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A ~8000 year fire history from an Arizona/Sonora borderland ciénega

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ABSTRACT

Sediment cores from the San Bernardino Ciénega near Douglas, Arizona and Agua Prieta, Sonora, Mexico were examined to reconstruct the fire history of this region and inform restoration efforts. A ~8000 year vegetation and fire history record was reconstructed from these sediments using fossil pollen and charcoal. Results from the fire reconstruction show an increase in fire activity coincident with the onset of ENSO, and an increase in fire frequency during the Medieval Climate Anomaly. Preliminary pollen data show taxa that reflect winter-dominated precipitation (*Ephedra* and *Artemisia*) correspond to times of greater fire activity. These fire data shed light on the long-term history of fire in desert environments that may be helpful in understanding what fire regimes may be expected with global warming and also how to best incorporate fire into management plans.

1. Introduction

In the southwestern United States the role of fire in the ecology and maintenance of many natural systems, such as the California chaparral and ponderosa pine (*Pinus ponderosa*) ecosystems, is well known (see Friederici, 2003; Keeley and Fotheringham, 2001; Keeley, 2002). Fire is a significant disturbance agent and defining process in maintaining the structure and function of these environments. Fire frequencies across the Southwest can be quite variable; California chaparral has a range of mean fire return intervals between ~10 and 30 years (Keeley and Fotheringham, 2001), while ponderosa pine ecosystems experience a mean fire return interval of between ~2 and 6 years (Savage and Swetnam, 1990). Much less is known about what the frequency and role of fire has been in other southwestern environments, such as grasslands and desert scrub. Some argue that fires are uncommon in desert ecosystems (Brown and Minnich, 1986; Felger et al., 2007; Mack et al., 1996; Wright, 1980), while others suggest that prior to the arrival of Euro-Americans fires were frequent and played a significant role in the maintenance of desert systems (Davis et al., 2002; McPherson, 1995; Turner et al., 2003). This disagreement largely stems from limitations in historical observations and lack of fire history data for the prehistoric period from these ecosystems. Understanding the role of fire in maintaining desert vegetation is important given that fire is increasingly being used as a management tool in these environments (e.g., Schussman and Gori, 2004).

Dendrochronology is often the analytical standard for fire history data; however in desert grasslands available trees do not typically yield fire history information. Lakes are also well-known sources for paleoecological information including vegetation and fire history. Lakes are rare in desert environments, but desert ciénega (wetland) sediments can provide information about pre-European vegetation and fire history. For example, Davis et al. (2002) used <2000 year old microscopic charcoal to show that fire decreased in the Sonoran Desert ca. 200 years ago with the displacement of native agriculture by Euro-American settlement.

To understand the role of fire in southwestern deserts, and the relationship between climate and fire in these systems, longer term records of fire and vegetation are needed. Climate conditions and controls since the last glacial maximum (ca. 21,000 cal yr BP) have changed dramatically. Variations in insolation, position of the westerlies, strength of the North American Monsoon (NAM), and occurrence of the El Nino-Southern Oscillation (ENSO) have all affected temperature and precipitation regimes in the southwestern United States/northern Mexico (hereafter borderlands) region (Bartlein et al., 1998; COHMAP, 1988; Thompson et al., 1993) and likely had impacts on the occurrence of fire.

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In this study we examine a ~8000 year local fire record from the San Bernardino Ciénega (SBC) to address the following questions:

- What was the prehistoric return interval of fire in lower elevation desert grassland communities?
- What is the relationship between fire and climate in the borderlands over time?
- How do changes in the seasonality of precipitation affect desert fire regimes as evident in sedimentary records?

1.1. Site description

San Bernardino Ciénega (31.3°N; 109.3°W, 1160 m asl) is located in the drainage of Black Draw Wash/Rio de San Bernardino (RSB) of southeastern Arizona, USA and northeastern Sonora, MX (Fig. 1) near the ecotone of Chihuahuan and Sonoran grassland and desert scrub. Average annual precipitation is 355 mm, mostly received from the summer monsoon in July–September, with a smaller secondary peak in precipitation in the winter (WRCC) (Fig. 2). Average annual temperature is 17 °C, with summer maximum temperatures exceeding 35 °C. Currently the ciénega surface is dry except for a few artificial impoundments and small perennial springs.

The dry ciénega surface is currently dominated by annual herbaceous taxa including *Salsola iberica* (Russian thistle), *Amaranthus palmeri* (carelessweed), *Ambrosia confertiflora* (burr ragweed), and *Portulaca* sp. (purslane). Wetted and active portions of the ciénega are dominated by *Cyperus* sp. (flat sedges), *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 incised channel on the margin of the ciénega is a mixed stand of *Populus fremontii* (Fremont cottonwood) and *Salix gooddingii* (black willow), with dense *Prosopis glandulosa* (honey mesquite) thickets on the upper banks of incised channel and uplands. Vegetation away from the ciénega surface is 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).

