentology	Radiocarbon of carbonates	53
41	Erlandson et al., 2007				Review Paper	Review Paper	NA	NA
42	Erlandson et al., 2009				Review Paper	Review Paper	NA	NA
43	Feakins et al 2014	34.777634	-120.039859	SW	Lake Sediment	Hydrogen isotopes, compound specific isotopes	Radiocarbon of organic material and Caesium and pollen stratigraphy	15
44	Field et al., 2006	34.287133	-120.035583	SW	Marine Sediment	foraminiferal assemblage	Varve chronology	Continuous

45	Fisler and Hendy 2008	34.2875	-120.036667	SW	Marine Sediment	foraminiferal assemblage	Radiocarbon of carbonates	20
46	Flores et al., 2017	33.987079	-120.222156	SW	Archeological record	Oxygen and carbon isotopes	Radiocarbon of carbonates	6
47	Flores et al., 2017	33.914652	-120.053465	SW	Archeological record	Oxygen and carbon isotopes	Radiocarbon of carbonates	8
48	Friddell et al 2003	34.271167	-120.072667	SW	Marine Sediment	oxygen isotopes	Radiocarbon of carbonates	28
49	Gardner et al., 1988	39.05	-122.835583	SW	Lake Sediment	Pollen assemblage, sedimentology	Oxygen isotope stratigraphy	3
50	Gardner et al., 1988	38.425167	-122.796167	SW	Marine Sediment	Foraminiferal assemblage, sedimentology, pollen assemblages, diatom assemblages	Radiocarbon of carbonates	2
51	Gavin et al. 2007	-	-	-	Review Paper	Review Paper	NA	NA
52	Gavin et al., 2003	49.3911	-125.748781	PNW	Dendrochronology	Dendrochronology	Radiocarbon of charcoal	120
53	Glassow et al., 2012	33.960648	-119.817915	SW	Archeological record	Oxygen and carbon isotopes	Radiocarbon of carbonates	15
54	Hallett and Anderson 2010	37.90857222	-119.2864	SW	Lake Sediment	charcoal, pollen assemblages	Radiocarbon of organic material and tephra	4
55	Hallett and Anderson 2010	37.59570278	-119.0067	SW	Lake Sediment	charcoal, pollen assemblages	Radiocarbon of organic material and tephra	5
56	Hallett et al., 2003	49.36	-121.4666667	PNW	Lake Sediment	charcoal	Radiocarbon of charcoal	11
57	Hallett et al., 2003	49.266667	-121.516667	PNW	Lake Sediment	charcoal	Radiocarbon of charcoal	10
58	Hermann et al 2018	-	-	-	Review Paper	Review Paper	NA	NA
59	Heusser 1978	34.266667	-120.066667	SW	Marine Sediment	Pollen assemblages, charcoal	Varve chronology	Continuous
60	Heusser 1983	48.59065	-123.503333	PNW	Marine Sediment	Pollen assemblages, charcoal	Varve chronology	Continuous
61	Heusser 1998	-	-	-	Marine Sediment	Review Paper	NA	NA

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62	Hiner et al 2016	36.231354	-121.482348	SW	Lake Sediment	Sedimentology, oxygen isotopes	Radiocarbon of carbonates and charcoal	9
63	Ingram 1998	37.576171	-122.261235	SW	Archeological record	Radiocarbon	Radiocarbon of carbonates	15
64	Jones and Kennett 1999	36.288439	-121.853672	SW	Archeological record	Faunal assemblages and oxygen isotopes	Radiocarbon of carbonates	7
65	Jones and Kennett 1999	35.642784	-121.177744	SW	Archeological record	Faunal assemblages and oxygen isotopes	Radiocarbon of carbonates	3
66	Jones and Kennett 1999	36.045231	-121.584481	SW	Archeological record	Faunal assemblages and oxygen isotopes	Radiocarbon of carbonates	7
67	Jones et al., 2008	35.668278	-121.284271	SW	Archeological record	Oxygen and carbon isotopes	Radiocarbon of carbonates	21
68	Jones et al., 2008	36.070611	-121.582634	SW	Archeological record	Oxygen and carbon isotopes	Radiocarbon of carbonates	7
69	Kaufman et al., 2020				Data synthesis	Data synthesis	NA	NA
70	Kennett and Ingram 1995	34.2875	-120.036667	SW	Marine Sediment	oxygen isotopes, foraminiferal assemblage, radiocarbon	Radiocarbon of carbonates	32
71	Kennett and Kennett 2000	34.2875	-120.036667	SW	Marine Sediment	oxygen isotopes	Radiocarbon of carbonates	20
72	Kennett et al., 2007	34.2875	-120.036667	SW	Marine Sediment	foraminiferal assemblage, radiocarbon, sedimentology	Radiocarbon of carbonates	20
73	Kim et al., 2004	41.682	-124.93	PNW	Marine Sediment	Alkenones	Radiocarbon of carbonates	3
74	Kim et al., 2004	34.535	-121.107	SW	Marine Sediment	Alkenones	Radiocarbon of carbonates	0
75	Kirby et al 2005			SW	Lake Sediment	sedimentology	Radiocarbon of organics	9
76	Kirby et al 2007	33.37	-117.22	SW	Lake Sediment	pollen assemblage, sedimentology	Radiocarbon of organic material and Caesium and pollen stratigraphy	26

