



Filling a Geographical Gap: New Paleocological Reconstructions From the Desert Southwest, USA

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In 1916 the time stamp for quantitative palynology was set with Lennart von Post's initial paper on pollen analysis and environmental change in the Scandinavian peat bogs. In the 1930s, Von Post provided a map of the known palynological reconstructions. This map showed many conspicuous gaps of geographic coverage that have endured to this day. In particular, environmental reconstruction in arid lands remain much less known, largely due to the paucity of depositional environments in these areas as well as challenges with preservation in regions either uniformly dry or subjected to strong wet/dry phases. Over the last decade we have examined linkages between desert wetland development and episodes of wet and arid conditions. Desert wetland, or *ciénegas*, are recharged by groundwater and appear to be sensitive to climate-driven groundwater fluctuations. These systems appear to “grow” during wet periods potentially associated with enhanced El Niño activity, suggesting an important linkage with groundwater dynamics and the quantity and frequency of winter precipitation delivery. Hydrologic conditions in *ciénegas* are also important controls on the preservation of pollen, where episodes of aridity coincide with periods of poor pollen preservation. We assess modern El Niño events, as analogs of past wet conditions, to provide context on the atmospheric controls for delivery of moisture into the desert southwest during winter. Our analysis shows that anomalously high and persistent moisture delivery into the region during El Niño events enables the growth of *ciénegas*, improves preservation of pollen and promotes the growth of fuels necessary to support wildfire. This paper examines *ciénega* sites located in the southwestern region of North America at the US/Mexico Border and discusses results that addresses a geographical gap identified by Von Post's original work in paleoenvironmental research.

Keywords: pollen, charcoal, *ciénega*, desert wetland, ENSO, El Niño

INTRODUCTION

The legacy of Lennart Von Post on quantitative paleoecology and palynology cannot be overstated. While Von Post did not invent palynology, he helped to cement this field of study through his foundational research conducted in Sweden and Norway during the late 1800s and early 1900s. Von Post's approach to paleoenvironmental reconstruction made its way to the American Deserts via the geochronological work of Ernst Antevs and American researcher Kirk Bryan (Mantén, 1967; Smiley, 1974). While Antevs did not focus on pollen analysis himself, he was interested enough in the technique to opine on the naming of the methodology (Antevs, 1944) and his work was

critical to subsequent paleoenvironmental work in the desert landscapes of southwestern North America (hereinafter “southwestern deserts”).

Early pollen work in the southwestern deserts focused on woodland expansion (Clisby and Sears, 1956; Martin and Gray, 1962; Martin, 1963; Mehringer, 1965; Meyer, 1973). This initial research reported observations of periods where no pollen or low pollen abundances were recovered. These results altered the relative abundances of pollen types, which was interpreted to be caused by differential preservation and the individual researchers ability to identify degraded pollen grains. For example, through careful examination, the crumbled or degraded pollen grains of *Pinus*, *Artemisia*, Poaceae, and Amaranthaceae are easily distinguishable by the presence of distinct wall or annulated pore characteristic of the particular type. However, degradation and preservation issues reveal the difficult nature of arid land palynology. In short, the lack of perennial lacustrine environments results in discontinuous records of environmental change. Further, simple abundance in arid lands seems lower than one might experience in temperate environments. Subsequent research concentrated on macrobotanical records within woodrat middens (see Betancourt et al., 1990), instead of the ephemeral sedimentary nature of desert wetlands (however see Davis et al., 2002; Mensing et al., 2008).

In arid regions, environments suitable for pollen preservation are limited to riparian deposits, ciénegas or wetlands (Davis et al., 2002; Minckley and Brunelle, 2007), or on the deflated surfaces of former lake beds (Clisby and Sears, 1956; Martin, 1963; Meyer, 1973). Of these environments, ciénegas are proven archives of past environments and climate conditions as they collect charcoal, pollen, and macrofossils over thousands of years (Martin, 1963; Hall, 1985; Hendrickson and Minckley, 1985; Davis et al., 2002; Minckley and Brunelle, 2007; Brunelle et al., 2010; Pigati et al., 2014). The global distribution of desert wetland deposits has not been mapped, but they are considered to be widespread, though in other literature they are referred to as ground water deposits associated with hot or cold springs, seeps, or other wetland complexes (Pigati et al., 2014; Sáez et al., 2016). However, systematic studies of these complex systems are relatively recent, variously focusing on lithological, isotopic, or biological indicators (Minckley and Brunelle, 2007; Quade et al., 2008; Minckley et al., 2013a; Brunelle et al., 2014; Pigati et al., 2014 and references therein, Sáez et al., 2016).

Arid and semi-arid environments occupy 40% of the terrestrial land area on earth and in many cases represent areas where recent human population growth rates are high relative to more mesic regions (18.5% between 1990 and 2000; Hassan et al., 2005). The consumption of natural resources associated with rapid population growth places intense pressure on water resources, such as ciénegas. In addition to being a ready source of water, ciénegas provide crucial ecosystem services including erosion mitigation and prevention of the associated lowering of the water table. Ciénegas have also been identified as regions of high conservation priority for many reasons including endemism (Minckley, 1969, 1992; Hendrickson and Minckley, 1985; Abell, 2000). In Arizona, USA where wetland environments occupy ~2% of the land area, ciénegas are critical habitat for at least

19% of the threatened, candidate, or endangered species within the state (Baker et al., 2004). However, beyond species of concern, desert ciénegas and riparian corridors may increase regional biodiversity by up to 50% in some cases (Sabo et al., 2005).

Over the last decade, we examined sediment collected from ciénega systems located in the southwestern deserts to understand the hydrology, ecology, disturbance regimes, climatology, and environmental change from these critical systems. Our work builds on the legacies of scholars working in this region, including Antevs, Martin, and Mehringer (e.g., Antevs, 1962; Martin, 1963; Mehringer, 1967). Consideration of ciénegas as repositories of environmental history was largely untouched until Hendrickson and Minckley (1985) published “Ciénegas—Vanishing Climate Communities in the American Southwest.” Paleocological research of these sedimentary environments was largely unexplored until Davis et al. (2002) published a synthesis of several sites that examined changes in burning regime with European settlement. However, a large-scale evaluation of ciénega form and function has not yet been undertaken (see Pigati et al., 2014).

In this paper, we present data from four ciénega sites in the Arizona/New Mexico-Mexico borderlands using multiproxy analyses. Herein, we present data from previously published research as well as new records to provide a regional perspective on vegetation and disturbance history from the borderlands region. We detail our approach to handling differential pollen preservation and explain how sedimentary indicators may also provide evidence for hydrology as a control on pollen preservation. Despite the analytical challenges associated with ciénega sediments, the environmental record we present here shows regional coherence of wet-dry episodes. We show that pollen records from ciénegas provide insight to past climatological states related to variations in winter precipitation. For the desert Southwest, this is currently associated with quasi-periodic El Niño Southern Oscillation (ENSO) variations. In the tradition of Von Post, our first objective is to identify conditions in the sedimentological proxy data (e.g., pollen and charcoal) that record changes in ciénega systems attributed to climate. For our second objective, we identify modern episodes that are analogous to conditions found in the paleocological record (strong El Niño conditions) associated with ciénega growth (e.g., wet episodes) to assess the dominant atmospheric drivers related to enhanced winter precipitation in the arid southwest.

To address our first objective, we utilize indices of pollen preservation and charcoal abundance. We assess pollen preservation in ciénega systems of southwestern New Mexico and southeastern Arizona as well as the relationship to past ENSO variability based on our modern understanding of ENSO and southwestern North American hydroclimate teleconnections (Heyer et al., 2017). Further, we put forward past fire activity near the ciénegas was covariant with ENSO variability, similar to connections observed in historic southwestern forest fire research (Swetnam and Betancourt, 1990). Considering fuel availability produced during antecedent wet seasons is closely linked to wildfire in arid and semi-arid environments globally (Krawchuk and Moritz, 2011), we consider our linkage of

past fire activity and ENSO variability viable. To address our second objective, on the impact that El Niño events have on Southwestern climate, we use high-resolution modern climate data to assess teleconnections between moisture delivery and southwestern precipitation anomalies during winter and spring of strong El Niño events as a mechanism for sustained wet conditions that are conducive for pollen preservation in ciénegas.

REGIONAL DESCRIPTION

The southwestern deserts, particularly those in the Sonoran and Chihuahuan systems, have a high concentration of ciénegas (Hendrickson and Minckley, 1985; Minckley et al., 2013b; Cole and Cole, 2015). These wetlands are found in a variety of geomorphic contexts along riverine or stream channels, off-channel seeps, landslide backfill, and valley bottoms, to name a few. Often ciénegas are proximal to fault lines, which are common in the desert basin and range structures of western North America (Minckley, unpublished).

The modern climatic context of the arid southwest of North America is characterized as having bimodal precipitation (Mock, 1996; Shinker, 2010). Winter precipitation has broad spatial-scale patterns with persistent light precipitation delivered by midlatitude frontal systems (Mock, 1996; Comrie and Glenn, 1998; Shinker, 2010). In contrast, summer precipitation is highly variable spatially and typically short in duration associated with convective thunderstorms delivered via the North American Monsoon System (NAMS; Mock, 1996; Adams and Comrie, 1997; Sheppard et al., 2002; Diem and Brown, 2006; Shinker, 2010). The modern NAMS developed after climate started to warm and the Laurentide ice sheet began to collapse at the end of the last ice age. This warming led to the formation of summer thermal lows that provide a mechanism for drawing moisture from the Gulf of Mexico and southeastern Pacific (Spaulding, 1991; Adams and Comrie, 1997; Minckley et al., 2004). The bimodal nature of precipitation in the southwest, especially the extra precipitation in the summer associated with the NAMS, provides effective moisture at the surface related to water- and energy-balance components important for ecosystem and water resources related to vegetation and the ciénega systems of the southwest (Shinker and Bartlein, 2010).

