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# Isotopic analysis of wetland development in the American Southwest

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**Abstract:** The analysis of stable isotope and elemental fractions of organic material collected from San Bernardino Ciénega was used to understand the history of vegetation composition and climate change within this desert wetland. A 4000-yr record of sediment buildup, based on four $^{14}C$ measurements, provides unique opportunities for the study of environmental conditions within an arid landscape and documents climate shifts from drier to wetter conditions in the late Holocene. $\delta^{13}C$, $\delta^{15}N$, and C:N values were measured from a 3.8 m deep sedimentary section to understand the dynamics of vegetation and hydrology in desert wetlands. Through this section we observe $\delta^{13}C$ and C:N values indicating a shift in the dominant source of organic matter within the section: prior to 850 cal. yr BP (below 60 cm), aquatic vascular plants and occasionally terrestrial vegetation were the primary organic sources, whereas freshwater algae were the dominant organic matter source above this level. These values indicate that while conditions remained arid at this locality, the amount of standing water on the ciénega has increased over time. These results document both climate change and vegetation evolution on the ecotone of the Sonoran and Chihuahuan deserts and demonstrate how the study of local sediment accumulation in ciénegas can provide critical information on changing conditions within arid environments.

**Key words:** Ciénegas, wetland development, Chihuahuan Desert, isotopes, climate change, sedimentation, Sonoran Desert, late Holocene.

## Introduction

Desert wetlands, or ciénegas, form large alluvial surfaces important for slowing seasonal flood pulses, promoting groundwater recharge and reducing stream channel degradation. These environments provide numerous ecological services in the arid American Southwest, including maintenance of perennial streamflow, crucial aquatic habitat, herbivore forage and migratory pathways for many taxa (Hendrickson and Minckley, 1985; Turner *et al*., 2003). When positioned in headwaters and low-ordered stream channels, ciénegas are typically aggradational environments, acting as traps of nutrients and organic matter, as well as storing sands, silts and clays during seasonal floods (Hendrickson and Minckley, 1985; Minckley and Brunelle, 2007). This aggradation contrasts with higher-ordered river cut-and-fill sequences associated with periods of higher effective moisture and associated streamflow (eg, Waters and Haynes, 2001).

The aerial extent of ciénegas in the American Southwest prior to the late nineteenth century is not well documented. However, given the historic descriptions of southwestern rivers as perennial streams with good forage, the widespread distribution of ciénegas within most riparian corridors is assumed (Hendrickson and Minckley, 1985; Logan, 2002; Turner *et al*., 2003). Prior to large-scale cattle ranching, desert wetlands were described as boggy, open environments with riparian gallery forests situated above the waterlogged soils of the valley bottoms (Turner *et al*., 2003). Since the late 1800s, many of these ciénegas have lost in-stream function through draining and subsequent conversion to agricultural fields and pastures. These changes have promoted twentieth-century channel incision and lowering of groundwater levels. Present-day efforts to restore and preserve the ecological function of these desert wetlands necessitate the study of presettlement conditions for the development of reference conditions for future management.

Aggradation, or growth, of ciénegas has been linked to centennial-scale changes in regional climate (Minckley and Brunelle, 2007). For example, Minckley and Brunelle (2007) linked times of rapid aggradation rates (up to 1 cm/yr) at San Bernardino Ciénega with regional proxies of increased moisture availability (Waters, 1989; Waters and Haynes, 2001; Holmgren *et al*., 2003). The authors suggested that times of rapid aggradation reflected more frequent or greater duration surface flow (Leopold *et al*., 1995; Etheredge *et al*., 2004). Sediments from increased flow

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buried organic surfaces, in turn forcing a vegetation response of rapid growth. During periods of slower aggradation, carbonate accumulation in San Bernardino Ciénega was higher, leading the authors to conclude that slow sediment aggradation and high carbonate accumulation were indicative of greater evapotranspiration from the wetland surface. Alternatively, high organic carbon content during times of reduced sediment accumulation may be indicative of still water conditions that allowed biogenic carbon from aquatic primary producers to accumulate, a condition that would also result in increases in carbon content in these sediments.

Changes in moisture availability and subsequent sediment accumulation rates also likely influenced the vegetation dynamics of San Bernardino Ciénega. Heffernan *et al*. (2008) observed significant change in the abundance of herbaceous vegetation at Sycamore Creek, AZ, USA as grazing pressure from cattle was reduced and the creek transitioned from a sparsely vegetated, gravel channel dominated by benthic algal productivity to densely vegetated wetlands (ie, ciénegas). The establishment of herbaceous vegetation and formation of ciénega conditions along Sycamore Creek was correlated with significant changes in the hydrology and biogeochemistry of the hyporheic zone (Heffernan *et al*., 2008). The vegetation matrix of stretches in Sycamore Creek was, in turn, found to influence the response to flood disturbance. Stretches dominated by benthic algae were more sensitive to flood frequency rather than flood magnitude, whereas the opposite pattern was found to hold true for densely vegetated ciénegas (Heffernan *et al*., 2008). Thus, reconstruction of the depositional and environmental history of San Bernardino Ciénega requires information on the vegetation history of the region as well.