2. Methods

2.1. Field

Sediments were collected during the summers of 2004 and 2005 from 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 at 5-cm intervals from 3.8 to 1.75 m and 2-cm intervals from 1.1 m to the present-day surface. From 1.75 to 1.1 the samples were collected at intervals according to the thickness of the layer, ranging from 4 to 11 cm. Thin sand layers between 1.4 and 1.75 m which represent a period of time when fluvial activity affected the ciénega surface were not analyzed. A 15-m long core was obtained from the SBNWR using a truck mounted 5″ (12.7 mm) hollow barrel auger. After collection, sediments were wrapped in plastic and aluminum foil or placed in sterile bags and transported to the University of Utah RED (Records of Environment and Disturbance) Lab. The core was described and cut into contiguous 1 cm sections for analysis. All samples are stored at ~1.5 °C.

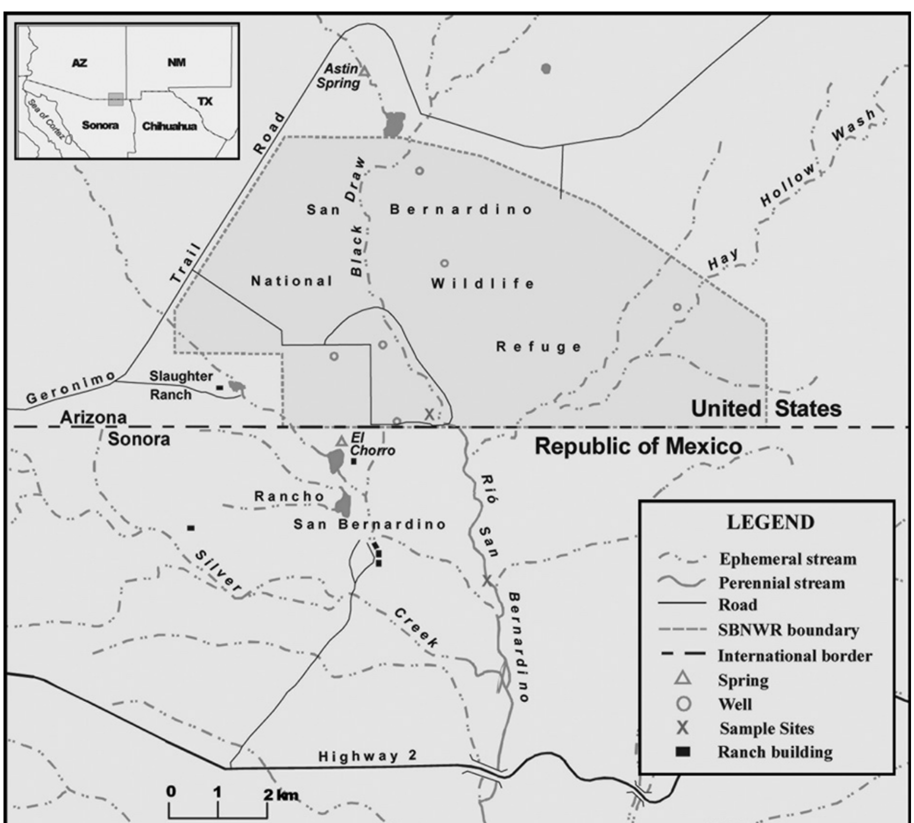

Fig. 1. Map of the study area.

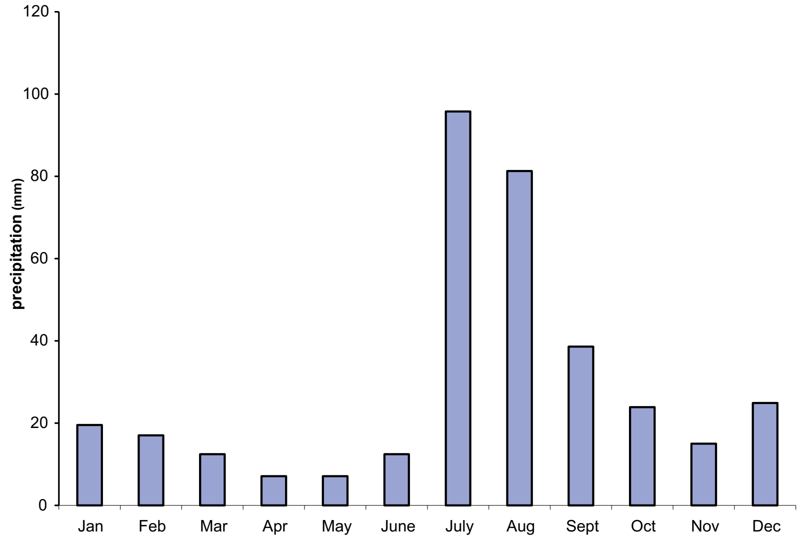

Fig. 2. Precipitation data from Douglas, AZ.

2.2. Dating

Chronology was based on radiocarbon ^{14}C age determinations (Table 1). Dates were converted to calendar years before present (cal yr BP) using CALIB 5.0.2 (Reimer et al., 2004).

2.3. Fire history

Volumetric samples were taken from the RSBA and SBNWR 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 (>1000 particles). Methods and rationale follow Clark (1988), Whitlock and Millspaugh (1996) and Gardner and Whitlock (2001). 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 may be similar to those of lake and bog surfaces.