In addition to the bimodal climate of the southwest, large-scale modes of variability such as ENSO impacts southwestern hydroclimate and ecosystems (Ropelewski and Halpert, 1986; Cole and Cook, 1998; Gershunov and Barnett, 1998a; Cayan et al., 1999; Dettinger et al., 2000). El Niño is the anomalous warming of the near-surface water off the western coast of South America that initiated about 5000 years ago (Enfield, 1992; Liu et al., 2014). Its atmospheric counterpart is the Southern Oscillation, which reflects changes in barometric pressure (Wallace and Gutzler, 1981; Enfield, 1992). Strong El Niño years in the modern record typically result in higher-than-normal winter precipitation in the southwestern United States; while strong La Niña typically causes lower-than-normal winter precipitation and is typically associated with regional drought (Shinker and Bartlein, 2009). Studies have identified a north-to-south precipitation dipole correlated with ENSO in the

western U.S., showing a strong relationship in the southwest between cool season (Oct-Mar) precipitation and El Niño events (Dettinger et al., 1998; Wise, 2010). Further, many studies have shown statistically significant correlations between ENSO and western North America precipitation, specifically in the southwest where spatially coherent correlations are found during the cool season (Dettinger et al., 1998; Heyer et al., 2017). However, various modes of ENSO are associated with different impacts on western NA hydroclimate (Ashok et al., 2007), and teleconnections can vary on decadal-to-centennial time scales (Gershunov and Barnett, 1998b), suggesting that southwest hydroclimate does not always respond to ENSO variability in a linear manner based on our modern understanding of southwest hydroclimate and ENSO correlations (Heyer et al., 2017). However, despite teleconnection variability (Gershunov and Barnett, 1998b), dipole variability (Wise, 2010) and different modes of ENSO (Ashok et al., 2007), paleo-sedimentary records suggest teleconnections between ENSO and southwest climate are similar to those observed in the modern record, and have persisted at century–millennial time scales (Barron and Anderson, 2010; Antinao and McDonald, 2013; Kirby et al., 2014; Hart et al., 2015). Further, paleoecological records have revealed the ENSO phenomenon is correlated with fire regimes of the southwest (Swetnam and Betancourt, 1990). Therefore, our research on San Bernardino Ciénega suggests that over centuries-to-millennial scales fire frequency trends are consistent with ENSO variability, with fire frequency increasing (decreasing) when El Niño (La Niña) was active (Brunelle et al., 2010).

Our work has been focused on ciénegas near the US/Mexico borderlands region in southern Arizona and New Mexico (**Figure 1**) in the monsoon-dominated ecotone of the Sonoran and Chihuahuan deserts and in a region well correlated with ENSO activity (Wise, 2010; Heyer et al., 2017). Total annual precipitation is around 254 mm (Western Regional Climate Center, 2017). Summer temperatures are generally around 37°C while winter temperatures rarely fall below freezing.

SITE DESCRIPTIONS

San Bernardino Ciénega (31.3°N; 109.3°W, 1,160 m asl; **Figure 1**) is located in the drainage of Black Draw Wash/Rio de San Bernardino (RSB) of southeastern Arizona, USA and northeastern Sonora, MX near the ecotone of Chihuahuan and Sonoran grassland and desert scrub (Minckley and Brunelle, 2007; Minckley et al., 2009, 2011; Brunelle et al., 2010). Currently the ciénega surface is dry except for a few artificial impoundments and small perennial springs.

Cloverdale Ciénega is located in the Peloncillo Mountains, Coronado National Forest, NM (31°26.141' N, 108°58.517' W, 1,640 m asl; **Figure 1**). Cloverdale Ciénega is situated at the ecotone between Madrean woodland and grassland (Brunelle et al., 2014), making this location sensitive to changes in community composition over time. Currently, the Madrean woodlands form a mosaic of clustered tree stands interspersed with patches of shrub and grass (Brown, 1982).

Canelo Hills Ciénega (31° 33.833'N, 110° 31.711'W, 1,506 m asl; **Figure 1**) is a Nature Conservancy preserve located southeast

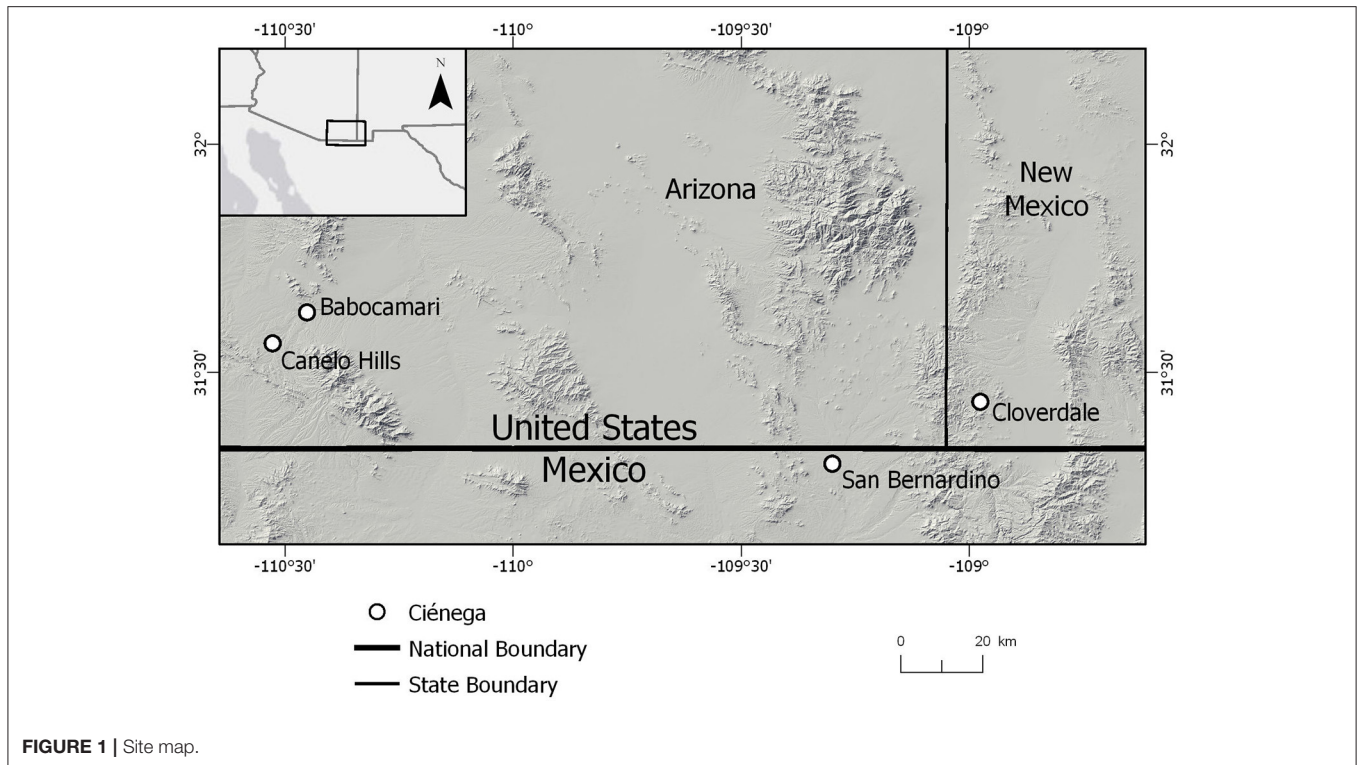


FIGURE 1 | Site map.

of Sonoita, Arizona on the east side of the Canelo Hills. The area is a Madrean grassland.

Babocamari Ciénega ($31^{\circ} 37.901'N$, $110^{\circ} 27.178'W$, 1,391 m asl; **Figure 1**) is southeast of Sonoita, Arizona and located between the Whetstone and Huachuca Mountains. The site is considered Madrean grassland.

METHODS

Field

San Bernardino

Sediments were collected from an active spring (Snail Spring), the incised channel wall of the Rio de San Bernardino arroyo (RSBA), and the ciénega surface of the San Bernardino National Wildlife Refuge (SBNWR). The RSBA samples were described and collected contiguously from a freshly exposed sediment face with a trowel. A 15-m long core was obtained from the SBNWR using a truck-mounted 5" (12.7 mm) hollow barrel auger (Minckley et al., 2007). The Snail Springs samples were collected using a modified Livingstone piston corer.

Cloverdale, Babocamari, and Canelo Hills Ciénegas

Sediment cores were collected using a vibracore system where manual probes indicated maximum sediment accumulation. The vibracore apparatus uses a cement leveling motor attached to a 3-inch aluminum tube inserted into the sediments until refusal (bedrock). Sediment was retained in the aluminum tube by placing an airtight cap on the top of the tube to create a vacuum, allowing the sediment

core to be removed from the ground without loss. The cores were transported in the aluminum tube to the University of Utah and split in the lab for description and sampling.

