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Paleohydrology and growth of a desert ciénega

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Abstract

A ~7000-year record of sediment accumulation from the San Bernardino ciénega in southeastern Arizona/northeastern Sonora records changes in effective moisture. Periods of rapid sedimentation between ca. 700 to 1100 cal yr BP and ca. 4100 to 4400 cal yr BP at San Bernardino are associated with a highstand at pluvial Lake Cochise, the presence of aquatic pollen taxa in New Mexican packrat middens and periods of incision in river channels in the San Pedro and Santa Cruz river valleys. These results suggest that ciénega deposits represent records of hydrological change and, as such, are important but under-utilized repositories of paleoclimatic information. These results also inform ciénega restoration efforts by highlighting the importance of subsurface and surface water flow through these environments. Effective restoration requires the development of conditions where groundwater maintains surface vegetation and seasonal floods are allowed to inundate the surface.

Keywords: Wetlands; Ciénegas; Hydrology; Paleoclimate; Conservation; Arizona/Mexico

1. Introduction

Since the late 1800s, natural wetlands in arid and semi-arid desert grasslands of the American Southwest and Northern Mexico have largely disappeared. Historically, desert wetlands, or *ciénegas*, were well distributed across the landscape and a valuable resource for native animals, plants, and prehistoric cultures (Davis et al., 2002). Ciénegas are low gradient wetlands found between 1000 and 2000 m elevation asl in the American Southwest

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(Hendrickson and Minckley, 1985). These wetlands form in headwaters and low-order streams with high groundwater tables, promoting surface inundation (Hendrickson and Minckley, 1985). As Euro Americans arrived in the Southwest, ciénegas were converted to agricultural and grazing fields, and more recently have been used as a source of groundwater for growing communities in the region (Hendrickson and Minckley, 1985). Since 1900, erosion associated with post-settlement channelization, and drawdown of local water tables have dried up most ciénega environments (Bryan, 1928; Hendrickson and Minckley, 1985). Many of the region's remaining ciénegas are now maintained through artificial impoundments and wells that draw water from depths far below the surface.

Recent desiccation and erosion leading to arroyo (i.e., incised channel) development caused by land usage is in contrast to prehistoric periods of climatically driven downcutting (Waters and Haynes, 2001). Waters and Haynes (2001) use cut and fill sequences from the Santa Cruz River (SC) and San Pedro Valley (SPV), Arizona to study Holocene alluvial down-cutting periods. Their research suggests that prior to extensive grazing and agriculture, down cutting in the larger river systems took place during periods of increased precipitation. In this paper we discuss growth rates and processes of ciénega development in the American Southwest using well-dated sedimentary sequences from the San Bernardino ciénega of southeastern Arizona. We compare these results with multiple climate proxy data from ciénegas, packrat middens, lake levels, and alluvial sequences from the northern Sonoran and Chihuahuan deserts to examine possible linkages between past climatic changes and the developmental history of ciénegas (Grimm et al., 1997). Understanding the mechanisms that control ciénega formation is of great use to land managers working to restore and preserve these valuable natural resources.

1.1. Regional setting

San Bernardino ciénega is located near the broad ecotone of the Chihuahuan and Sonoran deserts 35 km east of Agua Prieta, Sonora MX/Douglas, Arizona USA (Fig. 1). Average annual precipitation is 366 mm with ~50% of that occurring during summer monsoonal storms in July and August (Western Regional Climate Center, Douglas AZ Climate summary 1948–2005, www.wrcc.dri.edu). Average annual temperature is 26 °C, with summer maximum temperatures exceeding 35 °C. Currently the inactive ciénega surface is dominated by annual herbaceous taxa including *Salsola iberica* (Russian thistle), *Amaranthus palmeri* (carelessweed), *Ambrosia confertiflora* (burr ragweed), and *Portulaca* sp. (purslane). Active ciénega vegetation includes *Cyperus* sp., *Carex* sp. (sedges), *Aster* sp. (sunflowers), *Anemopsis californica* (yerba mansa), *Mimulus guttatus* (seep monkey flower), and *Nasturtium officinale* (watercress) (Marrs-Smith, 1983). The riparian area near the present-day outflow of the ciénega (called Black Draw in the U.S. and Rio San Bernardino in Mexico) contains stands of *Populus fremontii* (Fremont cottonwood) and *Salix gooddingii* (black willow) bracketed by dense *Prosopis glandulosa* (honey mesquite) stands on the upper banks of the arroyo cuts and into the uplands. Vegetation away from the ciénega surface is Chihuahuan desert scrub, dominated by shrubs such as *Larrea divaricata* (creosotebush), *Prosopis*, *Acacia*, and grasses such as *Hilaria mutica* (tobosa) and *Bouteloua barbata* (Sonoran grama) (Marrs-Smith, 1983).