One way to test these competing interpretations of sediment accumulation rates and environmental history within ciénegas would be to identify the source(s) of the organic matter buried within their sediments. Analysis of the carbon and nitrogen content of sedimentary organic matter has been effectively used to distinguish between input of terrestrial vascular plant remains and aquatic algae to ancient sediments (Ember *et al*., 1987; Meyers, 1994; Andrews *et al*., 1998; Kaushal and Binford, 1999; Brenner *et al*., 1999). Terrestrial vascular plants typically have high concentrations of cellulose, lignin and other low nitrogen-containing compounds, which leads to higher carbon to nitrogen ratios (C:N > 20) for these plants relative to algae ($4 \leq$ C:N $\leq 10$) (Meyers, 1994). Though degradation prior to burial and during early diagenesis can affect the preservation of sedimentary organic matter in soils, the C:N value is often retained in subaqueous sediments even after a significant fraction of organic carbon has been consumed prior to burial (Meyers, 1994). Thus, C:N values for organic matter that accumulated during periods of high or low aggradation can serve as a proxy for the relative contribution of terrestrial and aquatic primary producers.

The carbon isotope composition ($\delta^{13}C$) of sedimentary organic matter can also serve as a valuable tool in the identification of sources of organic matter. For terrestrial vegetation, the metabolic pathway used for carbon fixation during photosynthesis creates the largest differences in $\delta^{13}C$ values. For plant types as $C_3$ trees, shrubs and cool climate grasses the mean $\delta^{13}C = -27 \pm 3$‰, while for $C_4$ warm climate grasses mean $\delta^{13}C = -13 \pm 2$‰) and for CAM plants such as cacti and succulents the $\delta^{13}C$ values are between the $C_3$ and $C_4$ values. These isotopic differences among plant types can be further affected by environmental stresses (ie, aridity, salinity) and by variation in the carbon isotope composition of $CO_2$ (O'Leary, 1988; Farquhar *et al*., 1989; Cerling *et al*., 2004). In freshwater environments, primary producers use the same photosynthetic pathways as those used by terrestrial plants, but $\delta^{13}C$ values are also strongly controlled by the physical conditions associated with growth (Bunn and Boon, 1993; Boon and Bunn, 1994; Raven *et al*., 2002). Variation in carbon isotope composition, concentration and source of dissolved inorganic carbon (DIC) as well as a significant reduction in the rate of diffusion of $CO_2$ in water versus air can cause the $\delta^{13}C$ values for freshwater primary producers to significantly deviate from those of terrestrial plants (Osmond *et al*., 1981; Raven *et al*., 2002). In well-mixed waters, mean $\delta^{13}C$ values for freshwater phytoplankton are much lower than those for terrestrial vegetation (temperate: $-28.6 \pm 1.3$‰; tropical: $-33.3$‰) (Hamilton *et al*., 1992; Forsberg *et al*., 1993; Cloern *et al*., 2002). In stagnant pools or benthic communities where algae may experience carbon-limitation, primary producer $\delta^{13}C$ values can be significantly elevated above values typical for $C_3$ plants (Wainright and Fry, 1994; Erez *et al*., 1998). Thus, if C:N values are used to discriminate between terrestrial and aquatic sources of organic matter, the $\delta^{13}C$ values of this material can then be used to make more nuanced interpretations of the type of organic matter preserved.

For this study, we examine a ~4300 year (3.8 m thick) sediment profile from San Bernardino Ciénega, with high resolution analysis of the period between 1100 and 700 cal. yr BP, to infer surficial changes in vegetation composition. We test the relationships between sediment accumulation and carbon sources using isotopic and elemental composition, comparing values during times of rapid and slow sediment accumulation. By substituting temporal for spatial changes of the ciénega surface we also examine local wetland vegetation dynamics of San Bernardino Ciénega.

### Site description

San Bernardino Ciénega (31.3333°N, 109.2646°W; 1161 m a.s.l.) spans the border of southeastern Arizona, USA and northeastern Sonora, Mexico, within a headwater tributary (Blackwater Draw/Rio San Bernardino) of the Rio Yaqui (Figure 1). The present-day channel of Blackwater Draw/Rio San Bernardino is mainly cut along the eastern margin of the prehistoric ciénega surface. The ciénega is between 1.0 and 3.4 km wide and 6 km long (Rosen *et al*., 2005). Presently, the ciénega surface is mostly dry except for artificial impoundments and a few perennial springs. The groundwater-table is ~5 m below the modern surface. On the now dry surface, local vegetation is a combination of $C_3$ and $C_4$ taxa (Table 1) including *Amaranthus palmeri*, *Ambrosia confertiflora*, *Portulaca* and *Salsola iberica*, distributed heterogeneously across the ciénega surface. Near artesian springs and restored wetlands, vegetation includes *Cyperus*, *Carex*, *Aster*, *Anemopsis californica*, *Mimulus guttatus* and *Nasturtium officinale* (Marrs-Smith, 1983). The incised channel of Blackwater Draw/Rio San Bernardino contains stands of *Populus fremontii*, *Salix gooddingii* and *Prosopis glandulosa*. Vegetation away from the ciénega is desert scrub, dominated by *Larrea divaricata*, *Prosopis glandulosa*, *Acacia constricta* and grasses such as *Hilaria mutica* and *Bouteloua barbata*.