Laboratory and Analytical

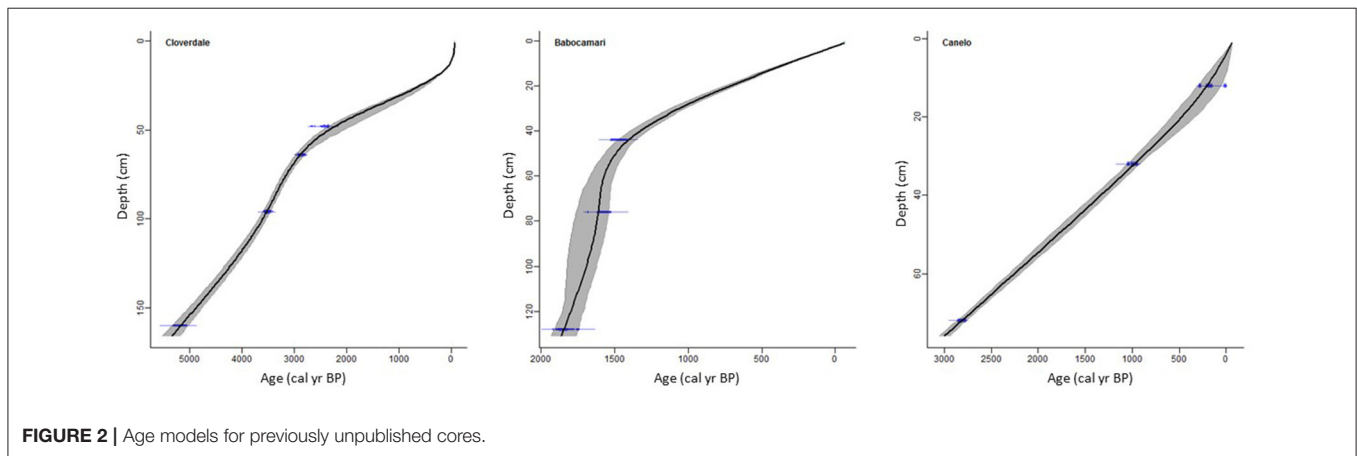
Once the cores were removed from the aluminum tube, the color and texture of the sediments were described. Every contiguous centimeter of the core was examined for charcoal analysis. For pollen analysis, samples were collected to acquire a minimum sample resolution of approximately every 200 years. The sediments were weakly stratified, massive, and organic.

Age-depth relationships were determined for the sediments based on AMS (accelerator mass spectrometry) dates on pollen concentrates, lead-210 chronology (when available), and the surface (collection year; **Table 1**). Ages are presented in calibrated years before present (cal yr BP) where 1950 CE is equal to year 0 cal yr BP. The age-depth models were generated in CLAM (Blaauw, 2010) using smoothing splines (**Figure 2**). The age model for San Bernardino was created using multiple linear regressions and was not rerun due to the multiple publications already based on the existing chronology (Brunelle et al., 2010 and citations therein).

Pollen extraction methods followed Faegri et al. (1989). For pollen analysis, we attempted to identify at least 300 terrestrial pollen grains to complete the rarefaction curve associated with pollen diversity (Maher, 1963). Pollen grains were identified at a magnification of 500X to the lowest possible taxonomic

TABLE 1 | Radiocarbon dates from the reported sites.

Depth	Core	Lab number	Method	Material	14C age	Calendar year	Error	Calibrated (CALIB 7.1) median probability
0–1	CC08C	–	Surface	–	–	–58	–	–
14–15	CC08C	–	Lead-210	Sediment	–	89	1	–
47–48	CC08C	CAIS 4477	AMS	Pollen	2,370	–	45	2,413
63–64	CC08C	CAIS 5469	AMS	Pollen	2,770	–	25	2,863
95–96	CC08C	CAIS 5470	AMS	Pollen	3,280	–	30	3,510
159–160	CC08C	CAIS 4478	AMS	Pollen	4,530	–	45	5,163
0–1	BAB10A	–	Surface	–	–	–60	–	–
43–44	BAB10A	CAIS 7339R	AMS	Pollen	1,580	–	24	1,468
75–76	BAB10A	CAIS 7340R	AMS	Pollen	1,663	–	24	1,564
127–128	BAB10A	CAIS 7341R	AMS	Pollen	1,899	–	30	1,848
0–1	CAN10A	–	Surface	–	–	–60	–	–
11–12	CAN10A	CAIS 7335	AMS	Pollen	190	–	25	180
31–32	CAN10A	CAIS 7336	AMS	Pollen	1,078	–	25	980
71–72	CAN10A	CAIS 7337	AMS	Pollen	2,720	–	25	2,814
0–1	RSB04	–	Surface	–	–	–54	–	–
40–42	RSB04	Beta-204829	AMS	Pollen	830	–	40	741
108–110	RSB04	Beta-204374	AMS	Pollen	1,200	–	40	1,128
155–160	RSB04	CAIS 1615	AMS	Pollen	1,700	–	45	1,609
175–180	RSB04	Beta-204828	AMS	Pollen	2,470	–	40	2,568
375–380	RSB04	Beta-203022	AMS	Pollen	3,900	–	40	4,335
346–347	SBNWR05	Beta-207161	AMS	Pollen	3,740	–	40	4,096
553–554	SBNWR05	Beta-207162	AMS	Pollen	3,920	–	40	4,354
667–668	SBNWR05	Beta-207163	AMS	Pollen	6,190	–	50	7,087

**FIGURE 2** | Age models for previously unpublished cores.

classification using published atlases (e.g., Erdtman, 1969; Kapp et al., 2000). Counts were converted to percentages based on the sum of total terrestrial grains and influx using the sedimentation rate calculated using the age models. In desert sediments, a 300-grain terrestrial count is not always obtainable because of poor preservation (Minckley and Brunelle, 2007; Minckley et al., 2011). Our standard has been to attempt 300-grain terrestrial counts or 300–1000 *Lycopodium* spore (exotic spore added as a tracer) tallies for each depth. If pollen counts do not exceed at least 100 terrestrial pollen grains we plot pollen presence instead of abundance to avoid artificial inflation of identifiable pollen

types as presenting ecological significance, an issue common in earlier studies as detailed in the Introduction.

A second way we avoid misinterpretation of desert pollen assemblages is by determining an index of pollen preservation (“preservation index”) where we consider the number of *Lycopodium* tracers to the total number of identified grains. Studying the way pollen has been preserved can help to determine changes in the deposition or preservation environment. This type of examination is a relatively underused technique (Tipping, 2000) that could be more widely used as an interpretive tool (Tweddle and Edwards, 2010). In our study, the preservation

index is used as an indicator of a decrease in water table height that would expose deposited grains to conditions of wetting and drying which are known to be consistent with deterioration (Campbell and Campbell, 1994; Tweddle and Edwards, 2010). The depth to water table in ciénega settings controls the water level at the surface. In turn, the water table is largely controlled by the amount of winter precipitation. High preservation indices are used to indicate wet (active) ciénega surfaces, while low indices indicate dry (inactive) surfaces.

Volumetric samples were taken from the sediments for charcoal analysis to reconstruct fire history. Sample volumes ranged from 1 to 10 cc based on the amount of charcoal found at various depths throughout the sections. Sample volume was adjusted to maintain a significant number of charcoal particles, but to reduce excessive counts (>1,000 particles). Methods and rationale follow Clark (1988) and Long et al. (1998). While taphonomic studies of large particle deposition on fluvial wetland surfaces have not been conducted, isotopic analysis of ciénega sediments indicates pooling and stagnation of surface waters (Minckley et al., 2009), suggesting sedimentation of charcoal fragments would be similar to those of lake and bog surfaces. Charcoal concentrations (particles/cm³) were converted to influx (particles/cm²/yr) using the age models.

Statistical Analyses

To compare ciénega CHAR record to regional charcoal variability, regional charcoal for Arizona, New Mexico, Southern Utah, and Southern Colorado (i.e., latitude >30, latitude <38, longitude ≤105, longitude ≥113) were collected from the paleofire database (Blarquez et al., 2014), and used in correlative analyses. A total of 13 sites were included, of which all sites are from mid-upper elevations (i.e., >2,300 meters) with the exception of the Montezuma Well site (near 1,100 meters). Prior to comparing regional charcoal to ciénega charcoal, regional charcoal data were averaged (i.e., long-term average 10,000 cal yr BP—present) and standardized to z-scores. Charcoal data were then composited using a locally weighted scatterplot smoother and bootstrapping techniques (Blarquez et al., 2014).

Prior to correlation analyses, the CHAR and pollen preservation ratio data were decomposed into pseudoannual values and then reaggregated into 100-year bins to be comparable to the Moy et al. (2002) El Niño event frequency reconstruction. The time series of all the ciénega sites were then averaged to provide a comprehensive trend of the series. To quantitatively describe the relationships between the ENSO index (Moy et al., 2002) and the preservation ratio and CHAR time series, a Pearson product-moment correlation was run on the time series providing correlation coefficients and *p*-values.