Analytical methods follow Long et al. (1998) and Mohr et al. (2000). The ~8000 year profile was divided into three time periods for the SBC analysis. RSBA sediments were analyzed for 2 time periods, 740–1440 cal yr BP and 2546–4400 cal yr BP. The intervening sediments were not analyzed due to changes in depositional environment. The SBNWR sediments were analyzed for their entire profile (4065–8082 cal yr BP). The bin for the RSBA sediments was 5 years since this represented the most highly resolved sediments for that section, while the bin for SBNWR was 1 year due to the modeled annual resolution for the youngest part of that core.

Table 1
Radiocarbon dates from ciénega sediments.

Site	Depth	Beta number	^{14}C yr	Cal yr BP (CALIB 5.0.2)
Rio San Bernardino arroyo (RSBA)	42 cm	Beta-204829	830 ± 40	676–797
	110 cm	Beta-204374	1200 ± 40	1051–1189
	160 cm	UGAMS-01615	1700 ± 45	1521–1715
	180 cm	Beta-204828	2470 ± 40	2428–2623
	380 cm	Beta-203022	3900 ± 40	4229–4428
San Bernardino National Wildlife Refuge core (SBNWR)	347 cm	Beta-207161	3740 ± 40	3979–4182
	554 cm	Beta-207162	3920 ± 40	4238–4442
	582 cm	UGAMS-01599	4075 ± 42	4435–4653
	668 cm	Beta-207163	6190 ± 50	6956–7180

2.4. Vegetation

Standard pollen processing and counting methods were utilized to reconstruct the dominance of winter vs. summer taxa (Faegri et al., 1989). Influx (grains/cm^2/year) was calculated to remove covariance of pollen abundance associated with percentage changes by other taxa within a pollen sum. Taxa were assigned to summer precipitation or winter-precipitation groups using published studies (Hevly, 1964; Martin, 1963; Mehringer, 1965; Webb and Hasbargen, 1997) and climate space evaluations for key taxa based on Thompson et al. (1999) and Williams et al. (2006). Webb and Hasbargen (1997) followed the assignment of *Ephedra* (Mormon tea) and *Artemisia* (sagebrush) to a winter-precipitation regime as established by Martin (1963) and Mehringer (1965), respectively. Taxa from the Asteraceae (sunflower family), Chenopodiaceae/Amaranthaceae (goosefoot/amaranth families) (Hevly, 1964) and Poaceae (grass) families (Mehringer, 1965) were assigned to summer dominated precipitation regimes. *L. divaricata* (creosote) and *Acacia greggii* (cat claw) were assigned to a summer dominated precipitation regime based on the relationships between January and July precipitation from Thompson et al. (1999).

The ratio of winter to summer taxa was calculated based on the above classifications. Winter influx sums were divided by summer influx sums so that increases in winter taxa could be easily identified. It should be noted that there are only two winter-precipitation taxa (*Ephedra* and *Artemisia*) included in our analysis, so while positive values (Fig. 3, far right panel) indicate increases in those genera, zero values indicate the absence of those two pollen types, not necessarily the absence of winter taxa.

3. Results

The fire history record is divided into five SBC zones or time periods based on changes in fire regime and abundance of taxa that indicate winter precipitation.

3.1. Zone SBC5: ~8100–5300 cal yr BP

Fire history is reconstructed based on samples with modeled annual resolution. Prior to 5300 cal yr BP, CHAR (particles/cm^2/yr) are low, with values less than 0.1 particles/cm^2/yr and an average influx of 0.001 particles/cm^2/yr. Background levels of charcoal are near zero (Fig. 3). A single peak is registered, and fire episode frequency is below 0.5 fire episodes per 100 years (fire episodes hereafter referred to as “fires”).

Pollen data suggest weak winter precipitation. During this time winter-precipitation taxa appear ca. 5400–5650, 6100, 6600, and 7750 cal yr BP, but none were associated with the single inferred fire. Pollen sample resolution is ca. 225 years per sample.

3.2. Zone SBC4: 5300–4400 cal yr BP

Fire history is reconstructed based on samples with modeled annual resolution. During the period 5300–4400 cal yr BP charcoal influx increases from near zero to 0.45 particles/cm^2/year. Fire frequency is high twice, centered on ~5100 (1.3 fires/100 years) and ~4400 cal yr BP (2.1 fires/100 years) (Fig. 3). The time between fires ranges between 50 and 200 years.

Pollen data suggest an increase in winter-precipitation taxa which is covariant with the timing of the increasing background charcoal. Resolution for the pollen samples is ca. 225 years.

3.3. Zone SBC3: 4400–2500 cal yr BP

For this zone fire history has a modeled resolution of 5 years. CHAR from 4400 to 2500 cal yr BP was relatively constant, averaging ~0.26 particles/cm^2/yr with a maximum of 0.86 particles/cm^2/yr. Average background charcoal was 0.26 particles/cm^2/year (Fig. 3). Fire event frequency averaged ~1.0 fires/100 years, with fire peaks well-spaced across the time period. Fire recurrence intervals indicate fires occurred approximately every 100 years.