## Methods

Sediments were collected from a 3.8 m section on the incised bank of Rio San Bernardino during the summer of 2004 (Figure 2). A fresh exposure of the section was made with a trowel and samples were collected at 2 cm contiguous intervals from the present-day surface to 1.10 m, and 5 cm contiguous intervals from 1.75 to 3.80 m depth. Between 1.10 and 1.75 m there was a set of unconformable, sand and marl facies that were sampled in bulk.

Bulk sediments were dated to develop age–depth relationships for the section using AMS radiocarbon determinations (Table 2). Dates were converted to calendar years before present (cal. yr BP) using CALIB 5.0.2 (Stuvier and Reimer, 1993). Linear interpolations between midpoint dates were used to calculate sedimentation rates.

Sampling density varied through the section. Isotopic and elemental analyses were performed on a subset of 50 samples. Forty

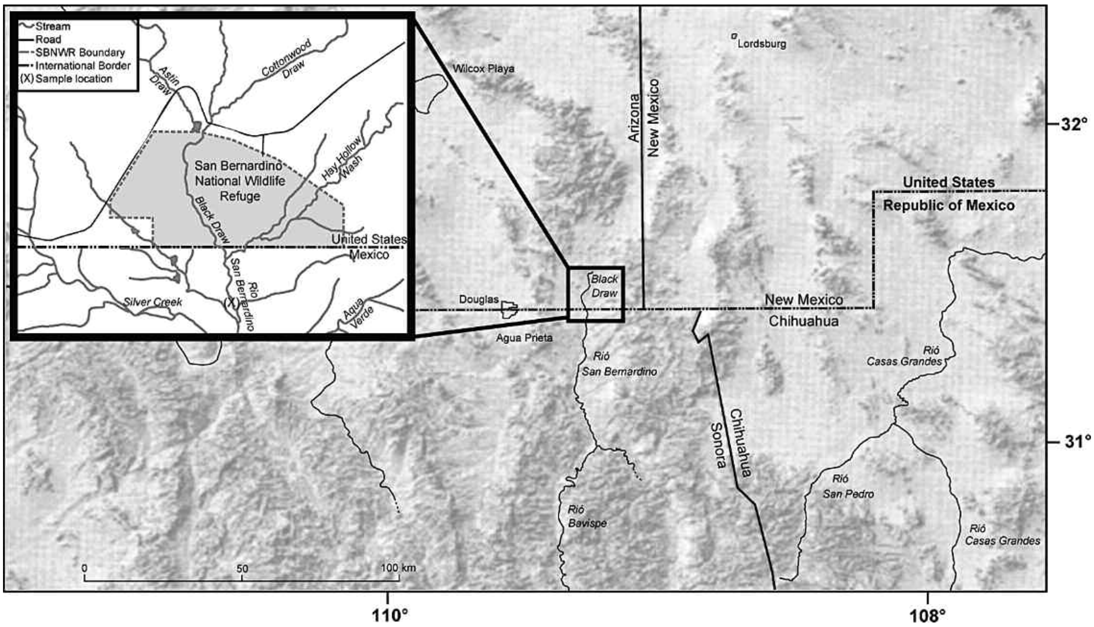


**Figure 1** The San Bernardino Ciénega is situated on the border between Arizona, USA and Sonora, Mexico. Inset map shows the local detail of the study area and sampling location (X)

**Table 1** Selected flora and associated photosynthetic pathways on and surrounding San Bernardino Ciénega

| Scientific name | Common name | $C_3$ or $C_4$ | Scientific name | Common name | $C_3$ or $C_4$ |
|---|---|---|---|---|---|
| Desert grasslands | | | | | |
| *Acacia constricta* | White thorn acacia | $C_3$ | *Muhlenbergia porteri* | Bush Muhley | $C_4$ |
| *Bouteloua chondrosioides* | Spruce top grama | $C_4$ | *Prosopis glandulosa* | Honey mesquite | $C_3$ |
| *B. curtipendula* | Grama grasses | $C_4$ | *Scleropogon brevifolius* | Burro grass | $C_4$ |
| *B. eriopoda* | Black grama | $C_4$ | *Sporobolus airoides* | Alkali Sacaton | $C_4$ |
| *Hilaria mutica* | Tobosa | $C_4$ | | | |
| Riparian vegetation | | | | | |
| *Baccharis salicifolia* | Seep willow | $C_3$ | *Populus fremontii* | Fremont cottonwood | $C_3$ |
| *Eragrostis neomexicana* | Lovegrass, Mexican | $C_4$ | *Salix gooddingii* | Goodding willow | $C_3$ |
| *Hymenoclea monogyra* | Burro brushes | $C_3$ | *Sorghum halapense* | Johnson grass | $C_4$ |
| *Poa bigelovii* | Bluegrass | $C_4$ | *Tamarix chinensis* | Salt cedar | $C_3$ |
| Ciénega vegetation | | | | | |
| *Amaranthus palmeri* | Palmer amaranth | $C_4$ | *Muhlenbergia asperifolia* | Scratch grass muhly | $C_4$ |
| *Ambrosia confertiflora* | Burr ragweed | $C_3$ | *Najas marina* | Hollow-leaf naiad | $C_4$ |
| *Aster pauciflorus* | Marsh alkali aster | $C_3$ | *Nasturtium officinale* | watercress | $C_3$ |
| *A. subulatus* | Hierba Del Marrano | $C_3$ | *Nymphaea odorata* | White water lily | $C_3$ |
| *Berula erecta* | Water parsnip | $C_3$ | *Polypogon monspeliensis* | Rabbit foot grass | $C_3$ |
| *Portulaca* sp. | Purslane | $C_4$ | *Potamogeton pectinatus* | Widgeon grass | $C_3$ |
| *Cyperus niger* | Flatsedge | $C_4$ | *Salsola iberica* | Russian thistle | $C_4$ |
| *C. odoratus* | Flatsedge | $C_4$ | *Typha domingensis* | Tule | $C_3$ |
| *Eleocharis parishi* | Spikerush | $C_3/C_4$ | *Zannichellia palustris* | Common pond mat | $C_3$ |