Correlations were performed between data from 7,700 cal yr BP to present for mean-pollen preservation, and from 8,100 cal yr BP to present for mean-charcoal accumulation. Correlations were between ciénega sites mean-pollen preservation, ciénega sites mean-charcoal accumulation, regional standardized charcoal accumulation, and El Niño events/100 years (Moy et al., 2002). From 8,100 to 5,400 cal yr BP, only the San Bernardino ciénega site was active, with pollen preservation

and charcoal accumulation at or near zero, as expected considering El Niño event inactivity. Therefore, correlation analyses from 8,100 to 5,400 cal yr BP is not based on an actual average. However, we assume a lack of pollen preservation and charcoal accumulation at the inactive ciénega sites was due to a lack groundwater recharge, which may represent a reduction of persistent winter and spring precipitation potentially associated with reduced El Niño events (Scanlon et al., 2006; Heyer et al., 2017). We suggest if the other three ciénega sites had been active, then pollen preservation and charcoal accumulation would have been close to zero, similar to the San Bernardino ciénega. Thus, assuming the other ciénega sites would have also had pollen preservation and charcoal accumulation near zero, we only use pollen preservation and charcoal accumulation data from the San Bernardino ciénega to calculate the long term mean-pollen preservation (i.e., 7,700 cal yr BP—present) and mean-charcoal accumulation (i.e., 8,100 cal yr BP—present). From 5,300 to 0 cal yr BP at least two ciénega sites recorded data, allowing for a mean to be calculated.

Modern Climate Analog Approach

While proxy data such as charcoal, pollen and macrofossils provide a record of past ciénega variability from an ecological perspective, paleoecological data does not provide a record of the climatic mechanisms that caused such variability (Shinker et al., 2006). Therefore, understanding modern climate mechanisms and processes that cause variability in ciénegas and the sensitivity and range of ecological responses to such changes are fundamental to ecosystem management. We incorporate a modern climate analog technique (Mock and Shinker, 2013) in order to understand the climate processes and mechanisms associated with ENSO conditions that are evident in the sedimentological record from ciénega sites across the United States/Mexico borderlands. The modern climate analog technique (Mock and Shinker, 2013) relies on the principle of uniformitarianism and assumes that modern synoptic and dynamic climate processes operated similarly today as they did in the past. The modern climate analog approach is an effective way to identify climate mechanisms associated with past environmental changes (e.g., as seen in reconstructed sedimentary pollen analyses; Mock and Brunelle-Daines, 1999; Shinker et al., 2006; Shinker, 2014). A modern climate analog is a conceptual model that uses modern extremes (e.g., wet or dry episodes) as analogs of past events (e.g., vegetation disturbance associated with changes in ciénega hydrology) to identify possible synoptic and dynamic patterns that may have caused past extremes (Edwards et al., 2001; Shinker, 2014). Such conceptual models of dynamic processes can provide examples of modern climatic mechanisms as analogs of historic and past hydroclimatic variability (Mock and Brunelle-Daines, 1999; Shinker et al., 2006; Mock and Shinker, 2013; Shinker, 2014).

The first step in the modern climate analog approach is to identify conditions in the sedimentological proxy data that record a change in vegetation and subsequently represents changes in the ciénega system, which would have signaled a change in the

hydrological cycle. The next step is to use an environment-to-circulation approach (Yarnal, 1993; Barry and Carleton, 2001; Yarnal et al., 2001; Mock and Shinker, 2013; Shinker, 2014), which considers the surface conditions based on information gained from the proxy data collected from cienega sediments. We use the Multivariate ENSO Index (MEI, Wolter and Timlin, 2011) to identify analogous periods (seasons, years) of anomalous conditions and treat the selected cases as the modern analog for past hydrologic variability seen in the sedimentary pollen record. By identifying extremes (i.e., El Niño conditions) in the modern record, the environment-to-circulation approach helps identify potential dominant synoptic processes that created the persistent conditions leading to the ecological changes seen in the sedimentary record.

We use five strong El Niño events from the MEI (Wolter and Timlin, 2011) for the period 1979–2017 (the common period for the atmospheric circulation data we use). The selected El Niño years (cases) represent similar conditions (e.g., El Niño modes consistent with anomalous wet winter and spring conditions in the southwest) to those found in the sedimentary analyses. Once selected, the case years are used to calculate and map composite-anomaly values to assess the spatial configuration of climate processes during the selected anomalous case years (the modern climate analogs). We use climate data from the North American Regional Reanalysis (NARR) dataset (Mesinger et al., 2006), which spans 1979–2017. Use of the NARR dataset is advantageous for two reasons: (1) it provides a variety of climate variables that represent atmospheric synoptic processes (e.g., atmospheric pressure; moisture availability, and vertical motion) as well as surface conditions (e.g., precipitation rate and soil moisture); and (2) The spatial resolution (32-km grids) of the NARR is at a finer scale than large-scale GCMs. The 32-km resolution of the NARR is valuable for our area of geographic study because it captures topographic and climatic diversity of the southwest (Heyer et al., 2017). For each climate variable in the NARR dataset we use, the seasonal value (e.g., DJF) of the selected modern analog case years are averaged together (composited) and compared to the long-term mean (1981–2010) to create composite-anomaly values.

Finally, we map composite-anomaly values for selected modern climate analog case years to analyze and assess the spatial and temporal variability of our selected modern climate analogs for surface and atmospheric conditions that would support ecological change identified in the paleoecological record. Atmospheric variables (e.g., atmospheric pressure and specific humidity) are mapped at a continental scale to illustrate the large spatial scales in which such variables operate. Similarly, the surface variables (e.g., precipitation rate and soil moisture) are mapped at the local or regional level to illustrate the spatial heterogeneity of such processes.

RESULTS

Core Description

The sedimentary deposits were massive, organic rich clays with interbedded layers of silt and sand.

Age Models

San Bernardino Ciénega

The San Bernardino age model is presented in Minckley and Brunelle (2007); Blissett (2010), and Brunelle et al. (2010) and is based on a series of linear regressions using 8 radiocarbon dates.

Cloverdale Ciénega

The Cloverdale age model (Brunelle et al., 2014) is based on a smoothing spline (CLAM spar 0.1, goodness-of-fit = 22.4, Blaauw, 2010) based on the surface age, a lead-210 date and 4 radiocarbon dates (Figure 2).

Canelo Hills Ciénega

The Canelo Hills Ciénega age model is not previously published. It is based on a smoothing spline (CLAM spar 0.3, goodness-of-fit = 1.99, Blaauw, 2010) based on the surface age, and 3 radiocarbon dates (Figure 2).

Babocamari Ciénega

The Babocamari Ciénega age model is not previously published. It is based on a smoothing spline (CLAM spar 0.2, goodness-of-fit = 4.25, Blaauw, 2010) based on the surface age, and 3 radiocarbon dates (Figure 2).

Pollen

San Bernardino Ciénega

The pollen data represent changes in abundances of various taxa over the last ~8,000 cal yr BP (Figure 3). The *Lycopodium* curve indicates depths that have greater or lesser preservation. For example, the time period centered on 2,750 cal yr BP records a greater abundance of identified *Lycopodium* than pollen grains and reduced pollen preservation. Other interesting shifts in pollen types include the increase in Poaceae, Cyperaceae, and Typhaceae/Sparganium type after ~4,500 cal yr BP.