77	Kirby et al 2010	33.37	-117.22	SW	Lake Sediment	sedimentology	Radiocarbon of organic material	26
78	Kirby et al 2012	34.253472	-116.920249	SW	Lake Sediment	Sedimentology, faunal assemblages	Radiocarbon of organic material and charcoal	33
79	Kirby et al 2014	34.77	-120.1162	SW	Lake Sediment	sedimentology, hydrogen isotopes	Radiocarbon of organic material and Caesium and pollen stratigraphy	16
80	Kirby et al 2015	33.37	-117.22	SW	Lake Sediment	sedimentology, hydrogen isotopes	Radiocarbon of organic material and carbonate	8
81	Kirby et al 2019	33.6733	-117.3542	SW	Lake Sediment	sedimentology	Radiocarbon of organic material	26
82	Kirby et al 2019	33.6734	-117.3641	SW	Lake Sediment	sedimentology	Radiocarbon of organic material	26
83	Konrad and Clarke 1998	37.970176	-119.318354	SW	Lake Sediment and Lichenometry	lichenometry and sedimentology	Radiocarbon of organic material	5
84	Konrad and Clarke 1998	37.140252	-118.629612	SW	Lake Sediment and Lichenometry	lichenometry and sedimentology	Radiocarbon of organic material	5
85	Leidelmeijer et al. 2021	39.590617	-122.978867	PNW	Lake Sediment	sedimentology	radiocarbon	12
86	Lightfoot and Cuthrell 2015	37.16305	-122.338183	SW	Archeological record	Review Paper	NA	NA
87	Lindstrom 1990	38.942579	-120.053067	SW	Dendrochronology	Dendrochronology	Radiocarbon of carbonates	14
88	Long et al., 1998	44.167778	-123.582222	PNW	Lake Sediment	sedimentology, charcoal, pollen analysis	Radiocarbon of organic material and 210Pb	27
89	Lyle et al., 2012	-	-	-	Review Paper	Review Paper	NA	NA
90	Macdonald and Case 2005	34.066667	-116.483333	SW	Dendrochronology	Dendrochronology	Dendrochronology	Continuous