samples were analyzed from the uppermost section based on *a priori* knowledge of rapid sedimentation rates (Minckley and Brunelle, 2007). The remaining samples were evenly distributed down-section from the unconformable sand and marls to the base of the exposed section (Figure 3). From each sample, a 200 mg subsample was allocated for stable isotope and elemental analysis of the organic fraction and a 100 mg subsample was allocated for total inorganic carbon (TIC) analysis. Subsamples for stable isotope and elemental analysis of organic matter were treated with 10% HCl to remove carbonates and then oven dried at 50°C for 48 h. Approximately 40 mg of each subsample was weighed and placed into pressed tin capsules, crimped and stored in a desiccator cabinet prior to analysis. Measurements of the elemental composition (C wt.% and N wt.%) and stable isotope composition ($\delta^{13}C$, $\delta^{15}N$) of sediment organic matter were made on the same subsample with stable isotope values calculated and reported. The TIC content of the second subsample was determined via $CO_2$ coulometry and compared with previous estimates using Loss-on-Ignition (LOI) (described below). Stable isotope, coulometric and elemental analyses were performed at the University of Wyoming Stable Isotope Facility using an 1108 Elemental Analyzer linked to a Thermo Finnigan Delta$^{Plus}$ XP Continuous Flow Stable Isotope Ratio Mass Spectrometer and at the University of Wyoming Analytical Geochemistry Facility.

Sediment characteristics were also determined using a combination of LOI and magnetic susceptibility analyses. LOI analyses provide data on the percent water, organic carbon and carbonate content of the sediments (Geyde *et al*., 2000). A subsample of

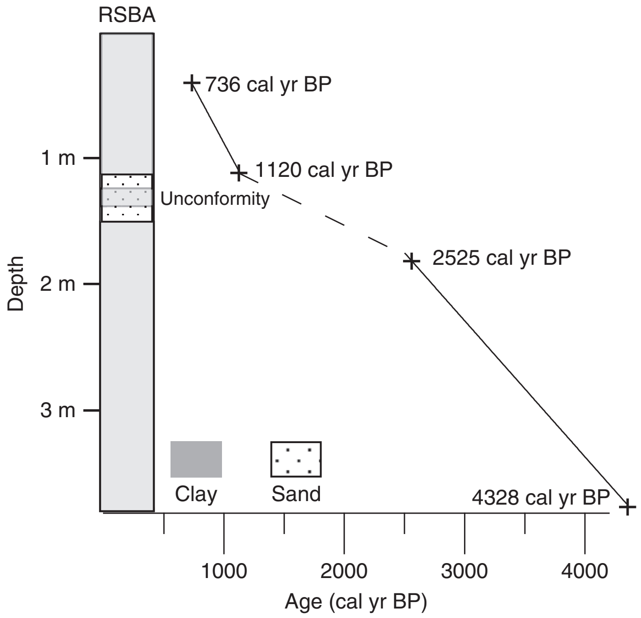


**Figure 2** Lithology, location of [14]C dates (+), and constructed age–depth model for San Bernardino Ciénega

**Table 2** Radiocarbon dates from bulk samples used to develop chronology for the Rio San Bernardino arroyo

| Depth (cm) | Beta number | $^{14}C$ date (yr BP) | cal. yr BP (midpoint)[a] |
|---|---|---|---|
| 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) |

[a]IntCal04.

1 $cm^3$ was taken from each contiguous sample, dried for 24 h at 90°C and weighed to determine residual water content. Samples were then combusted at 550°C for 2 h and weighed to determine percent organic matter. Finally, samples were combusted at 900°C for 2 h and weighed to determine percent carbonate content (after Dean, 1974). Because our primary interest is organic carbon content trends rather than absolute values for total organic content and because LOI is the common method used for these measurements in terrestrial paleoenvironmental reconstructions, we follow this method (see Shuman, 2003). However, because organic matter and TIC determinations using LOI may over-represent actual carbon content in sediments (Meyers and Teranes, 2001; Heiri *et al.*, 2001; Santisteban *et al.*, 2004), we compare estimations of percent organic C (TOC) and percent inorganic carbon (TIC) between LOI to those determined by elemental and coulometric analysis to evaluate these methods of calculating percent organic and inorganic C.

Magnetic susceptibility (MS) (measured in electromagnetic units (emu)) of the samples was contiguously measured to determine the ability of the sediment to take a magnetic charge (Geyde *et al.*, 2000). This analysis allows for the discrimination of allochthonous versus autochthonous sedimentation onto the ciénega surface (ie, high MS values are indicative of greater mineral sediment transport onto the surface). For our analyses, 10 $cm^3$ of sediment was placed in plastic containers and measured in a Bartington cup-coil magnetic-susceptibility instrument.