1.2. Site description

San Bernardino ciénega, 31.3333°N; 109.2646°W, 1161 m asl, is located in the drainage of Black Draw Wash/Rio San Bernardino (RSB) of southeastern Arizona, USA and northeastern Sonora, Mexico (Fig. 1), which connects downstream with the Rio Yaqui. The historic ciénega is 1–3.4 km wide and 6 km long (Rosen et al., 2005). Surface flow through RSB is mostly ephemeral. The region's bimodal precipitation regime features winter frontal storms resulting in low, relatively constant stream flow and summer convective storms resulting in periodic high stream flows (flash floods) (Etheredge et al., 2004). Currently the ciénega surface is mostly dry except for artificial impoundments and a few perennial springs. Permanent sub-surface water is ~5 m below the present-day surface. Indirect and direct draining and land use changes of the ciénega surface has caused the RSB to become incised in the past ~100 years dropping the water table to its current position (Bryan, 1928).

2. Methods

Sediments from four locations were collected during the summers of 2004 and 2005. Three sampling locations were from San Bernardino ciénega including Snail Springs (active ciénega surface), Rio San Bernardino arroyo (RSBA) channel wall (incised channel

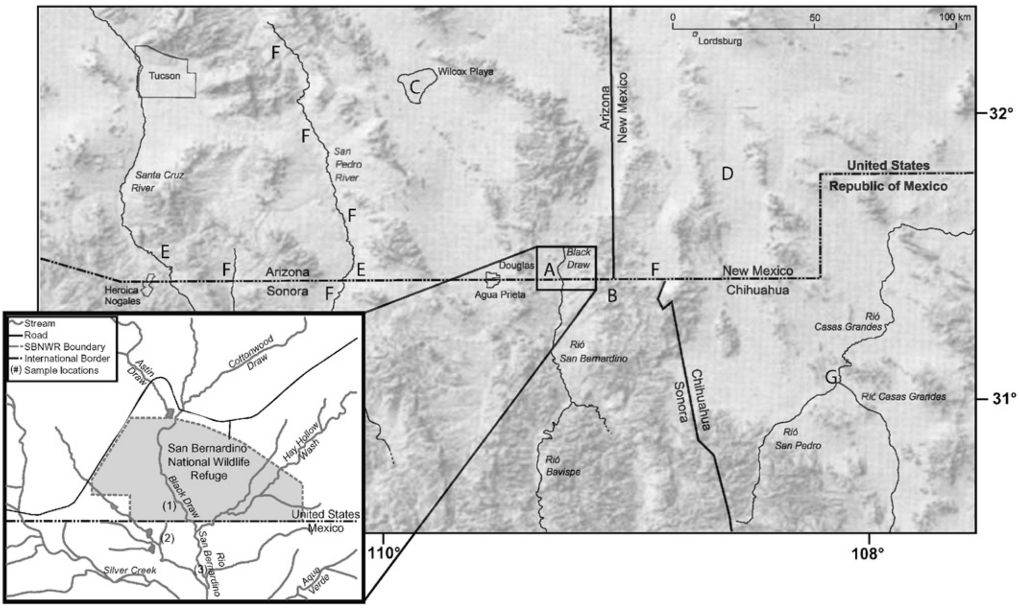

Fig. 1. Map showing the location of San Bernardino ciénega (A), Los Ojitos (B), and studies referenced in text including pluvial lake Cochise (C) (Waters, 1989), vegetation history of the Playas Valley New Mexico (D) (Holmgren et al., 2003), alluvial history of the Santa Cruz and San Pedro rivers Arizona (E) (Waters and Haynes, 2001), regional ciénegas (F) (Davis et al., 2002), and alluvial history of the Rio San Pedro Casa Grandes confluence Mexico (G) (Nordt, 2003). Inset map shows the spatial relationships between (1) San Bernardino National Wildlife Refuge (SBNWR) core, (2) Snail Spring, and (3) Rio San Bernardino Arroyo (RSBA) sampling locations. Also shown are the headwater drainages of the San Bernardino ciénega region.