91	MacDonald et al 2016	38.3395	-119.4984	SW	Lake Sediment	sedimentology, carbon and nitrogen isotopes, charcoal, pollen analysis	Radiocarbon of organic material and tephra	8
92	Malamud-Roam et al 2006	37.997233	-122.453821	SW	Marine Sediment	Oxygen and carbon isotopes, pollen, macrofossil assemblage, sedimentology	Radiocarbon of organic material and carbonate	116
93	Malamud-Roam et al 2007				Review Paper	Review Paper	NA	NA
94	Marchitto et al., 2010	25.2	-112.7	SW	Marine Sediment	magnesium/calcium foraminifera	Radiocarbon of carbonates	22
95	Marcott et al., 2013				Review Paper	Review Paper	NA	NA
96	Marlon et al. 2006	48.16	-114.36	PNW	Lake Sediment	charcoal, pollen assemblages	Radiocarbon of organic material and 210Pb	
97	Marlon et al. 2006	44.28	-110.17	PNW	Lake Sediment	charcoal, pollen assemblages	Radiocarbon of organic material and 210Pb	
98	Marlon et al. 2006	44.66	-110.62	PNW	Lake Sediment	charcoal, pollen assemblages	Radiocarbon of organic material and 210Pb	12
99	Marlon et al. 2006	44.92	-110.35	PNW	Lake Sediment	charcoal, pollen assemblages	Radiocarbon of organic material and 210Pb	
100	Marlon et al. 2006	45.7	-114.99	PNW	Lake Sediment	charcoal, pollen assemblages	Radiocarbon of organic material and 210Pb	15
101	Marlon et al. 2006	45.84	-113.44	PNW	Lake Sediment	charcoal, pollen assemblages	Radiocarbon of organic material and 210Pb	8
102	Marlon et al. 2006	45.89	-114.26	PNW	Lake Sediment	charcoal, pollen assemblages	Radiocarbon of organic material and 210Pb	10

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103	Marlon et al. 2006	46.08	-123.9	PNW	Lake Sediment	charcoal, pollen assemblages	Radiocarbon of organic material and 210Pb	14
104	Marlon et al. 2006	46.32	-114.65	PNW	Lake Sediment	charcoal, pollen assemblages	Radiocarbon of organic material and 210Pb	
105	Mayewski et al., 2004				Review Paper	Review Paper	NA	NA
106	McGann 2008	37.6305	-122.3665	SW	Marine Sediment	Radiocarbon	Radiocarbon of carbonates	11
107	McGann 2011	37.223333	-123.243333	SW	Marine Sediment	Radiocarbon	Radiocarbon of carbonates	14
108	McGann 2015	36.392167	-123.342	SW	Marine Sediment	pollen assemblage	Radiocarbon of carbonates	5
109	McQuiod and Hobson 2001	48.633333	-123.5	PNW	Marine Sediment	Diatom assemblage, silicoflagellate assemblage	Radiocarbon of carbonates	
110	Mix et al 1999	42.117	-125.75	PNW	Marine Sediment	oxygen isotopes, foraminiferal assemblage	Radiocarbon of carbonates	16
111	Mix et al 1999	41.682	-124.93	PNW	Marine Sediment	oxygen isotopes, foraminiferal assemblage	Radiocarbon of carbonates	9
112	Moffitt et al., 2014	34.37	-121.13	SW	Marine Sediment	foraminiferal assemblage	Radiocarbon of carbonates and oxygen isotope stratigraphy	5
113	Moffitt et al., 2015	34.37	-121.13	SW	Marine Sediment	foraminiferal assemblage	Radiocarbon of carbonates and oxygen isotope stratigraphy	5
114	Mohr et al., 2000	41.333	-122.55	PNW	Lake Sediment	charcoal, pollen assemblages	Radiocarbon of organic material and 210Pb	5
115	Mohr et al., 2000	41.4	-122.583	PNW	Lake Sediment	charcoal, pollen assemblages	Radiocarbon of organic material and 210Pb	8

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116	Nederbragt and Thurow 2001	48.59065	-123.503333	PNW	Marine Sediment	sedimentology	Varve chronology	Continuous
117	Nederbragt and Thurow 2001	48.590617	-123.503417	PNW	Marine Sediment	sedimentology	Varve chronology	Continuous
118	Negrini et al., 2006	36.004447	-119.785517	SW	Lake Sediment	Geomorphology and sedimentology	Radiocarbon of organic material and carbonate	18
119	Oster et al., 2017	37	-122.1833333	SW	Speleothem	Oxygen and carbon isotopes	Uranium series	17
120	Pellatt et al., 2001	48.59065	-123.503333	PNW	Marine Sediment	pollen assemblage	Radiocarbon of carbonates	8
121	Platzman and Lund 2019	35.3	-120.05	SW	Lake Sediment	Sedimentology and paleomagnetism	Radiocarbon of organic material and 137Cs paleomagnetic secular variation	41
122	Reyes and Clague 2004	50.75	-123.766667	PNW	Geomorphology	Moraine stratigraphy	Radiocarbon of organic material	18
123	Rick 2011	34.003841	-120.176931	SW	Archeological record	Faunal assemblage and human remains	Radiocarbon of organic material, carbonates, and charcoal	28
124	Roark et al 2003	34.2875	-120.036667	SW	Marine Sediment	Radiocarbon	Radiocarbon of carbonates	37
125	Schimmelmann et al., 2013	34.2875	-120.036667	SW	Marine Sediment	Radiocarbon	Radiocarbon of organic material	21
126	Shuman et al 2018	-	-	-	Review Paper	Review Paper	NA	NA
127	Spaulding 1990	35.45	-115.1	SW	Terrestrial Midden	oxygen and carbon isotopes, sedimentology	Radiocarbon of organic material	6
128	Steinman et al 2019	48.5417	-119.5818	PNW	Lake Sediment	oxygen isotopes	Radiocarbon of organic material, 210Pb, 137Cs, and tephrachronology	25