From 4400 to 3400 cal yr BP the ratio of winter to summer taxa fluctuates at a frequency of 50–100 years suggesting greater seasonal precipitation variability. After 3400 until 2500 cal yr BP, winter-precipitation taxa were absent from the pollen assemblages. The resolution for the pollen data is approximately 50 years per sample.

3.4. Zone SBC2: 2400–1100 cal yr BP

The sediments during the time period 2400–1100 cal yr BP are interbedded sand and clay layers. These sediments are likely evidence high magnitude flooding across the ciénega surface (Minckley and Brunelle, 2007). Because this fluvial activity eroded the ciénega surface in this location, the age model is not extended through these sediments (Fig. 3).

3.5. Zone SBC1: 1100–740 cal yr BP

The fire history in this zone has a modeled resolution of 5 years. These last 360 years of the record had the highest charcoal influx, ranging from 2 to 30 particles/cm^2/yr, and averaging 8.3 particles/cm^2/yr. Background charcoal made a stepped increase to ~1.0 particle/cm^2/year, tapering off to ~0.5 particles/cm^2/year during the last 100 years of the record (Fig. 3). Frequent peaks mark the highest fire episode frequencies of the record, ranging from 0.001 to 2.6 fire episodes per 100 years. These results reflect both

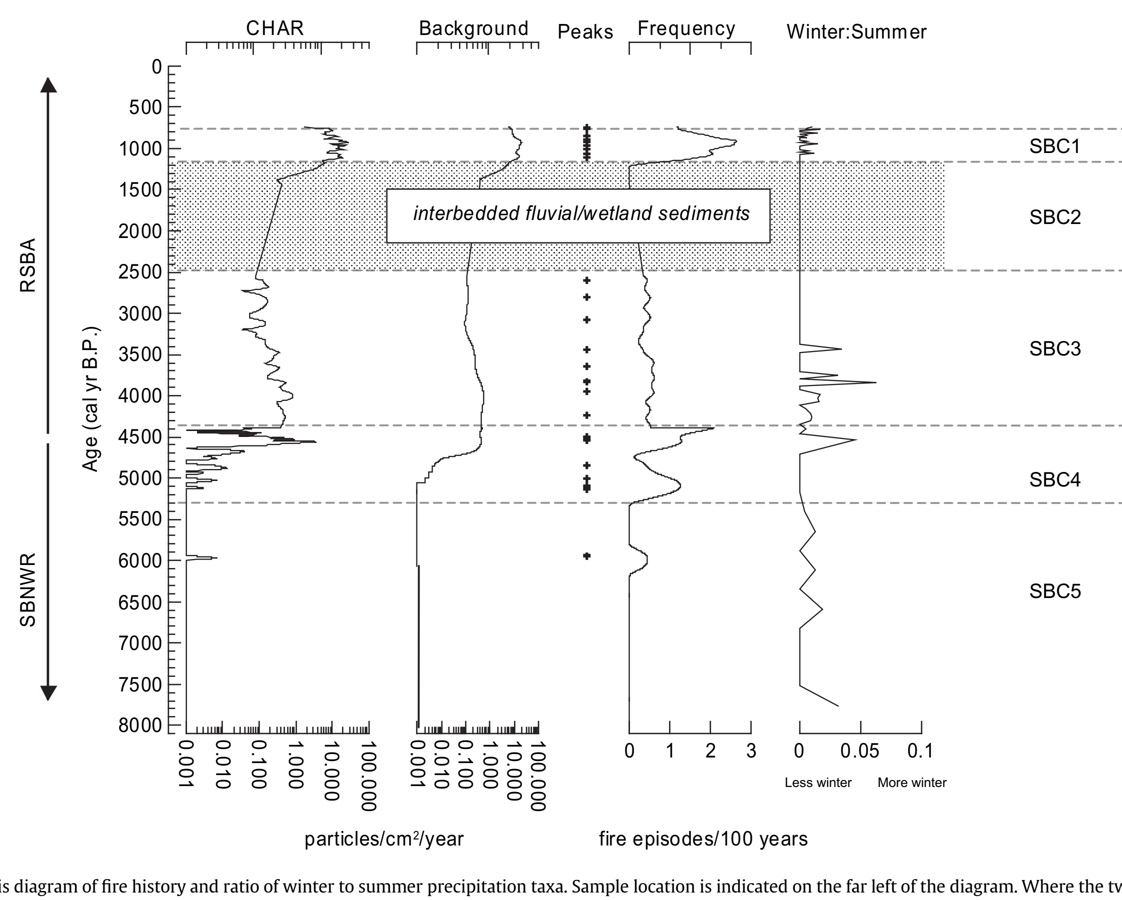

Fig. 3. Synthesis diagram of fire history and ratio of winter to summer precipitation taxa. Sample location is indicated on the far left of the diagram. Where the two datasets overlap for the time period 4000–4400, values in the proxy are in agreement, suggesting correspondence of the age models. RSBA data are shown for the overlap due to their higher resolution. San Bernardino Ciénega (SBC) zones 1–5 are based on distinct changes in fire and precipitation regimes.

prolonged fire free periods during the oldest part of this zone, and fires as frequent as one every 38 years for the middle of this zone.