Table 1
Radiocarbon dates from ciénega sediments

Site	Depth (cm)	Beta number	^{14}C yr	Cal yr BP-CALIB5.0.2 (midpoint)
Snail springs	57–59		150 ± 40	225 (225)
Rio San Bernardino arroyo (RSBA)	42	Beta-204829	830 ± 40	676–797 (740)
	110	Beta-204374	1200 ± 40	1051–1189 (1120)
	180	Beta-204828	2470 ± 40	2428–2623 (2526)
	380	Beta-203022	3900 ± 40	4229–4428 (4328)
San Bernardino National Wildlife Refuge core (SBNWR)	347	Beta-207161	3740 ± 40	3979–4182 (4080)
	554	Beta-207162	3920 ± 40	4238–4442 (4340)
	668	Beta-207163	6190 ± 50	6956–7180 (7068)

exposing desiccated ciénega sediments), and the dry ciénega surface of the San Bernardino National Wildlife Refuge (SBNWR). Los Ojitos ciénega, located 25 km southeast of San Bernardino ciénega, was also sampled. At Snail Springs and Los Ojitos, 0.65 and 0.68 m cores, respectively, were retrieved using a modified Livingstone corer (Wright et al., 1983). The RSBA samples were collected contiguously from a freshly exposed sediment face with a trowel at 2-cm intervals from the present-day surface to 1.10 m depth and 5-cm intervals from 1.75 to 3.80 m depth. Between 1.10 and 1.75 m there was a set of unconformal surfaces evidenced by sand deposits that were not analyzed. From the ciénega surface on the SBNWR, a ~15-m long core was obtained using a truck mounted 5-inch hollow barrel auger. After collection, sediments were described, wrapped in plastic and aluminum foil or placed in sterile bags, and transported to the University of Utah, RED Lab (Records of Environment and Disturbance) for analyses.

2.1. Dating

Chronology for each section was based on radiocarbon ^{14}C age determinations, or in the case of Los Ojitos time since restoration of the ciénega (Figs. 2 and 3). Los Ojitos was restored through the reconnection of the stream to the ciénega surface in 1999. Multiple dates were obtained for the arroyo (RSBA) and ciénega (SBNWR) sites (Table 1). A single ^{14}C date was obtained for the Snail Springs core, and the sedimentation rate was calculated considering this date and the present-day surface as -54 ^{14}C years.[1] Dates were converted to calendar years before present (cal yr BP) using the program CALIB 5.0.2 (Stuiver and Reimer, 1993). Linear interpolations between dates were used to calculate sedimentation rates for each section (Fig. 3).

2.2. Lithological analysis

Loss on ignition (LOI) analyses provided information on sedimentation history of the ciénega by providing a proxy of organic productivity through time. LOI analyses provide data on percent water, organic, and carbonate content. From these percentages, information on terrestrial clay and silt input onto the surface can be inferred (Geyde

[1]Radiocarbon age 0 is 1950 based on the spike in ^{14}C that resulted from atmospheric nuclear testing.

et al., 2000). Samples of 1 cm^3 were taken contiguously from RSBA section and at 5–7 cm intervals from the Snail Springs and SBNWR cores. Los Ojitos sediments were not analyzed for LOI since they only represent ~5 years of accumulation the organic carbon values would be orders of magnitude higher than the other sites. Samples were dried for 24 hours at 90 °C and weighed to determine residual water content. Samples were then combusted at 550 °C for two hours and weighed to determine percent of organic content. Finally, samples were combusted at 900 °C for two hours and weighed to determine percent of carbonate content (after Dean, 1974).

The magnetic susceptibility (MS) (measured in electromagnetic units [emu]) of the samples was contiguously measured. MS measures the ease with which sediment takes a magnetic charge. Sediments derived from terrestrial systems include minerals from the parent rock that have a higher MS than sediments produced in an organic environment. MS is therefore an excellent proxy for erosion into aquatic systems where most autochthonous production has little to no magnetic component. MS data are related to the LOI data by providing another proxy for allochthonous sediment input. 10 cm^3 sediment was placed in plastic containers and measured in a Bartington cup-coil magnetic-susceptibility instrument.