Cloverdale Ciénega

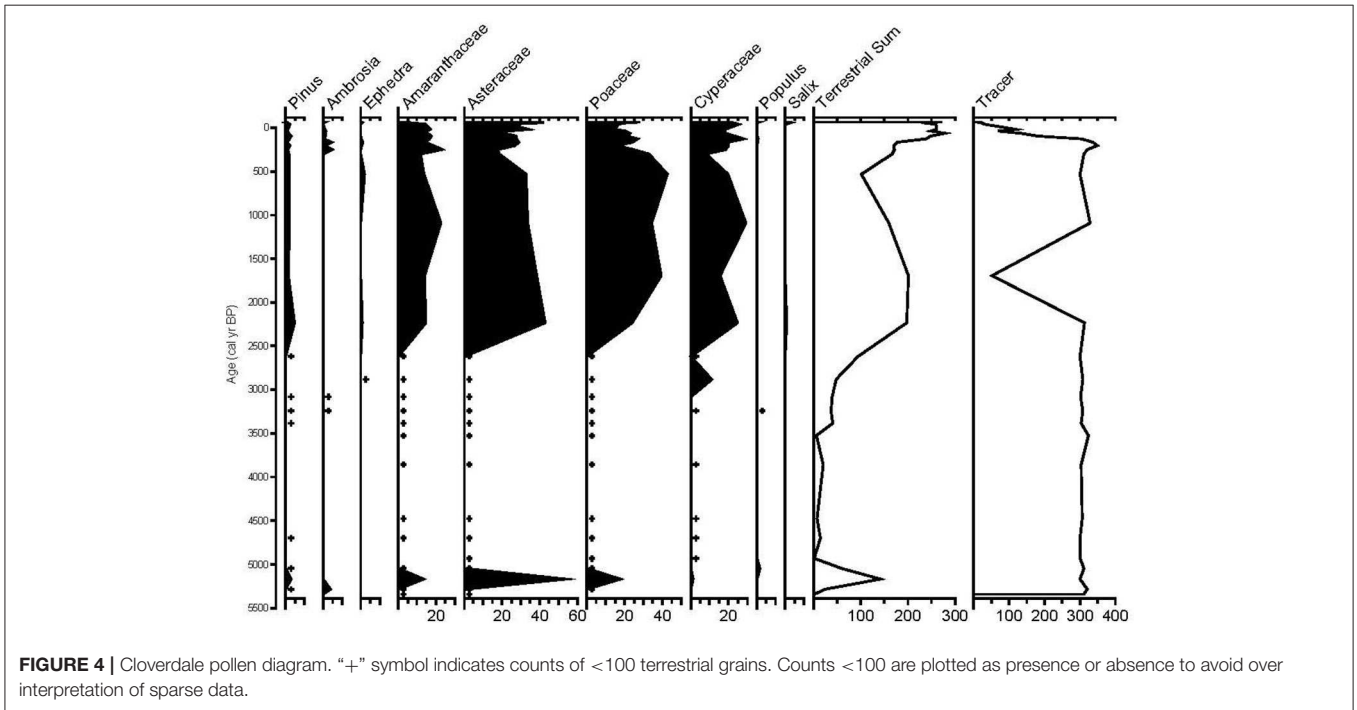
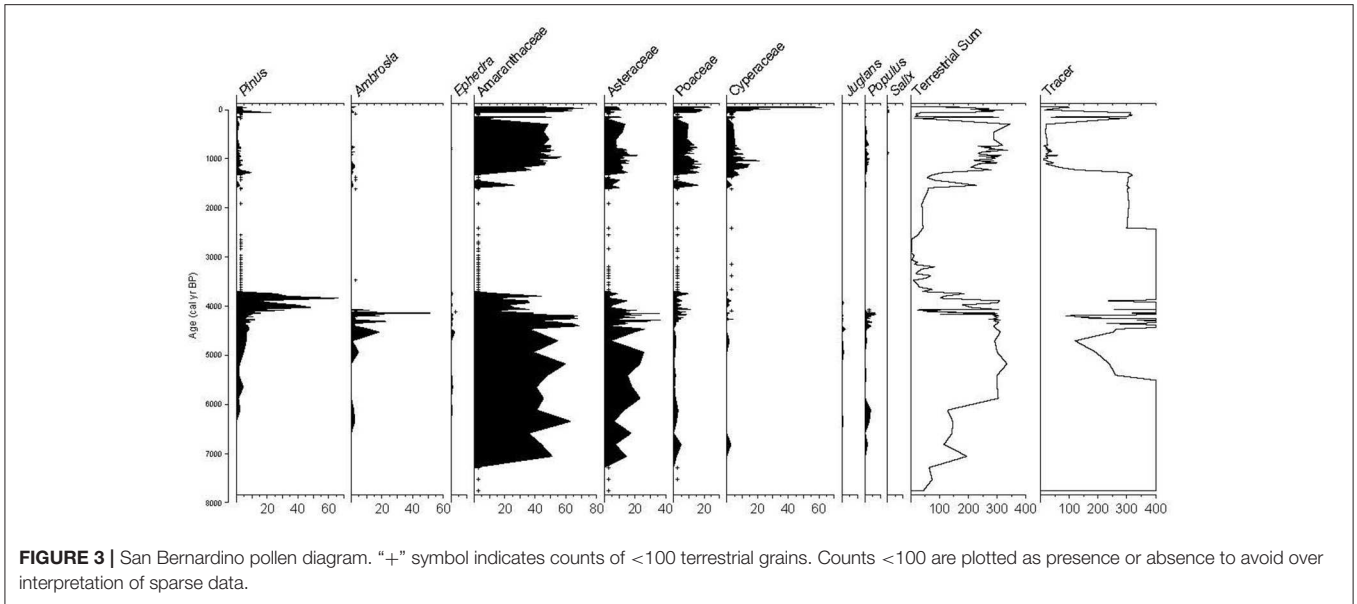
As with the SBNWR site, the amount of *Lycopodium* represents the preservation of the pollen grains for the last ~5,500 cal yr BP (Figure 4). At this site preservation is excellent from the beginning of the record until about 500 years ago. Other distinctive changes in the pollen include a decline and then subsequent increase in Cyperaceae centered on ~3,500 cal yr BP.

Canelo Hills Ciénega

The Canelo Hills record spans the last ~3,000 cal yr BP. Increased preservation as indicated by a decrease in *Lycopodium* improves from the beginning of the record toward present (Figure 5). Cyperaceae and grasses also increase toward present. Taxa extralocal to the cienega remain relatively constant with slight fluctuations (e.g., Amaranthaceae).

Babocamari Ciénega

The Babocamari record represent the last ~1,800 cal yr BP (Figure 6). Preservation is variable over time as indicated by increases and decreases in *Lycopodium*. Cyperaceae shows a strong increase toward present starting at ~900 cal yr BP. All other taxa remain relatively constant over the record.



Charcoal

San Bernardino Ciénga

The San Bernardino Ciénga charcoal record is the longest published fire history from the desert southwest (Figure 7). The record spans the last ~8,000 cal yr BP. From ~8,000 to ~5,000 cal yr BP there is essentially no charcoal in the SBNWR record. After ~5,000 cal yr BP the charcoal influx (CHAR) increases to a sustained level from 5,000 to 4,000 cal yr BP. After 4,000 cal yr BP the CHAR stabilizes around a new mean, increasing again around 1,500 cal yr BP.

Cloverdale Ciénga

The Cloverdale charcoal record initiates at ~5,000 cal yr BP and remains relatively constant for the entire record (Figure 7). There is a small decrease in CHAR centered on ~1,500 cal yr BP and it increases significantly in the last couple hundred years.

Canelo Ciénga

The Canelo Hills charcoal record represents the last ~3,000 cal yr BP (Figure 7). The CHAR slowly increases from the start of the record to present.

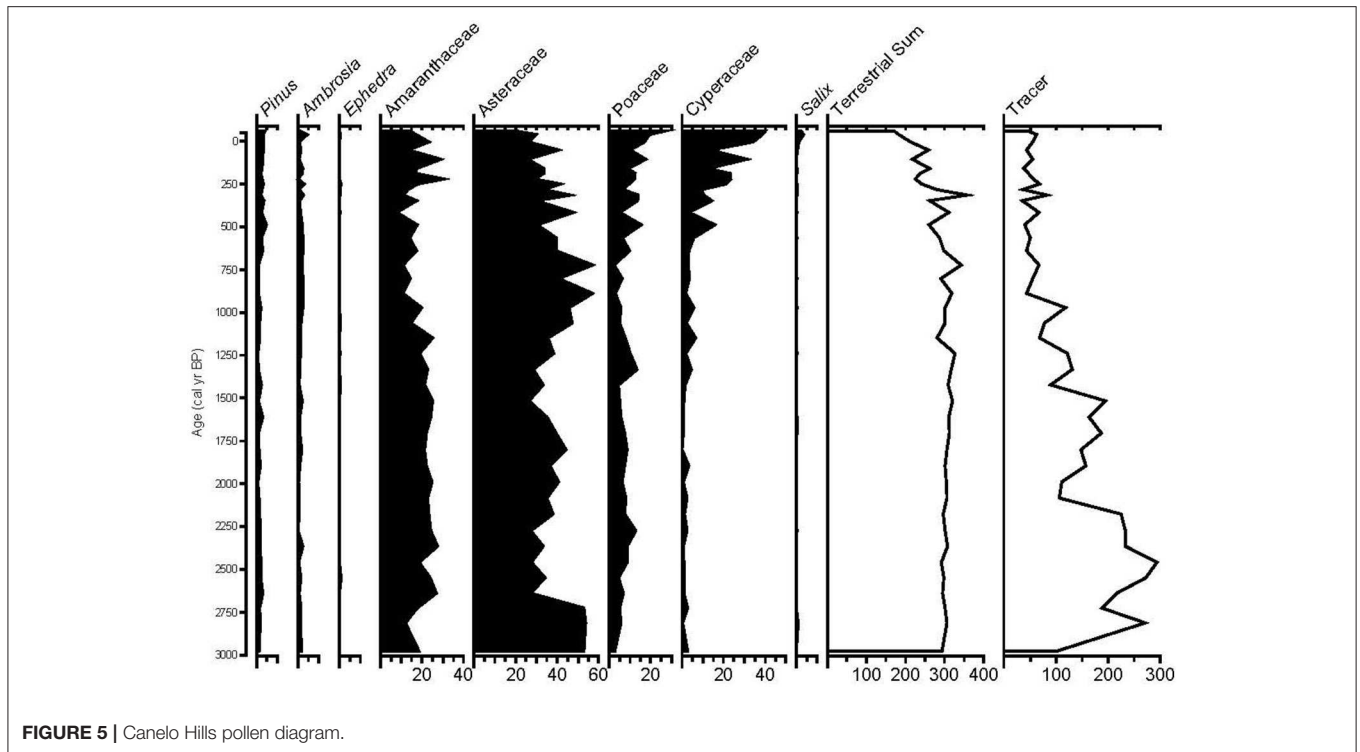


FIGURE 5 | Canelo Hills pollen diagram.