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129	Steinman et al 2019	48.5394	-119.5615	PNW	Lake Sediment	oxygen isotopes	Radiocarbon of organic material, 210Pb, 137Cs, and tephrachronology	36
130	Steinman et al., 2016	50.83	-116.39	PNW	Lake Sediment	Oxygen and carbon isotopes	Radiocarbon of organic material, 210Pb, 137Cs, and tephrachronology	15
131	Steinman et al., 2016	54.685	-122.617	PNW	Lake Sediment	Oxygen and carbon isotopes	Radiocarbon of organic material, 210Pb, 137Cs, and tephrachronology	10
132	Steinman et al., 2016	48.874	117.338	PNW	Lake Sediment	Oxygen and carbon isotopes	Radiocarbon of organic material, 210Pb, 137Cs, and tephrachronology	11
133	Stine 1990	38.008101	-119.016233	SW	Geomorphology	Sedimentology and geomorphology	Radiocarbon of organic material and tephrochronology	29
134	Stine 1994	37.950538	-119.01395	SW	Dendrochronology	Dendrochronology and tree stump ages	Radiocarbon of organic material	17
135	Taylor et al. 2016	40.7	-121.59	PNW	Dendrochronology	Dendrochronology	Dendrochronology	Continuous
136	Tomosovych and Kidwell 2018	33.48	-118.59	SW	Marine Sediment	Faunal assemblages	Radiocarbon of carbonates	12
137	Tomosovych and Kidwell 2018	32.7555	-117.3617	SW	Marine Sediment	Faunal assemblages	Radiocarbon of carbonates	12
138	Tunnicliffe et al 2001	48.59065	-123.503333	PNW	Marine Sediment	Faunal assemblages	Radiocarbon of organic material and carbonate	34

139	Viau et al., 2006				Review/Modeling Paper	Review/Modeling Paper	NA	NA
140	Walsh et al. 2017	46.9231	-121.5836	PNW	Lake Sediment	Sedimentology, charcoal abundance	Radiocarbon of organic material and tephrochronology	7
141	Walsh et al. 2017	46.9114	-121.6571	PNW	Lake Sediment	Sedimentology, charcoal abundance	Radiocarbon of organic material and tephrochronology	8
142	Walsh et al. 2017	46.9198	-121.5886	PNW	Lake Sediment	Sedimentology, charcoal abundance	Radiocarbon of organic material and tephrochronology	10
143	Whitlock et al 2008	41.21	-122.5	PNW	Lake Sediment	pollen assemblage, charcoal	Radiocarbon of organic material, 210Pb, tephrachronology, and charcoal tie points	Not available
144	Whitlock et al 2008	41.35	-122.56	PNW	Lake Sediment	pollen assemblage, charcoal	Radiocarbon of organic material, 210Pb, tephrachronology, and charcoal tie points	5
145	Whitlock et al 2008	41.4	-122.58	PNW	Lake Sediment	pollen assemblage, charcoal	Radiocarbon of organic material, 210Pb, tephrachronology, and charcoal tie points	8
146	Whitlock et al 2008	42.02	-123.46	PNW	Lake Sediment	pollen assemblage, charcoal	Radiocarbon of organic material, 210Pb, and tephrachronology	23

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147	Whitlock et al 2008	44.16	-123.58	PNW	Lake Sediment	pollen assemblage, charcoal	Radiocarbon of organic material and tephrachronology	5
148	Whitlock et al 2008	45.81	-123.57	PNW	Lake Sediment	pollen assemblage, charcoal	Radiocarbon of organic material and 210Pb	20

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Appendix B¶
Appendix B includes the latitude, longitude, region, and proxy type of all studies used in the coded analysis of previously published records (step 2 of systematic review).¶
Paper
... [16]

Appendix C

Appendix C contains the data accessed for time series plots (Figs. 4, 5).