3. Results

3.1. Lithology

The composite record of three sampling locations from San Bernardino ciénega indicates long periods of aggrading organic rich, clay-sands punctuated with unconformities of sand and cobbles (Fig. 2). The bottom-most sediments were composed of clay and cobble from 6.68 to 7.02 m. Above this unit were clay and gravel until 6.21 m. From 2.40 to 6.21 m sediments are clay dominated with periodic deposits of sandy clays. A sandy unconformity between 2.30 and 2.40 m was capped by a marl-like clay from 2.15 to 2.30 m. Another sandy unconformity was present from 2.05 to 2.15 m. Above 2.05 m, sediments were dominated by clays that continue to the top of the active cienega surface at Snail Springs. At Los Ojitos, sediments were entirely comprised of organic material.

3.2. Sedimentation rates

The three sections sampled from the main San Bernardino ciénega (Snail Springs, RSBA, and SBNWR) reflect different periods of deposition (Fig. 3). Snail Springs reflects the last ~225 years of deposition, the RSBA reflects ~740–4328 cal yr BP and the SBNWR represents ~4080–7068 cal yr BP. (Figs. 2 and 3). The uppermost sediments (740 cal yr BP to present; top 0.42 m) from RSBA were homogenized, likely from plowing during the agricultural period of the San Bernardino ciénega, and were not considered in our analysis. Using the composite record of all San Bernardino ciénega sections, aggradation rates of the ciénega deposits were low (0.04 cm/yr) between 4340 and ca. 7068 cal yr BP (3.40–6.68 m depth) (Fig. 3). After 4340 cal yr BP, sedimentation increased to 0.88 cm/yr until 4080 cal yr BP (3.40–5.50 m depth). Sedimentation rates decreased to 0.11 cm/yr from 2526 to 4328 cal yr BP (1.80–3.40 m depth). From 1120 to 2526 cal yr BP (1.10–1.80 m depth) there was a set of unconformities characterized by fluvially derived sand lenses and marl deposits. Above these unconformous surfaces, sedimentation is 0.18 cm/yr between

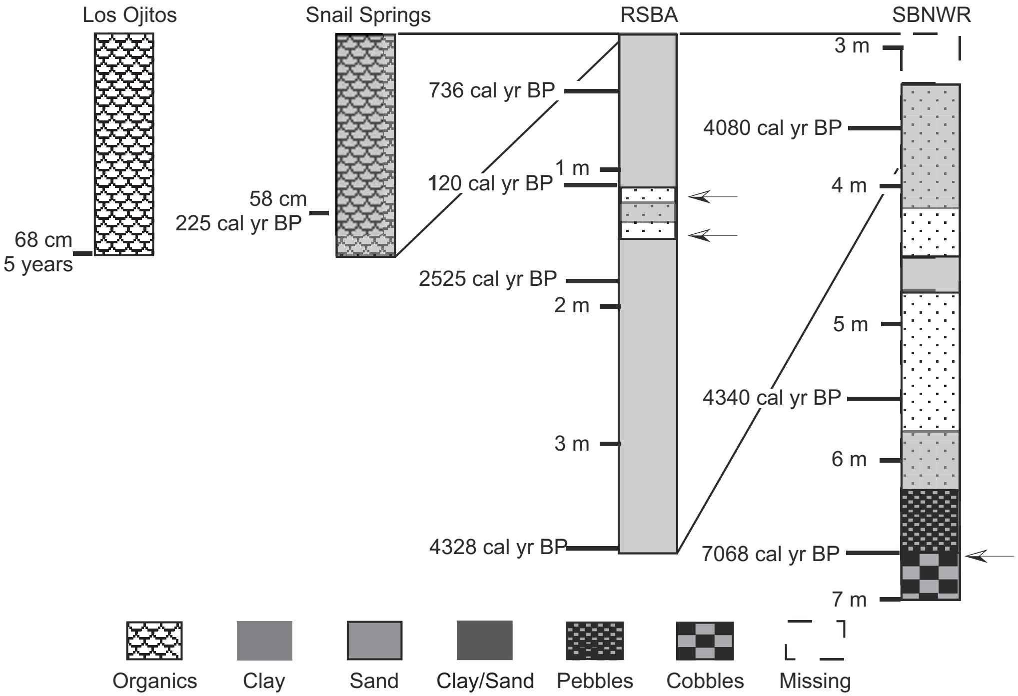

Fig. 2. Lithology of Los Ojitos, Snail Spring, Rio San Bernardino Arroyo (RSBA), and San Bernardino ciénega (SBNWR) sections. The vertical relationship between each section is indicated by the solid black line. Depths that were sampled for radiocarbon dating are shown on the left of each section. Arrows indicate the location of unconformities within each section.