Changes in the ratio between winter and summer taxa fluctuate between 20 and 30 years. The resolution of the pollen samples is approximately 11 years/cm.

4. Discussion and conclusions

The record presented here spans ~8100–740 cal yr BP and examines macroscopic charcoal and pollen in order to reconstruct the past frequency of fire in the borderlands desert grassland system. In addition, we proposed to evaluate the role of climate in fire regime over time, particularly early Holocene NAM and mid- to late-Holocene ENSO. The onset of ENSO is generally accepted to be ca. 6000 cal yr BP, with the modern periodicity reached by ~5000 cal yr BP (see Keefer et al., 1998; Moy et al., 2002; Rollins et al., 1986; Sandweiss et al., 2002; Thompson et al., 1995 for further discussion).

Relationships between ENSO and fire in the Southwest have already been identified from forested regions (Swetnam and Betancourt, 1990). Swetnam and Betancourt (1990) found that large areas burned when the southern oscillation index (SOI) was positive. These results suggest that changes in the seasonality of precipitation may account for much of the variability in fire occurrence in the southwestern United States (Swetnam and Betancourt, 1990).

4.1. Zone SBC5: 8100–5300 cal yr BP

The main climate feature in the borderlands during this time period was the NAM (Bartlein et al., 1998; Minckley and Brunelle, 2007). Although the summer insolation maximum had reached its maximum, insolation was still higher than present (Kutzbach and Webb, 1998), and monsoonal circulation remained stronger than present as a result (Bartlein et al., 1998).

During this time period, little charcoal occurs in the sediments from zone SBC5, with charcoal deposited over a ca. 40 year period, centered on 5950 cal yr BP. The minimal number of levels showing peaks in winter taxa suggests summer precipitation probably dominated during this time (see also Holmgren et al., 2007). This suggests that when winter precipitation was minimal, fire was rare.

4.2. Zone SBC4: 5300–4400 cal yr BP

While SBC5 was marked by low charcoal influx (CHAR) (Fig. 3), zone SBC4 exhibits an increase in CHAR and background charcoal. The high input of charcoal corresponds to an increase in winter-precipitation taxa around 4500 cal yr BP. We hypothesized that the increase in background charcoal, fluctuations in fire event frequency, and increase in winter-precipitation taxa resulted from early ENSO-like climate variability. Although other climate phenomena can impact the amount of winter precipitation, the timing of the change in fire and winter-precipitation taxa at SBC is consistent with the onset of El Niño events in the Southern Hemisphere (Keefer et al., 1998; Moy et al., 2002; Rollins et al., 1986; Sandweiss et al., 2002). Holmgren et al. (2007) examined packrat midden assemblages from the Chihuahuan desert, northeast of the SBC, which indicate that desert shrubs appear ca. 5000 cal yr BP. They attribute this change in vegetation to increased winter insolation and/or the onset of ENSO. Based on the correspondence between increased CHAR, background charcoal, and winter-precipitation taxa, our data appear consistent with linkages between El Niño conditions and fire occurrences in the southwestern U.S. (Swetnam and Betancourt, 1990, 1998).

4.3. Zone SBC3: 4400–2500 cal yr BP

After 4400 cal yr BP CHAR and background charcoal remain high and vary around a much higher mean (Fig. 3). The relatively high charcoal influx suggests increased biomass (fuel) on and around the ciénega and is supported by an increase in total pollen influx at the same time. Between 4400 and 3400 cal yr BP, peaks in winter taxa occur every 50–100 years, after which winter taxa appear to drop from the record for ca. 1000 years. The absence of the winter taxa, *Ephedra* and *Artemisia*, may be related to poor preservation or a shift to other winter taxa not accounted for in this analysis. Three fires did occur between 3500 and 2400 cal yr BP, but at a lower frequency than previous, suggesting a secondary driver such as prolonged biomass accumulation may also condition fire activity. Additional pollen analyses from other sites are needed to better understand the significance of winter precipitation and other mechanisms promoting fire occurrence for this time period.

4.4. Zone SBC2: 2500–1100 cal yr BP

The sediments from 2500 to 1100 cal yr BP are interbedded sands and clays.

It is likely that the sand layers indicate periods of above average flow across the ciénega. This is supported by results from previous analyses that indicated this period was associated with a period of greater-than-present moisture throughout the study region (Minckley and Brunelle, 2007; Minckley et al., 2009; Nordt, 2003; Waters and Haynes, 2001).

4.5. Zone SBC1: 1100–740 cal yr BP

Zone SBC1 represents the most recent portion of the ciénega record. The last 700 years of the record are missing because of 19th and 20th century agricultural tilling. We estimated that the top 30–50 cm were mixed based on average plow depths and anecdotal information from the current ranch owner (Valer Austin, personal communication). Therefore our analysis began ~40 cm below the present-day surface to avoid homogenized sediments.