# Results

The section examined from San Bernardino Ciénega represents the time period 4330 to ~685 cal. yr BP (Figures 2 and 3). Aggradation rates of the ciénega deposits were 0.11 cm/yr from 4330 to 2525 cal. yr BP (380–180 cm depth). From 2525 to 1120 cal. yr BP (180–110 cm depth) there was a set of unconformities characterized by fluvially derived sand lenses and marl deposits. AMS dates were obtained above and below this set of unconformities. Above these unconformities, sedimentation is 0.18 cm/yr between 1120 and 685 cal. yr BP (110–36 cm). The record is truncated at 685 cal. yr to present (top 36 cm) because of homogenization of the sediments, likely from plowing associated with historic agricultural activities.

Sedimentation rates and lithology were used to divide the record from San Bernardino Ciénega into four horizons. The lowest horizon consists of organic-rich clays and sands extending from 380 to 180 cm depth (*c.* 4330–2550 cal. yr BP), and is capped by an unconformable deposit of sands and cobbles that span 180 to 110 cm depth (*c.* 2550–1120 cal. yr BP). Above the unconformity, deposition of organic-rich clays and sands resumed and two subsections were identified, extending from 110 to 52 cm (1120–800 cal. yr BP) and from 52 to 32 cm (800–685 cal. yr BP).

Measurements of organic and inorganic carbon content via LOI, elemental and coulometric analyses were found to yield similar trends through the section (Figure 3). However, significant differences in the absolute values calculated using each method were observed. For $TOC_{LOI}$, measurements ranged from 2.7% to 9.2% through the entire section with lower TOC wt.% observed for sediments below 110 cm. In contrast, elemental analysis of acid-rinsed sediments ($TOC_{EA}$) showed significantly lower organic C wt.% (0.3% to 2.2%). As with LOI measurements, the lowest wt.% were calculated for sediments below 110 cm and a strong positive correlation and linear relationship was detected between these measurements (Figures 3 and 4).

For $TIC_{LOI}$, measurements ranged from 1.1% to 8.6%, with extremely high TIC measurements restricted to sediments below 110 cm. Coulometric analysis of sediments ($TIC_{CA}$) found a much greater range in TIC wt.% (0.0–10.7%) through the section. As with LOI measurements, the highest TIC wt.% were calculated for sediments below 110 cm and a strong positive correlation and linear relationship was detected between these methods (Figure 4).

Using the linear regression equations determined above, we converted $TOC_{LOI}$ and $TIC_{LOI}$ values to $TOC_{EA}$ and $TOC_{CA}$ values, respectively, to look for differences in the observed trends in TOC and TIC over time between these methods (Figure 4). No statistically significant difference was detected between $TOC_{EA}$ values and converted $TOC_{LOI}$ values (Student *t* test, $t = -0.411$, $p = 0.682$), but the variance in converted $TOC_{LOI}$ values was significantly greater than that for $TOC_{EA}$ values (*F* test, $F = 1.768$, $p = 0.046$). Aside from one large outlier, both methods for measuring TOC showed a similar trend through the section with a large decrease in TOC values below the unconformity (Figure 3). Converted $TOC_{LOI}$ values were consistently lower than equivalent $TOC_{EA}$ values below the unconformity (Figure 4). The single outlier occurs at the unconformity where the $TOC_{EA}$ value was significantly greater than the equivalent converted $TOC_{LOI}$ value. As for TIC measurements, no statistically significant difference was detected between mean $TIC_{CA}$ and $TIC_{LOI}$ values (Student *t* test, $t = -0.140$, $p = 0.889$) or between the variance associated with each method (*F* test, $F = 1.079$, $p = 0.776$). Converted $TIC_{LOI}$ and $TIC_{CA}$ values show similar trends through the section, but above 58 cm and between depths of 58–82 cm converted $TIC_{LOI}$ measurements are slightly lower and slightly higher than $TIC_{CA}$ measurements, respectively. Based on these results, all comparisons between TIC wt.%, TOC wt.%, and other sediment