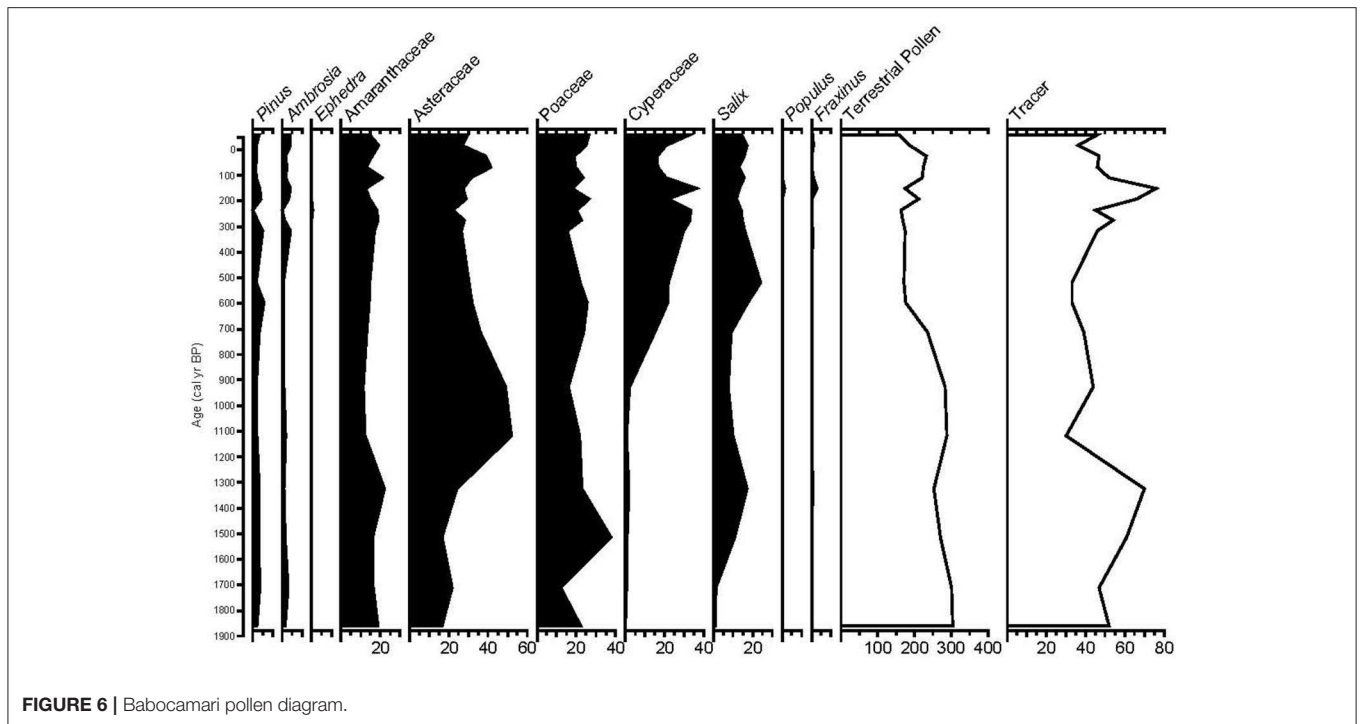


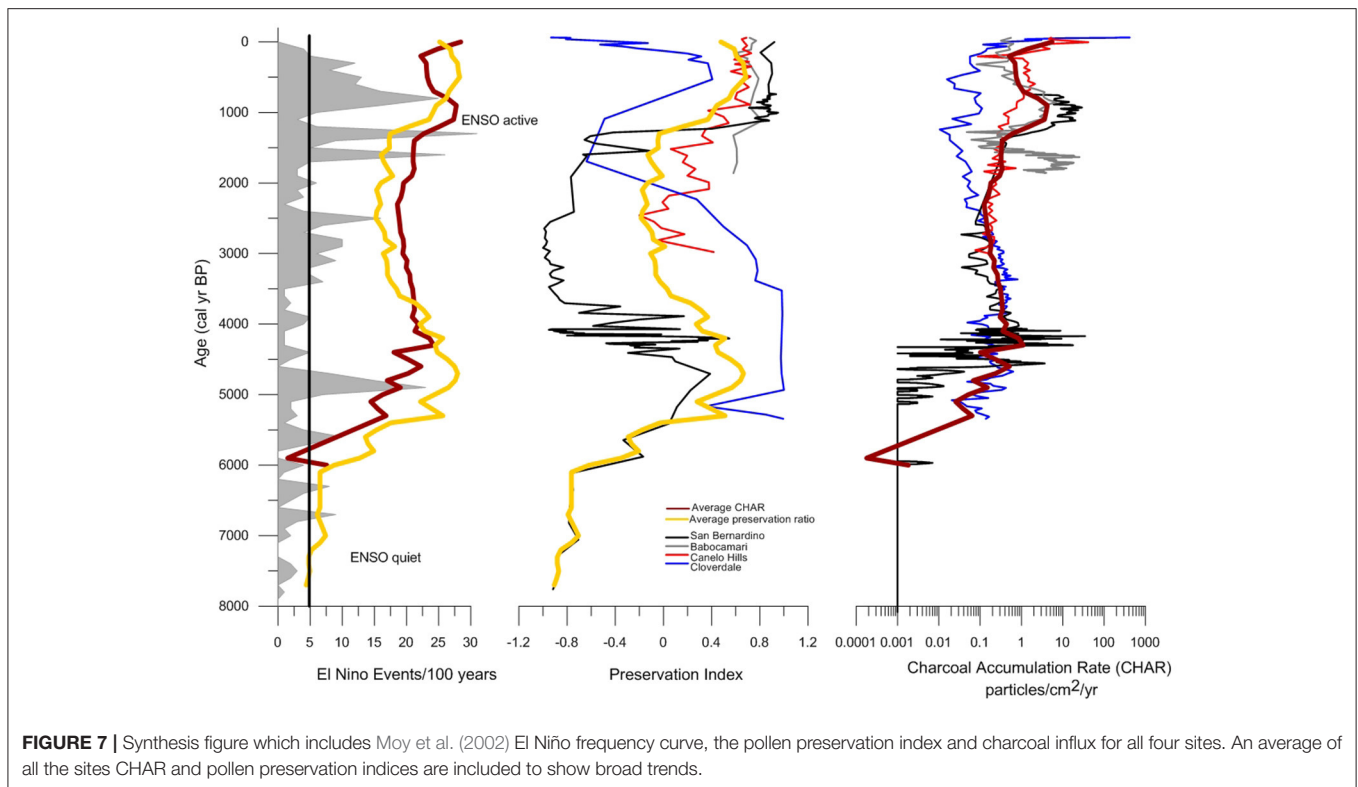
FIGURE 6 | Babocamari pollen diagram.

Babocamari Ciénega

The Babocamari record represents the last ~1,800 cal yr BP (Figure 7). The CHAR is relatively stable for the entire period and is of similar magnitude to the Canelo Hills and San Bernardino Ciénega records.

Modern Climate Analog

Our modern climate analog results illustrated in Figure 8 show composite-anomaly values based on the five strongest El Niño events from the Multivariate ENSO index (MEI) (Wolter and Timlin, 1993, 1998) and include 1982/1983; 1986/1987;



1991/1992; 1997/1998; and 2015/2016 compared to the long-term mean (1981–2010). We show winter (DJF) and spring (MAM) composite-anomaly values because these seasons represent the greatest impact of El Niño teleconnections in the region (Heyer et al., 2017). Additionally, winter and spring are important seasons for prolonged and persistent wet conditions that would support preservation of pollen in ciénegas.

During both winter and spring seasons, the southwest region experienced lower-than-normal atmospheric pressure at the 500 mb level (**Figure 8A**) indicative of persistent low pressure troughs. Such conditions are associated with counterclockwise flow of air around the region that deliver greater-than-normal moisture from the south via 850 mb specific humidity (**Figure 8B**). While the 500 mb Omega (vertical velocity) composite-anomaly maps (**Figure 8C**) indicate a mixture of weaker-than-normal (winter) and stronger-than-normal (spring) rising motions these motions are still associated with greater-than-normal moisture availability via specific humidity at the 850mb level. Both winter and spring months exhibit greater-than-normal precipitation values (**Figure 8D**) in our region of interest indicating persistent wet conditions through multiple seasons. The greater-than-normal precipitation along with lower-than-normal temperatures (not shown) contribute to the persistence of greater-than-normal soil moisture (**Figure 8E**) during both winter and spring months.

Statistical Relationships

The correlations between El Niño frequency and mean-pollen preservation ratios and mean-charcoal accumulation (CHAR) were compelling. The results show a correlation between El Niño

event frequency and CHAR and pollen preservation, however the correlation coefficient values strengthen when a lag in the data is considered. The optimal lag between El Niño frequency and CHAR is at 500 years while the optimal lag between El Niño frequency and pollen preservation ratios is at 300 years.

DISCUSSION

In this paper we present a quantitative approach for the interpretation of arid-land pollen sequences and introduce two new Southwestern desert sites. By merging the traditional summation and proportioning of terrestrial and non-terrestrial pollen, first demonstrated by Vonpost (1916) with a Boolean (presence/absence) and preservation evaluation, interpretations of absence or degradation can be placed in an ecological context. Ciénegas have been shown to be highly sensitive to hydrologic change and might be one of the few terrestrial ecosystems where state-changes have been identified (Scheffer et al., 2001; Scheffer and Carpenter, 2003; Folke et al., 2004; Heffernan, 2008; Minckley et al., 2011, 2013b). We utilize modern climate analogs of strong El Niño years to provide mechanisms for winter and spring moisture delivery into the region that would support ecological conditions of ciénega growth and pollen preservation.