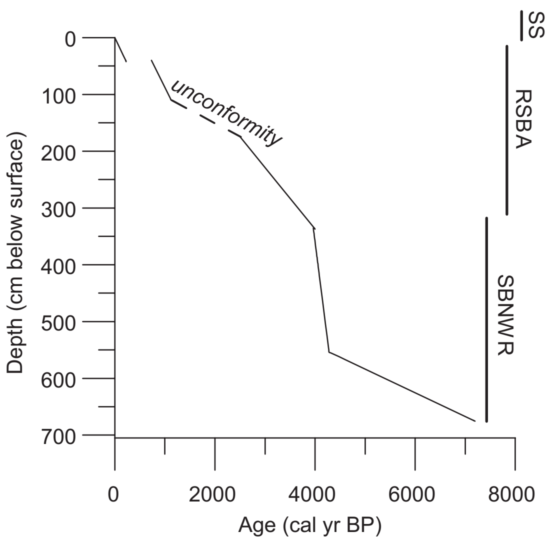

Fig. 3. Age-depth relationships for Snail Springs (SS), Rio San Bernardino arroyo (RSBA), and San Bernardino National Wildlife Refuge (SBNWR) core. Depth of each section is from the present-day ciénega surface. The unconformity in the RSBA section is indicated by the dashed line. Sedimentation rates are based on linear interpolations between each date, which are indicated by the inflection points.

740 and 1120 cal yr BP (1.10–0.42 m). During the past 225 cal years, (upper 58 cm of Snail Springs core) sedimentation has increased to 0.21 cm/yr.

3.3. Organic and inorganic carbon

Organic carbon was relatively low throughout the record, averaging 2.3% (Fig. 4). Two exceptions were evident between ca. 4500–5500 cal yr BP and ca. 500–1000 cal yr BP, when organic carbon increased to >6%. Inorganic carbon was low (<1%) throughout the SBNWR section, but relatively high (>7%) in the lower portion of the RSBA section, decreasing to ~2% towards the present. There was a significant difference (5–7%) in the inorganic carbon content measured from RSBA and SBNWR during the period of temporal overlap between the two sections. These differences may represent differential