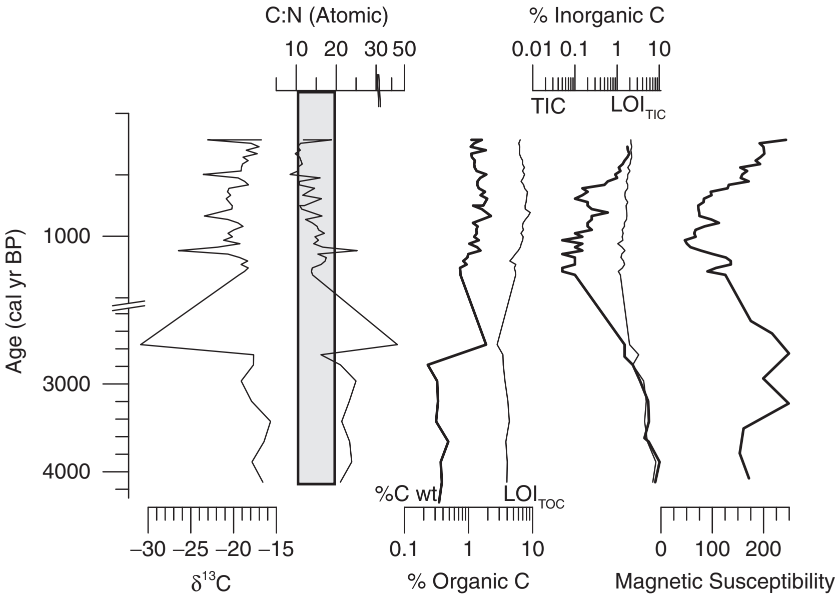


**Figure 3** Comparison of the $\delta^{13}C$, C:N (atomic), % organic C (based on % weight (bold line) and LOI at 500°C), % inorganic C (based on cloumetric titration (bold line) and LOI at 900°C), and magnetic susceptibility for Rio San Bernardino arroyo sediments. The break in the y-axis represents the unconformity. The grey box over the C:N curve represents the mixing zone between terrestrial and aquatic vegetation. Values above 20 are of terrestrial origin, whereas values lower than 10 are indicative of algal origins. Organic carbon represents plants growing on the ciénega surface. Inorganic carbon represents residual minerals from evapotranspiration. Magnetic susceptibility is representative of sediment transport through the fluvial system

parameters were made using measurements via elemental and coulometric analyses.

Organic carbon content was relatively low (0.5%) below 200 cm (>2800 cal. yr BP) and ranged between 0.2% and 0.5%. Two measurements were taken from the unconformable section (180–110 cm, ~2500 to 1120 cal. yr BP), yielding values of 0.2% and 1.9%. Between 110 and 74 cm (1120 to 920 cal. yr BP), organic carbon increases from 0.8% to a maximum value of 2.2%. After this peak, organic carbon decreases to ~1.1% by 32 cm, between 920 and 680 cal yr BP. For the section between 52 and 32 cm (800–680 cal. yr BP), median organic carbon content is 1.2%. Strong negative correlations were detected between organic carbon content and $\delta^{13}C$ values between 110 and 52 cm (Spearman coefficient = –0.67, $p < 0.001$) and 52 and 32 cm (Spearman coefficient = –0.73, $p = 0.009$). No correlation was detected between these parameters below 110 cm (0.167, $p = 0.66$).

Inorganic carbon content is highest below 200 cm (>2800 cal. yr BP), ranging between 2.4% and 10.7%. In contrast, above the unconformity inorganic carbon is low (<2.0%). Inorganic carbon is extremely low in the section between 110 and 52 cm (1120–800 cal.

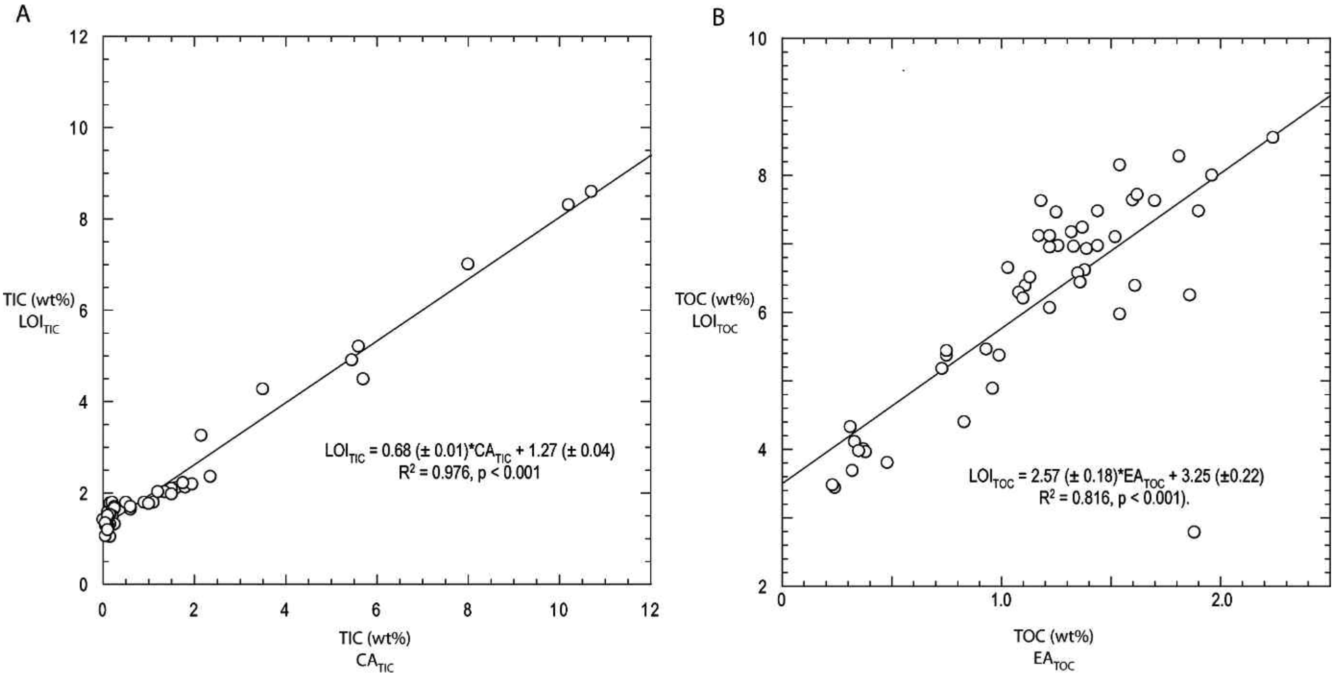


**Figure 4** Bivariate plot of (A) TIC measurements (wt.% $CO_3$) from coulometric analysis ($CA_{TIC}$) and LOI ($TIC_{LOI}$) and (B) TOC measurements (wt.% C) made from elemental analyses ($EA_{TOC}$) and LOI ($TOC_{LOI}$). Results from linear regression analysis are reported for each