Our interpretive approach allows us to address potential mechanisms driving ciénega development and controls on their growth related to regional climate and land-use (Brunelle et al., 2014). Winter and subsequent spring precipitation appears important to ciénega form and function through recharging groundwater systems that feed ciénega complexes. Without

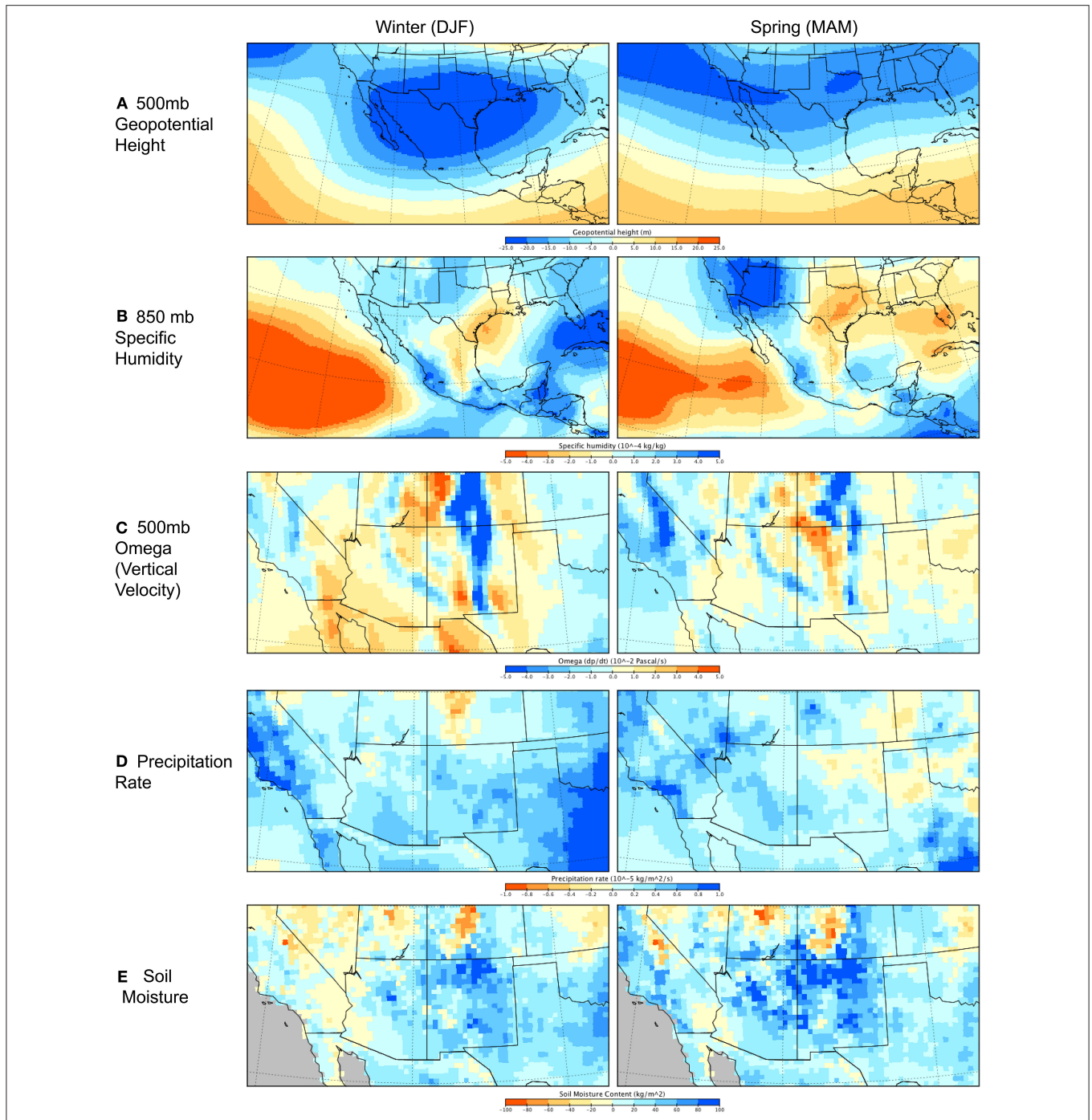


FIGURE 8 | Composite-anomaly maps for strong El Niño events 1982/1983; 1986/1987; 1991/1992; 1997/1998; and 2015/2016. Each map contains composite-anomaly values for winter (DJF) and spring (MAM) from the selected strong El Niño events compared to the long-term mean (1981–2010). **(A)** 500 mb geopotential height indicating anomalous ridges (red) or troughs (blue); **(B)** 850 mb specific humidity indicating moisture availability; **(C)** 500 mb omega (vertical velocity) indicating rising (blue) or sinking (red) motions; **(D)** Precipitation rate at the surface; and **(E)** Soil moisture.

critical inputs of winter and spring precipitation to support a water table emergence at the surface, ciénegas are intermittently dry or nonexistent. Groundwater lags have been shown to have long residence times of decades to centuries (Rodríguez et al., 2005; Wolaver et al., 2013) In the Southwest, winter and spring

precipitation is enhanced during El Niño events (Heyer et al., 2017). Scanlon et al. (2006) indicated that periods of frequent El Niño events result in three times as much groundwater recharge in the desert Southwest as compared to periods of frequent La Niña events. Flint et al. (2004) demonstrated with their

models that the southern part of the Great Basin gets 220% greater-than-mean recharge during El Niño years. These studies suggest a potential link between ENSO and ciénega state changes. Alternatively, groundwater discharge systems may also respond to local groundwater depletion via extraction in the present day (see Pigati et al., 2014; Sáez et al., 2016).

San Bernardino Ciénega

At San Bernardino Ciénega the pollen preservation ratio is low from the beginning of the record $\sim 8,000$ cal yr BP until $\sim 5,000$ cal yr BP (Minckley and Brunelle, 2007; Minckley et al., 2009, 2011). This transition in preservation coincides closely with our understanding of the initiation of ENSO active conditions (> 5 El Niño events per 100 years; Moy et al., 2002). Prior to the onset of active ENSO, the site was an intermittent wetland based on the sediment characteristics and the presence of some aquatic-type pollen grains such as Cyperaceae (Figure 3). After $\sim 5,000$ cal yr BP preservation increases (Figure 7) as does the abundance of wetland pollen taxa (Figure 3). Not only does the pollen preservation ratio track the initiation of ENSO-active conditions at $\sim 5,000$ cal yr BP, but it also decreases during the “quiet active” ENSO period from $\sim 4,500$ to $2,000$ cal yr BP (fewer than 5 El Niño events per 100 years), increasing again with the increase in El Niño activity after $\sim 2,000$ cal yr BP.

The fire history at San Bernardino Ciénega also correlates closely with the timing of the initiation of active ENSO conditions (Figure 7). There is essentially no charcoal in the San Bernardino Ciénega record until before $5,000$ cal yr BP (Brunelle et al., 2010). Prior to $5,000$ cal yr BP, the majority of rainfall in the region would have been from summer monsoons. In the Southwest, increased winter precipitation results in increases in the production of spring flowering annuals, which creates fine herbaceous fuels during the summer (Swetnam and Betancourt, 1990; Bowers, 2005). The production of these fuels creates a fuel continuity which would normally not be present in arid Southwestern desert ecosystems. Prior to the onset of El Niño events, there would have been ignition in the desert with summer convective storms, but the lack of fine fuel associated with enhanced winter precipitation would have prevented fire spread. The absence of charcoal prior to $\sim 5,000$ cal yr BP does suggest minimal fire activity prior to that time. In addition to the step-wise increase in charcoal at $\sim 5,000$ cal yr BP, there is a second increase in charcoal influx at $\sim 1,500$ cal yr BP, coincident with when El Niño activity enters its most active phase (Figure 7). This suggests that once winter precipitation provided the fine fuel source and fuel connectivity, fire activity and charcoal production increased, connecting charcoal records and El Niño activity.

Cloverdale Ciénega

The Cloverdale Ciénega initiates when ENSO enters the active phase $\sim 5,000$ cal yr BP (Figure 7). We propose that the increase in groundwater recharge associated with El Niño-enhanced winter and spring precipitation allowed the water table to rise to the point of surface saturation/standing water and the ciénega to form. Scanlon et al. (2006) assert that groundwater recharge in the desert southwest is controlled by the occurrence of wet winters and springs associated with El Niño conditions. The

pollen preservation at Cloverdale Ciénega also improves with increased activity of El Niño events (Moy et al., 2002; Figure 7). Preservation decreases slightly with a small decrease in El Niño events $\sim 2,000$ cal yr BP, but then preservation increases with the subsequent increase in El Niño events. Wetland taxa like Cyperaceae decrease during the “quiet” El Niño period starting around $4,500$ cal yr BP possibly indicating a lowering of the water table (Minckley et al., 2013b; Figure 4). While the pollen preservation signal remains high for the remainder of the record, Cyperaceae percentages drop with the introduction of cattle to the site $\sim 1,600$ CE (Brunelle et al., 2014). This extensive use of the region for cattle grazing at this time led to woody plant encroachment and a shift in the vegetation community clearly recorded in the sedimentary pollen record (Brunelle et al., 2014).

The charcoal accumulation rate from Cloverdale Ciénega follows the general trends of El Niño frequency with a slight decline in charcoal accumulation associated with the quieter ENSO period (Figure 7). The charcoal record suggests a fire regime controlled by the presence of fine fuels, which would be enhanced by anomalous winter and spring moisture typical of strong El Niño events in the region (Figure 8, also see Heyer et al., 2017). The large increase in charcoal accumulation in the latest part of the record appears to be a decoupling of the natural fire regime and is likely associated with the encroachment of woody plants at this time (Brunelle et al., 2014). The decrease in complete combustion associated with woody fuels would lead to an increase in the production of charcoal (Marlon et al., 2006).

Canelo Hills Ciénega

The preservation ratio at Canelo Hills increases from the onset of the record at $\sim 3,000$ cal yr BP to present. The wetland record from Canelo Hills doesn't initiate until $\sim 3,000$ cal yr BP which is when El Niño enters a consistently active phase. The initiation of Canelo Hills is likely related to the winter precipitation recharge of the aquifer which then allowed water at the surface of the ciénega. In addition to an increase of preservation, Cyperaceae grains become increasingly more abundant from about 500 cal yr BP to present, likely indicating the expansion of the ciénega site. The charcoal accumulation rate slowly increases from the start of the record to present with dips coincident with decreases in the El Niño frequency curve. This again suggests a connection between El Niño years and fine fuel production and accumulation.