Zone SBC1 includes the Medieval Climate Anomaly (MCA), ~950–750 cal yr BP (Bradley et al., 2003). In North America the impact of the MCA was regionally variable (Bradley et al., 2003; Stine, 1994). However, in the western U.S. the consistent climatic signal during the MCA is that of prolonged drought (Brunelle and Anderson, 2003; Cook et al., 2004; Stine, 1994).

The fire record from SBC shows a unique signal during the MCA. Background charcoal reaches the highest level of the entire record and fire peaks are frequent, with fires occurring as often as one every 38 years. The end of the MCA shows a decline in both background charcoal and fire frequency, likely associated with the end of the MCA-related drought in western North America (Cook et al., 2004). While indigenous peoples most certainly used this perennial source of water, the relative absence of charcoal in the SBC sediments before and after the MCA indicates that intentional burning was not common. Despite increasing indigenous populations in the American southwest during the MCA (see discussion in Parker, 2002), any additive burning for agriculture or hunting on the SBC would likely be contained in the background charcoal signal, not as a peak.

During zone SBC1 the fluctuation between winter and summer dominated taxa occurred every ~50 years between 1150 and 950 cal yr BP and at 10–20 year intervals between 950 and 740 cal yr BP. These intervals may be too coarse to reflect individual El Niño events, however, the variations in the dominance of winter versus summer taxa do reflect ENSO scale variability (Moy et al., 2002).

4.6. Present and future implications

Although this study represents a single site, it adds a critical dataset to the baseline of fire history in desert grasslands along the U.S./Mexico border. The record from the SBC suggests that variability in winter precipitation, likely related to ENSO, is the primary driver for fire occurrence and frequency in borderland desert grassland systems. While understanding the past is interesting, perhaps the greatest value of this study is that it contributes to predicting and managing for climate change in sensitive desert grasslands.

Future ENSO variability under increased CO_2 scenarios is unclear. Current model outputs for future ENSO events show high variability, and little can be conclusively stated about its future manifestations (IPCC, 2001; Yeh and Kirtman, 2005). What is consistent in models of future climate is that the borderlands are going to get warmer. Wells (2007) states that future predictions for southwestern deserts include drier-than-modern conditions, and the IPCC (2007) report states that minimum winter and maximum summer temperatures are *likely* to increase in the southwestern U.S. and precipitation is *likely* to decrease (emphasis from authors).

Expanding our understanding of fire regimes to other southwestern ecosystems before and through the onset of modern ENSO variability may be important to our management and conservation strategies as climates change due to enhanced greenhouse warming. Given the ambiguity of how future climate change may affect ENSO (Wara et al., 2005; Yeh and Kirtman, 2005), and by extension fire regimes in this region, flexible management strategies must be considered. If ENSO variability decreases, our research suggests that natural fires may again become extremely rare to non-existent. Management scenarios for this region should consider both options (active vs. quiet ENSO) when using fire as a conservation and restoration tool (Jackson and Hobbs, 2009).

As climate warms the role of fire in the desert grasslands is likely to change. Warming and the continuation of ENSO variability will likely increase fire frequency (similar to the MCA) while extreme warming and the shift to a persistent El Niño climate would likely lead to the absence of fires (similar to >5000 cal yr BP). The main conclusion gleaned from the SBC charcoal record is that despite arguments to the contrary (Brown and Minnich, 1986; Felger et al., 2007; Mack et al., 1996; Wright, 1980), fires do occur in desert environments and have been more frequent toward the present. Additional long-term records of fire from the desert are needed to support these conclusions and further clarify the role of fire in these systems.

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References

Bartlein, P.J., Anderson, K.H., Anderson, P.M., Edwards, M.E., Mock, C.J., Thompson, R.S., Webb III, T., Whitlock, C., 1998. Paleoclimate simulations for North America over the Past 21,000 years: features of the simulated climate and comparisons with paleoenvironmental data. Quaternary Science Reviews 17, 549–585.

Bradley, R.S., Hughes, M.K., Diaz, H.F., 2003. Climate in medieval time. Science 302, 404–405.

Brown, D.E., Minnich, R.A., 1986. Fire and changes in creosote bush scrub of the western Sonoran desert, California. American Midland Naturalist 116, 411–422.

Brunelle, A., Anderson, R.S., 2003. Sedimentary charcoal as an indicator of late-Holocene drought in the Sierra Nevada, California and its relevance to the future. The Holocene 13, 21–28.

Clark, J.S., 1988. Particle motion and the theory of stratigraphic charcoal analysis: source area, transportation, deposition, and sampling. Quaternary Research 30, 81–91.

COHMAP Members, 1988. Climatic changes of the last 18,000 years: observations and model simulations. Science 241, 1043–1052.

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

Davis, O.K., Minckley, T., Moutoux, T., Jull, T., Kalin, B., 2002. The transformation of Sonoran Desert wetlands following the historic decrease of burning. Journal of Arid Environments 50, 393–412.

Faegri, K., Kaland, P.E., Kzywinski, K., 1989. Textbook of Pollen Analysis. Wiley, New York, pp. 323.