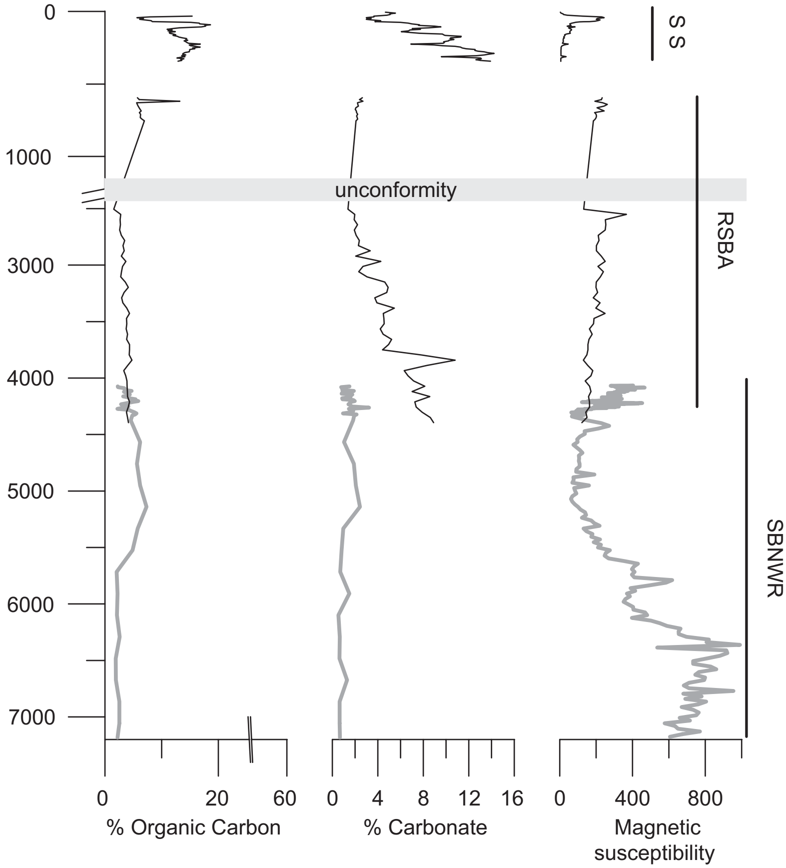

Fig. 4. Composite of the changes of percent organic and inorganic carbon and magnetic susceptibility for Snail Springs (SS), Rio San Bernardino arroyo (RSBA), and San Bernardino National Wildlife Refuge (SBNWR) core. The break in the x-axis for organic carbon illustrates the dominance of organic growth in these wetlands in the absence of surface flooding at Snail Spring. High magnetic susceptibility in the lower portions of the San Bernardino National Wildlife Refuge core may be indicative of greater sediment input during the middle Holocene. Gray bar indicates unconformal section of the Rio San Bernardino arroyo section that contained two thick sand lenses.

evaporation rates across the ciénega surface at the time of deposition. Alternatively, the relatively high inorganic carbon content of the lower section of RSBA may indicate secondary leaching of carbonate associated with lateral movement of groundwater towards the incised modern baseline of the Rio San Bernardino channel.

From 3000 cal yr BP to the unconformity at ca. 2500 cal yr BP, organic carbon remained relatively constant, between 1% and 2%. After the unconformities, at ca. 1100 cal yr BP, organic carbon was higher than previous and inorganic carbon was slightly lower than previous. The uppermost sediments from Snail Springs have the highest organic and inorganic carbon in the record ranging from 6% to 54% for the organic carbon and 3% to 14% for the inorganic carbon.

3.4. Magnetic susceptibility

MS readings were highest (>800 emu) in the SBNWR samples and lowest (~3 emu) in the Snail Springs samples. Because MS data can vary due to changes in atmospheric pressure and temperature, and the MS for each section was measured on different days, the trends within each site were considered rather than absolute numbers (Fig. 4). Prior to 5200 cal yr BP there were two periods of high MS. The first occurs from ca. 7000 to 6500 cal yr BP and was associated with low organic carbon. The second was centered on 5800 cal yr BP was associated with low inorganic carbon. After 5800 cal yr BP, MS decreases until 4500 cal yr BP when a general increasing trend begins. MS stabilizes ca. 3500 cal yr BP except for the peak towards the top of the Snail Springs section, likely associated with 20th century settlement.

4. Discussion

Ciénegas in the American Southwest provide critical habitat for numerous endangered and endemic species of plants and animals. As such, it is important to understand the history of these environments for both conservation of existing ciénegas and the restoration of inactive surfaces. The results of this study demonstrate that ciénega growth can be quite rapid (up to 1 cm yr^{-1}) under proper conditions and that occasional erosional episodes are part of the natural cycle of these systems.

In the case of the San Bernardino ciénega, when the surface was functioning as a "living" cienega, the accumulating sediments reflect in situ growth from the decomposition of macrophytes growing on the surface and fluvially transported sediment deposition. Sheet flooding, particularly during the summer monsoon, mobilizes high volumes of sediment from the surrounding uplands (Etheredge et al., 2004). When these floods encounter the broad, vegetated ciénega surface, the energy of the water is dispersed and the sediment load, composed mainly of silts, clays, and sands, is deposited. We hypothesize that the high MS during times of rapid aggradation reflects more frequent and longer duration surface flows (Leopold et al., 1995; Etheredge et al., 2004). This allocthonous input buries part of the organic surface forcing the vegetation to respond with rapid growth. In contrast, during slow periods of aggradation, organic carbon is elevated, suggesting more autochthonous input likely from denser root mats and local decomposition. In addition, carbonates are higher during the slow accumulation periods. The combination of slow accumulation and high carbonates may indicate greater evapotranspiration from the surface as less moisture slows productivity and promotes the precipitation and leaching of carbonates. Alternatively, high organic carbon during slow accumulation rates could indicate standing or slow moving water allowing increases in biogenic carbon from snails and diatoms, which would also increase carbon content in the sediments.

The data from the San Bernardino ciénega indicate that ciénega growth rates are temporally variable. During most of the past 7068 years this environment has been slowly aggrading. However, this generally slow process of accumulating sediments is punctuated by periods of rapid development (i.e., 4400–4100 and 1100–700 cal yr BP). These rapid growth periods indicate that ciénegas may respond quickly to changes in surface and subsurface hydrology associated with times of greater effective moisture.