yr BP), ranging between 0.0% and 1.0% with mean and median values of 0.2 ± 0.2%. In the overlying section, inorganic carbon content increases significantly and ranges between 1.1% and 1.9% with a mean value of 1.6 ± 0.3% and a median value of 1.7%. In this section, inorganic carbon content was not significantly correlated with other parameters, but a weak negative and weak positive correlation between TIC and C:N values (–0.394, $p = 0.042$) and TOC (0.389, $p = 0.045$) were found. No correlations were detected between TIC and these parameters within the two lowest sections.

Magnetic susceptibility (MS) is highest below 200 cm (>2800 cal. yr BP), ranging between 150 and 250 emu. MS generally decreases from the unconformable sand unit at 110 cm (1120 cal. yr BP) to a low 46 emu at 90 cm (1015 cal. yr BP). From this low, MS generally increases towards the top of the section to a peak of 244 emu at 32 cm (680 cal. yr BP). In the upper part of the section (52–32 cm), MS was positively correlated with C:N values (0.646, $p = 0.032$), but no correlation was detected between MS and TIC ($p = 0.069$), TOC ($p = 0.664$) and $\delta^{13}C$ ($p = 0.612$). In the interval from 110 to 52 cm (1120 to 800 cal. yr BP), MS was positively correlated with TIC (0.520, $p = 0.004$), but no correlation with TOC ($p = 0.627$), $\delta^{13}C$ ($p = 0.181$) or C:N ($p = 0.186$) was detected. Within the lowest section (375–200 cm, 4350–2800 cal. yr BP), MS was found to have a strong negative correlation with inorganic carbon content (–0.756, $p = 0.030$), but no correlation with TOC ($p = 0.125$), $\delta^{13}C$ ($p = 0.877$) or C:N ($p = 0.795$) was detected.

The median carbon isotope values were statistically distinct for three of the four intervals (Kruskall-Wallis ANOVA, $H = 18.977$, $p = <0.001$). The median carbon value between depths of 375 and 200 cm (4300–~2800 cal. yr BP) was −17.8‰. Within the unconformable section (*c*. 2550–1125 cal. yr BP), two measurements were made. The lowermost (180–175 cm) showed a significant excursion from the general trend, with a carbon isotopic value of −30.9‰, in contrast to the capping marl (165–150 cm), which had a similar $\delta^{13}C$ value to that of the deeper sediments (−17.7‰). From 110 to 52 cm (1100–800 cal. yr BP) median $\delta^{13}C$ values drop to −20.1‰ with negative deviations at 95 cm (–26.5‰, 1050 cal. yr BP) and 75 cm (–23.4‰, 935 cal. yr BP). For the uppermost sediments between 52 and 32 cm (800–685 cal. yr BP), median $\delta^{13}C$ values were −18.9‰, with two excursions of lower $\delta^{13}C$ values (<–23.0‰) around 800 and 685 cal. yr BP.

Median C:N values for lithologic sections with sufficient sample numbers are statistically distinct (Kruskal-Wallis One Way ANOVA on Ranks, $H = 26.483$, $p < 0.001$). For the upper part of the section, 52–32 cm (800–690 cal. yr BP), the median C:N value is 11.0 and ranges from a low of 8.5 at 52 cm (800 cal. yr BP) to a high of 18.9 near 32 cm (690 cal. yr BP). Between this section and the unconformity, 110 to 52 cm (1100–800 cal. yr BP), the median C:N value increases significantly to 14.7 and ranges from 10.9 at 56 cm (820 cal. yr BP) to a high of 25.3 near 96 cm (1050 cal. yr BP). Within the unconformable section 180–110 cm (*c*. 2550–1125 cal. yr BP), the lowermost sample (180–175 cm) had the highest C:N value (47.2) whereas the C:N value for the capping marl (165–150 cm) was more similar to values detected in the overlying sediments (C:N = 14.1). Below the unconformity, C:N ratios increased significantly, having a median value of 22.3 (range 21.06–24.95). No correlations were found between $\delta^{13}C$ and C:N within the upper (52–32 cm: 0.385, $p = 0.216$) and lower (350–200 cm: –0.241, $p = 0.532$) sections, but a strong negative correlation was detected between these values in the middle section (110–52 cm: –0.623, $p < 0.001$).

# Discussion

Interpreting sedimentary records from desert wetlands is complicated by the transitional nature of these systems. Ciénegas show many characteristics consistent with both pedogenic and full wetland environments, which can affect the underlying assumptions used when interpreting the isotopic and elemental record. If ciénega sediments are derived from terrestrial soil, then the patterns in isotopic and elemental compositions should likely follow a pedogenic model of interpretation. However, since ciénegas are components of fluvial environments, we consider these sediments to more closely resemble marsh/wetland sediments. As such, the isotopic and elemental proxies applied to this study should be influenced by processes inherent to riparian and aquatic environments.