Felger, R.S., Broyles, B., Wilson, M.F., Nabhan, G.P., Turner, D.S., 2007. Six grand reserves, one grand desert. In: Felger, R.S., Broyles, B. (Eds.), Dry Borders: Great Natural Reserves of the Sonoran Desert. University of Utah Press, 799 p.

Friederici, P., 2003. Ecological Restoration of Southwestern Ponderosa Pine Forests. Island Press, 561 p.

Gardner, J.J., Whitlock, C., 2001. Charcoal accumulation following a recent fire in the Cascade Range, northwestern USA, and its relevance for fire-history studies. The Holocene 5, 541–549.

Hevly, R.H., 1964. Pollen analysis of Quaternary archaeological and lacustrine sediments from the Colorado Plateau. Ph.D. dissertation, University of Arizona, Tucson.

Holmgren, C.A., Norris, J., Betancourt, J.L., 2007. Inferences about winter temperatures and summer rains from the late Quaternary record of C4 perennial grasses and C3 desert shrubs in the northern Chihuahuan Desert. Journal of Quaternary Science 22, 141–161.

IPCC, 2001. In: Houghton, J.T., et al. (Eds.), Climate Change 2001: The Scientific Basis. Contribution of Working Group I to the Third Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 881 p.

IPCC, 2007. In: Solomon, S., Qin, D., Manning, M., Chen, Z., Marquis, M., Averyt, K.B., Tignor, M., Miller, H.L. (Eds.), Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

Jackson, S.T., Hobbs, R.J., 2009. Ecological restoration in the light of ecological history. Science 325, 567–569.

Keefer, D.K., deFrance, S.D., Moseley, M.E., Richardson III, J.B., Satterlee, D.R., Day-Lewis, A., 1998. Early maritime economy and EL Nino events at Quebrada Tacahuay, Peru. Science 281, 1833–1835.

Keeley, J.E., Fotheringham, C.J., 2001. Historical fire regimes in Southern California shrublands. Conservation Biology 15, 1536–1548.

Keeley, J.E., 2002. Native American Impacts on fire regimes of the California coastal ranges. Journal of Biogeography 29, 303–320.

Kutzbach, J., Webb III, T., 1998. Conceptual basis for understanding late-Quaternary climates. In: Wright Jr., H.E., Kutzbach, J.E., Webb III, T., Ruddiman, W.F., Street-Perrot, F.A. (Eds.), Global Climates Since the Last Glacial Maximum. University of Minnesota Press, Minneapolis, Minnesota, USA, pp. 5–11.

Long, C.J., Whitlock, C., Bartlein, P.J., Millspaugh, S.H., 1998. A 9000-year fire history from the Oregon Coast Range, based on a high-resolution charcoal study. Canadian Journal of Forestry 28, 774–787.

Mack, F., Hoffstadt, J., Esser, G., Goldammer, J.G., 1996. Modeling the influence of vegetation fires on the global carbon cycle. In: Levine, J.S. (Ed.), Global Biomass Burning. Atmosphere, Climatic, and Biospheric Implications. The MIT Press, Cambridge, MA, USA, 551 p.

Marrs-Smith, G.E., 1983. Vegetation and flora of the San Bernardino Ranch, Cochise County, Arizona. Unpublished Masters thesis, Arizona State University, 95 p.

Martin, P.S., 1963. The Last 10,000 Years. University of Arizona Press, Tucson, 87 p.

McPherson, G.R., 1995. The role of fire in the desert grasslands. In: McClaran, M.P., VanDevender, T.R. (Eds.), The Desert Grassland. The University of Arizona Press, Tucson.

Mehringer Jr., P.J., 1965. Late Pleistocene vegetation in the Mojave Desert of southern Nevada. Journal of the Arizona Academy of Science 3, 172–188.

Minckley, T.A., Brunelle, A., 2007. Paleohydrology and growth of a desert ciénega. Journal of Arid Environments 69, 420–431.

Minckley, T.A., Clementz, M., Brunelle, A.R., Klopfenstein, G.A., 2009. Isotopic analysis of wetland development in the American Southwest. The Holocene 19, 737–745.

Mohr, J.A., Whitlock, C., Skinner, C.N., 2000. Postglacial vegetation and fire history of the eastern Klamath Mountains, California, USA. The Holocene 10, 587–601.

Moy, C.M., Seltzer, G.O., Rodbell, D.T., Anderson, D.M., 2002. Variability of El Nino/Southern Oscillation activity at millennial timescales during the Holocene epoch. Nature 420, 162–165.

Nordt, L., 2003. Late Quaternary fluvial landscape evolution in desert grasslands of northern Chihuahua, Mexico. Geological Society of America Bulletin 115, 596–606.

Parker, K.C., 2002. Fire in the Pre-European lowlands of the American Southwest. In: Vale, T.R. (Ed.), Fire, Native Peoples, and The Natural Landscape. Island Press, Washington, DC, pp. 101–141.