In the borderlands of the American Southwest, multiple lines of evidence suggest centennial-scale variations in effective moisture (Fig. 5). The lake-level history of pluvial Lake Cochise, 100 km northwest of San Bernardino ciénega, indicates high stands prior to 6038 cal yr BP and another ca. 4500 cal yr BP (Waters, 1989). Pollen data collected from packrat middens in the Playas Basin in New Mexico, 90 km northeast of San Bernardino ciénega, contained trace amounts of *Potamogeton* pollen ca. 4500 and 825 cal yr BP, suggesting nearby surface waters (Holmgren et al., 2003). Synchronous arroyo incision in the San Pedro and Santa Cruz valleys, ~100 and 150 km west of the San Bernardino ciénega, centered on 4400, 2700, 1800, and 900 cal yr BP suggest periods of high runoff (Waters and Haynes, 2001). Two of these downcutting events in the San Pedro and Santa Cruz arroyos are temporally consistent with periods of rapid aggradation at San Bernardino. Thus both processes of arroyo cutting (in the absence of watershed disturbance) and cienega aggradation, are associated with periods of high effective moisture. The exceptions to the temporal agreement between San Bernardino ciénega and San Pedro/Santa Cruz river systems are at ca. 1800 cal yr BP, and ca. 2500 cal yr BP which was when the unconformal surfaces formed in the RSBA section (Fig. 2). This unconformity at RSBA also indicates high effective moisture as more water (more energy) changed this system from a depositional to an erosional environment. Comparison of sites across the Southwest (Fig. 5) support our hypothesis of rapid ciénega growth associated with periods of anomalously high effective moisture.

Davis et al. (2002) also present desert ciénega records from the San Pedro and Santa Cruz river valleys with similar patterns of temporally variable growth rates. For example, the Animas Creek ciénega had rapid sedimentation between 5400 and 6000 cal yr BP. Three ciénegas, Sonoita, Los Fresnos and St. David, indicate a period of rapid growth between 1800–3000 cal yr BP, and Cook's Lake and Bingham ciénegas had rapid growth in the past 500 years. The rapid growth rates in these six ciénegas are not coincident with those from the San Bernardino ciénega, but they do suggest time intervals of high effective moisture in the deserts of the Southwest. The differences between these records and the San Bernardino ciénegas may reflect the environmental context of each study site and/or heterogeneity in the spatial distribution of precipitation (Mock, 1996; Adams and Comery, 1997).

Ciénega growth rates appear to reflect the accumulation of organic matter and increased surface flooding and terrestrial sediment deposit during seasonal rains. Ciénega growth can be extremely rapid as evidenced by the 68 cm of organic material that formed over 5 years at Los Ojitos ciénega. In contrast, temperate wetland (i.e., bogs) growth is governed by interactions between plant growth, plant decay, and water table height (Winston, 1994). However, both ciénegas and bogs are effective proxies for changes in effective moisture.