Paper	**Latitude**	**Longitude**	**Region**	**Archive**	**Figure Number**	**Accessed From**	**Link**
Addisson et al 2017	40.8656	-124.573	PNW	Marine sediment	4	NOAA Paleoclimate Database	https://www.ncdc.noaa.gov/paleo-search/study/21650
Barron et al 2003	42.682	-124.93	PNW	Marine sediment	4	NOAA Paleoclimate Database	https://www.ncdc.noaa.gov/paleo-search/study/5867
Braje et al 2012	34.038578	-120.37907	SW	Archaeological Record	5	In original paper: Table 1	https://www.sciencedirect.com/science/article/abs/pii/S1040618211005301
Kennett et al., 2007	34.2875	-120.036667	SW	Marine sediment	5	Author webpage	http://php.scripts.psu.edu/dept/liberalarts/sites/kennett/data.php
Kirby et al 2015	33.37	-117.22	SW	Lake sediment	5	NOAA Paleoclimate Database	https://www.ncdc.noaa.gov/paleo-search/study/20106
Long and Whitlock 1998	44.167778	-123.582222	PNW	Lake sediment	4	NOAA Paleoclimate Database	https://www.ncdc.noaa.gov/paleo-search/study/2252
MacDonald et al 2016	38.3395	-119.4984	SW	Lake sediment	5	Harvard Dataverse	https://dataverse.harvard.edu/dataset.xhtml?persistentId=doi:10.7910/DVN/P3MCFX
McGann 2015	36.392167	-123.342	SW	Marine sediment	5	In original paper: Table 2	https://www.sciencedirect.com/science/article/pii/S1040618215000610?casa_token=PAo4SBfUSPMAAAAA:g2YzlQACCS_MKrtKGcIN8PbTF0vc44mFxqyNfO_1ojeGltRavFpodrSo1aT7mUaM_KuPUM3aupM
Steinman et al 2016	50.82	-116.39	PNW	Lake sediment	4	NOAA Paleoclimate Database	https://www.ncdc.noaa.gov/paleo-search/study/21250

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Data Availability

Data generated for this manuscript is included in the Appendices.

Author Contributions

HMP and TMH conceptualized and designed the project. All authors completed data curation and literature review. HMP conducted data analysis and wrote the manuscript. All authors contributed to editing of the manuscript.

Competing Interests

The authors declare that they have no conflict of interest.

Acknowledgements

We acknowledge National Science Foundation SF support to T. Hill (NSF OCE 1832812), and the UC Davis Dissertation Year Fellowship for support to H. Palmer. We acknowledge all members of the UC Davis Geology Oceans and Climate Change Course (GEL 232) in Spring 2018 for their contributions to initial data gathering and framing of this project. We thank two anonymous reviewers and John Barron whose input significantly improved this paper. Finally, we acknowledge that this paper includes histories and discussion of Indigenous peoples of Western North America (Turtle Island) who have stewarded the land and sea for millennia. We aim to document the broad histories of interactions between people and environment, but we acknowledge that this record is incomplete due to the erasure of Indigenous histories and oral traditions, genocide of knowledge keepers, and destruction of cultural artifacts. We acknowledge the keepers of intergenerational Indigenous knowledge who maintain stories and data of the human, ecosystem, and climate impacts of settler colonization described here. We do not attempt to name all tribes whose ancestral and present homelands make up this study area, but we acknowledge that the majority of the geographic area covered here represents unceded land of Indigenous tribes and that data used here from previously published studies may have been acquired without consent from Indigenous peoples. We direct readers to the open-source resource: nativelands.ca to identify the homelands of the diverse Indigenous people of this region and encourage readers to use this resource as a starting place to learn about the land and marine stewardship of Indigenous peoples past and present.

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