Reimer, P.J., Baillie, M.G.L., Bard, E., Bayliss, A., Beck, J.W., Bertrand, C.J.H., Blackwell, P.G., Buck, C.E., Burr, G.S., Cutler, K.B., Damon, P.E., Edwards, R.L., Fairbanks, R.G., Friedrich, M., Guilderson, T.P., Hogg, A.G., Hughen, K.A., Kromer, B., McCormac, F.G., Manning, S.W., Ramsey, C.B., Reimer, R.W., Remmele, S., Southon, J.R., Stuiver, M., Talamo, S., Taylor, F.W., van der Plicht, J., Weyhenmeyer, C.E., 2004. IntCal04 Terrestrial radiocarbon age calibration, 26–0 ka BP. Radiocarbon 46, 1029–1058.

Rollins, H.B., Richardson III, J.B., Sandweiss, D.H., 1986. The birth of El Niño: geoarchaeological evidence and implications. Geoarchaeology: An International Journal 1, 3–15.

Sandweiss, D.H., Maasch, K.A., Burger, R.L., Richardson III, J.B., Rollins, H.B., Clement, A., 2002. Variations in Holocene El Niño frequencies: climate records and cultural consequences in ancient Peru. In: Chambers, F., Ogle, M. (Eds.), Climate Change: Critical Concepts in the Environment, vol. II. Routledge, London and New York, USA., 407 p.

Savage, M., Swetnam, T.W., 1990. Early and persistent fire decline in a Navajo ponderosa pine forest. Ecology 70, 2374–2378.

Stine, S., 1994. Extreme and persistent drought in California and Patagonia during mediaeval time. Nature 369, 546–549.

Schussman, H., Gori, D., 2004. An ecological Assessment of the Bureau of Land Management's Current Fire Management Plans: Materials and Recommendations for Future Fire Planning. The Nature Conservancy, Arizona, Chapter, 86 p.

Swetnam, T.W., Betancourt, J.L., 1990. Fire-southern oscillation relations in the southwestern United States. Science 249, 1017–1020.

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

Thompson, L.G., Mosely-Thompson, E., Davis, M.E., Lin, P.N., Henderson, K.A., Cole-Dai, J., Bolzan, J.F., Liu, K.b., 1995. Late Glacial Stage and Holocene tropical ice core records from Huascaran, Peru. Science 269, 46–50.

Thompson, R.S., Whitlock, C., Bartlein, P.J., Harrison, S.P., Spaulding, W.G., 1993. Climatic changes in the western United States since 18,000 yr B.P. In: Wright Jr., H.E., Kutzbach, J.E., Webb III, T., Ruddiman, W.F., Street-Perrott, F.A., Bartlein, P.J. (Eds.), Global Climates since the Last Glacial Maximum. University of Minnesota Press, Minneapolis, pp. 468–513.

Thompson, R.S., Anderson, K.H., Bartlein, P.J., 1999. Atlas of Relations Between Climatic Parameters and Distributions of Important Trees and Shrubs in North America. U.S. Geological Survey Professional Paper 1650 A&B.

Turner, R.M., Webb, R.H., Bowers, J.E., Hastings, J.R., 2003. The Changing Mile Revisited: An Ecological Study of Vegetation Change With Time in the Lower Mile of an Arid and Semiarid Region. University of Arizona Press, 300 p.

Wara, M.W., Ravelo, A.C., DeLaney, M.L., 2005. Permanent El Niño-like conditions during the Pliocene warm period. Science 309, 758–761.

Waters, M.R., Haynes, C.V., 2001. Late Quaternary arroyo formation and climate change in the American Southwest. Geology 29, 399–402.

Webb, R.H., Hasbargen, J., 1997. Floods, ground-water levels, and arroyo formation on the Escalante River, south-central Utah. Learning from the Land, Grand Staircase-Escalante National Monument Science Symposium Proceedings.

Wells, G., 2007. The fire–climate connection. Joint Fire Science Program Fire Science Digest Issue 1.

Whitlock, C., Millspaugh, S.H., 1996. Testing the assumptions of fire-history studies: an examination of modern charcoal accumulation in Yellowstone National Park, USA. The Holocene 6, 7–15.

Williams, J.W., Shuman, B., Bartlein, P.J., Whitmore, J., Gajewski, K., Sawada, M., Minckley, T., Shafer, S., Viau, A.E., Webb III, T., Anderson, P.M., Brubaker, L.B., Whitlock, C., Davis, O.K., 2006. An Atlas of Pollen–Vegetation–Climate Relationships for the United States and Canada. American Association of Stratigraphic Palynologists Foundation, Dallas, TX.

WRCC, Western Regional Climate Center. Douglas AZ Climate Summary 1948–2005. www.wrcc.dri.edu.

Wright, H.A., 1980. The role and use of fire in the semidesert grass–shrub type. Forest Service General Technical Report INT 85, Intermountain Forest and Range Experiment Station, Ogden, Utah, USA.

Yeh, S.-W., Kirtman, B.P., 2005. Pacific decadal variability and decadal ENSO amplitude modulation. Geophysical Research Letters 32, L05703. doi:10.1029/2004GL021731.