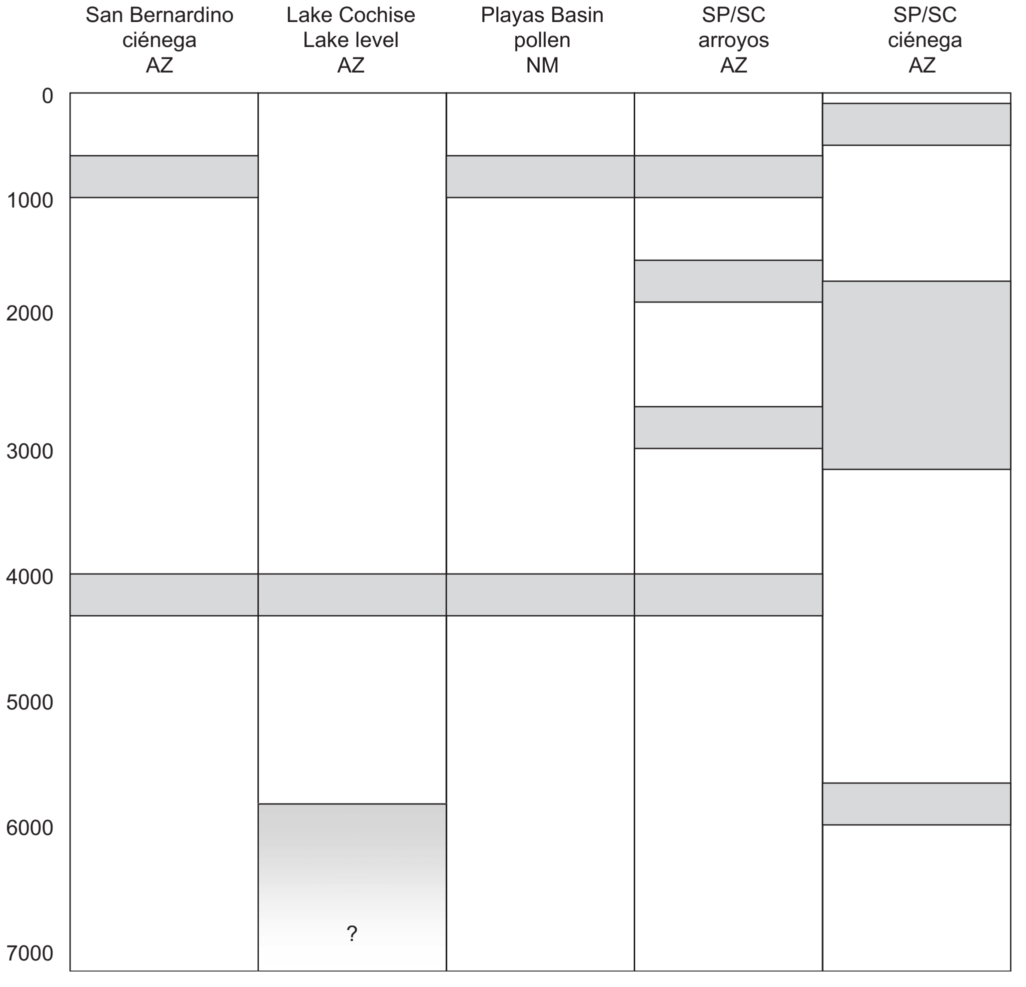

Fig. 5. Summary of the timing of rapid growth (gray shading) of the San Bernardino ciénega with Lake Cochise highstands, presence of aquatic pollen in New Mexico packrat middens, arroyo cutting in the San Pedro Valley (SPV) and Santa Cruz (SC) drainage, and periods of ciénega aggradation from the same valleys. "W" indicates periods of arroyo cutting that are clearly related to periods of increased precipitation (Waters and Haynes, 2001).

Ciénega surfaces may remain in a state of equilibrium for long periods of time, as evidenced by long periods of slowly accumulating sediments. The threshold by which the degradation of the surface occurs is not often exceeded, evidenced by the few unconformities in sediments examined from San Bernardino ciénega. However, once degradation begins, restoring equilibrium can take significant periods of time (e.g., Fig. 5, 1100–2500 cal yr BP). The regional arroyo history suggests that these unconformities likely represent extraordinary increases in surface flow, which led to scouring of the ciénega surface (Waters and Haynes, 2001; Nordt, 2003).

The historic incision of sediments at San Bernardino ciénega represents a change in this environment not seen since ca. 1100 cal yr BP. Associated with the downcutting that has occurred since the late 1800s, has been a drop in the local groundwater table that resulted in the desiccation of this desert wetland. With the loss of dense surface vegetation, the ciénega no longer has the capacity to slow flood pulses and encourage aggradation. Instead of a flood pulse slowing as it reaches the vegetated cienega surface, flood waters are channelized and serve to scour the new flood plain. Therefore, to re-establish ciénegas, restoration efforts need two components. The first must create conditions that allow the development of thick surficial vegetation. At the SBNWR these conditions are being created by constructing wells to pump the groundwater to flood the dry cienega surface. The second component of successful restoration is the return of seasonal sheet floods across the surface. Sheet flooding would assist in re-vegetating the surface and deposit the terrestrial clays and silts found in the pre-Settlement deposits. However, a return of a natural hydrological balance can only be re-established by infilling of the incised river channels.

A future complication to ciénega restoration will come from changes in climate variability. Prehistoric arroyo cutting was often associated with a transition of warm-dry conditions to cool-wet conditions destabilizing vegetation and likely increasing surface runoff (Nordt, 2003). Currently, anthropogenic modification of both upland and riparian habitats, as well as climate may result in similar surficial conditions that maintain instability of these surfaces into the foreseeable future (Grimm et al., 1997). Given the importance of desert wetlands to the biological and environmental diversity of western North America, continued studies of the long-term evolution of these environments is crucial to habitat conservation efforts in the region.

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