Babocamari Ciénega

Babocamari Ciénega is the youngest ciénega of the four sites, with a $\sim 1,800$ cal yr BP record. As with Cloverdale and Canelo Hills, there seems to be a strong connection between the state of ENSO and the initiation of the ciénega. Babocamari initiates after the very highest peaks in El Niño event frequency (Figure 7). There is strong support for the relationship between greater El Niño event frequency and increased groundwater recharge in the Southwestern deserts (e.g., Flint et al., 2004; Scanlon et al., 2006).

Also, like at Canelo Hills, we observe a relatively recent increase in Cyperaceae. At Babocamari the increase begins at about 900 cal yr BP, but then drops from ~ 150 to 50 cal yr BP ($1,800$ – $1,900$ CE). This decrease is likely associated with EuroAmerican impacts to the landscape (e.g., grazing,

water diversion, etc.), however we also see the recovery of the Cyperaceae wetland community in the most recent sample which likely reflects the restoration efforts underway at the ciénega.

Site Synthesis

Continuous records of environmental change reveal how environments respond to past natural perturbations, and provide insight into the trajectory and rate of change environments may experience in the future. Looking for a coherent pattern for the interpretation of desert wetland records is difficult, because unlike temperate lakes which can be produced from glaciation, ciénegas are controlled by local hydrologic conditions (Minckley et al., 2013b). In addition, during periods of disturbance or drought the sediments can be lost (Heffernan, 2008; Heffernan et al., 2008; Minckley et al., 2013b), so we lack a regional context that only multiple sites of similar age can provide. However, there are nested patterns in the data presented here. Wet-dry episodes seen in the longest record, San Bernardino Ciénega, are either repeated in the other records through temporal overlap of ecological histories recorded or the initiation of the younger records. This suggests that there is a regional climate linkage to the development, growth and senescence of these wetlands.

The relationship between fire and ENSO is well recorded in the regional upland forests records of the Southwest (Swetnam and Betancourt, 1990). To assess this relationship from the ciénega records, the average CHAR and pollen preservation ratios were calculated for the 4 sites. These averaged time series were then correlated with the El Niño frequency curve (Moy et al., 2002) to determine if statistically significant relationships exist [e.g., is the frequency of El Niño affecting the fire regime (CHAR) or state (wet vs. dry) of the wetland (as indicated by the pollen preservation ratio)]. When correlations were run on parallel time series (e.g., “no lag”), the correlation 95% confidence interval between El Niño frequency and CHAR was -0.04 to 0.38 with a p -value of 0.10 , and the correlation 95% confidence interval between El Niño and pollen preservation was 0.10 – 0.50 with a p -value of 0.05 (Table 2). These values do suggest that some of the variability in CHAR and pollen preservation are controlled by the frequency of El Niño. However, when one examines the CHAR and pollen preservation curves in comparison with the El Niño frequency curve (Figure 8) a temporal offset is evident. It is ecologically consistent that if there was a period of increased El Niño frequency that the increase in ciénega CHAR might follow with some lag. To better understand ciénega system lags, correlation analyses were performed at 100, 200, 300, 400, and 500 years. The analyses demonstrated that average ciénega CHAR correlates best with El Niño frequency at a lag of 500 years with a correlation 95% confidence interval of 0.26 – 0.62 and p -value of 0.000026 . The same exercise was conducted between El Niño and average ciénega pollen preservation data, with the optimal correlation 95% confidence interval of 0.25 – 0.61 and p -value of 0.00004 identified with a lag of 300 years (Table 2). Again, given the lag in groundwater recharge and emergence following a period of wet winters and springs (high El Niño frequency), and the lag in the drying of a ciénega system following a series of dry winters (low El Niño frequency), it is not surprising the best fit between the two time series included a several

TABLE 2 | Summary of correlation analyses and results.

Variables	95% Confidence interval	p -value
Mean-pollen preservation and mean-charcoal accumulation	0.22–0.59	0.0001
Mean-pollen preservation and El Nino events	0.10–0.50	0.005
Mean-pollen preservation and El Nino events 300 yr lag	0.25–0.61	0.00004
Mean-charcoal accumulation and El Nino events	-0.04 – 0.38	0.10
Mean-charcoal accumulation and El Nino events 500 yr lag	0.26–0.62	0.000026
Mean-charcoal accumulation and regional standardized charcoal	-0.28 – 0.16	0.57

hundred year lag. Also, the fact that we are dealing with multiple (likely imperfectly) age-modeled systems should be considered in the evaluation of the statistical correlations between these time series. The compelling result is the relatively high correlation values given the comparison of climatic forcings and ecological responses.

Another observation using the averaged CHAR data comes from the analysis of the averaged ciénega CHAR with the regional standardized CHAR. A 95% confidence interval of -0.26 to 0.15 , and a p -value of 0.57 (Table 2) indicate a lack of relationship between averaged ciénega CHAR and regional standardized CHAR. While ponderosa pine systems demonstrate a relationship with ENSO (Swetnam and Betancourt, 1990), many of the sites in the regional aggregate represent other forest types where fuel availability is less limited than the low elevation ciénega sites. In the American Southwest, upper elevation fire regimes are limited by moisture (low moisture and fire) whereas fire regimes in the deserts are limited by fuel availability (Krawchuk and Moritz, 2011). A Pearson's correlation between average ciénega pollen preservation and average ciénega CHAR reveal a 95% confidence interval of 0.22 – 0.59 and p -value of 0.0001 , suggesting fuel availability limited fire at our sites (Table 2). Further, the different controls on fire regime are strongly reflected in the lack of correlation between the average ciénega CHAR and the regional standardized CHAR (Table 2).

von Post (1946) identified the regions of the world where vegetation history was fairly well known. Conspicuously, temperate regions were well represented, while arid regions were largely blank. This map would be fairly similar today. Desert regions have limited depositional contexts where pollen data are preserved and, as such, quantifying past changes requires a degree of creativity. Our approach has been to take the traditional quantitative method as we have learned it and apply it as best we can in these contexts. However, palynology, as is necessarily practiced in arid environments, requires applying ecological knowledge to the variability within pollen counts (i.e., poor pollen preservation has meaning, and plotting percentages is not always appropriate). In doing so we can provide novel interpretations to the continuous history of place that sedimentary records provide us.

In addition to providing the general paleoenvironmental information for the sites presented here, there are four main interpretations that we make from these records. (1) The length of the sedimentary record provides information on groundwater levels (surface saturation via pollen preservation). (2) The pollen preservation index can be used to determine when sediments are continuously vs. intermittently wetted, which we propose as a proxy for winter precipitation. (3) Our evidence of fire history provides an indirect record of fuel connectivity away from the wetlands largely associated with fine fuel production. (4) Finally, our assessment of modern climate analogs during strong El Niño years provides a mechanism for consistent and persistent delivery of moisture into the region during winter and residual effective moisture during spring, which supports an active ciénega state, pollen preservation and production of fine fuels.

CONCLUSIONS

In the palynological tradition of Lennart Von Post, this paper utilized pollen data to understand the past environment in a poorly known region. We contribute two new ciénega reconstructions to the existing body of work of the relatively sparse paleoenvironmental record in the desert Southwest. Our objectives were to (1) identify conditions in the sedimentological proxy data (e.g., pollen and charcoal) that record changes in ciénega systems attributed to climate; and (2) to assess the dominant atmospheric drivers related to enhanced winter precipitation in ciénega systems. In addition to providing baseline information on the taxa present and fire regimes, we also detected connections between the frequency of El Niño events and sedimentary proxy.

We identified the pollen preservation index as a means to determine when sediments are continuously vs. intermittently wetted, which in this region is a proxy for winter precipitation. We also determined that the length of the sedimentary record provides information on groundwater levels (surface saturation) and the state and input of winter precipitation as well as persistence of effective moisture into spring months. Finally, fire history from ciénegas may be an indirect record of ENSO through the production of fine fuels. We propose that with continued analysis and the addition of more sites, desert ciénega records may be valuable in filling in the gaps of environmental reconstruction as an independent indicator of past El Niño activity.

By using modern climate analogs of strong El Niño events, we provide context for the teleconnections between such modes of variability and persistent wet conditions within desert Southwest

ciénegas. Since pollen preservation in ciénegas is dependent upon wet conditions and winter season precipitation associated with El Niño events that persist into spring in the Southwest, our modern climate analog results provide mechanisms for moisture delivery into the region that would support active ciénegas. This delivery is a function of persistent lower-than-normal pressure and higher-than-normal moisture availability delivered into the region from the subtropics. Our results are specific for the prolonged wetter-than-normal conditions that persist into spring during strong El Niño events. In other words, wetter-than-normal winters alone are not enough to provide moisture availability through subsequent spring months. Thus, analyses of prolonged wet ciénega conditions should consider the impact of persistence associated with multiple season anomalies, such as those that occur during strong El Niño events. Our results suggest that increased El Niño intensity or persistent El Niño events support enhanced and prolonged wet conditions from winter into spring months within ciénega ecosystems. Such persistence of moisture from winter through spring supports both pollen preservation as well as providing conditions conducive for establishment of fine fuels and increased fire activity.

AUTHOR CONTRIBUTIONS

AB and TM: field collection, lab analysis, data analysis, preliminary manuscript writing, editing, revisions; JS: modern climate analog analysis and writing, editing, revisions; JH: correlation analysis, regional charcoal analysis, writing, editing, revisions.

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The handling editor declared a shared affiliation, though no other collaboration, with one of the authors, AB.

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