## Ciénega dynamics 4300 cal. yr to present

Original descriptions of desert ciénegas and riparian corridors in general suggest a great spatial and presumably temporal variability in vegetation and hydrodynamics prior to European settlement (Hendrickson and Minckley, 1985; Logan 2002; Turner *et al*., 2003). This may be due to the fact that the long-term hydrologic balance in these systems is dominated by the interplay between inflowing groundwater and evaporation (Cole, 1968). This interplay, combined with the mixture of aquatic and terrestrial environments complicates the interpretation of isotopic, elemental and percent organic and inorganic C values from these sediments. The percent organic C composition data can be interpreted as a proxy for biomass or productivity of the ciénega (Minckley and Brunelle, 2007). However, using percent C alone it is not possible to determine whether these data represent biomass from terrestrial grasses and riparian macrophytes or an aquatic signal from algal blooms and eutrophication of stagnant pools. Percent inorganic C, which we interpret as an evapotranspiration proxy, may represent an increase in surface water and associated increase of calcium carbonate precipitates from the water column. In the case of the isotopic and elemental data, the individual values of $\delta^{13}C$ may represent a combination of abiotic and biotic factors that differ significantly between terrestrial and aquatic environments (Farquhar *et al*., 1989; Lajtha and Michener, 1994; Raven *et al*., 1994, 2002; Cloern *et al*., 2002). Using multiple proxies within a sediment profile, we can begin to interpret how ciénegas develop through time.

### *4300–2500 cal. yr BP*

The period between 4300 and 2500 cal. yr BP was characterized by initially high, but decreasing MS, TOC and TIC values. The relatively high terrestrial input and high $\delta^{13}C$ values (−17.8‰) during the early portion of this record likely indicate a greater abundance of $C_4$ vegetation locally. These results, along with an increased percentage of inorganic C in the sediments, support an interpretation of initially arid conditions at the site (Schulze *et al*., 1998; Evans and Belnap, 1999; Penuelas *et al*., 1999; Brenner *et al*., 2001; Billings *et al*., 2002). The interpretation of initial aridity is supported by the C:N ratio (16.9), which suggests a mixture of wetland and terrestrial constituents on the ciènega surface.

### *2500–1100 cal. yr BP*

The unconformable sediments may represent a single or multiple events that destabilized the ciènega surface. This section had initial peaks in MS, $TOC_{EA}$, and C:N, suggesting significant terrestrial input from the watershed and surrounding slopes. Subsequent sands overlaying the marl had lower than previous MS, increasing $TOC_{EA}$ and low TIC. This latter sequence may be representative of ciènega recovery with a surface destabilizing flood, suggested from the high MS values and subsequent changes in $TOC_{EA}$ and TIC.

### *1100–800 cal. yr BP*

After 1100 cal. yr BP, MS generally decreases until *c*. 1000 cal. yr BP, suggesting continued stabilization of the ciénega surface and possibly lower flooding frequency. After 1000 cal. yr BP, MS begins to increase with two peaks punctuating the record (*c*. 950 and 825 cal. yr BP). $TOC_{EA}$ and TIC indicate that both surficial biomass and actual evapotranspiration rose over this time period. Trends in the C:N ratio suggest that initially the local vegetation was predominantly terrestrial rather than aquatic. However the long-term trajectory suggests overall reductions in terrestrial vegetation on the ciènega surface.

### *800–685 cal. yr BP*

After 800 cal. yr BP, decreased C:N values and inferred increased contribution of aquatic algae suggest that surface water was present for at least part of the year. In light of the primarily aquatic algal origin for the organic matter at this time, the high $\delta^{13}C$ values suggest low water flow and limited mixing of the water column (Finlay *et al*., 1999; Schelske and Hodell, 1995; Hodell and Schelske, 1998; Finlay, 2001). The decreasing trend in percent organic C and increasing trend in percent inorganic C support the interpretation that water was ponded and stagnation of the water was likely occurring. However, seasonal (summer) flooding likely continued to introduce sands, silts and clays to the ciénega, as evidenced by increasing MS values and the strong positive correlation between MS and C:N values towards the top of the section. Around 800 cal. yr BP, C:N ratios consistently exhibit values below 10, indicating the establishment of subaerial conditions (surficial water ponding) at the sampling location. The percent inorganic C continued to increase after 800 cal. yr BP, consistent with continued high evapotranspiration from the ciénega surface.

## Implications for ciènega development

Trends in the organic and inorganic percentages have been discussed in previous work on southwestern ciénegas (Minckley and Brunelle, 2007). The addition of stable isotope and elemental analysis to these data provides a way to separate terrestrial and aquatic environments (Cloern *et al*., 2002). This multiproxy approach has been widely used in marine and lacustrine sediments, but not in fluvial systems (Jasper and Hayes, 1993; Eadie *et al*., 1994; Hassan *et al*., 1997; Richard *et al*., 1997; Middelburg and Nieuwenhuize, 1998; Andrews *et al*., 1998; Kaushal and Binford, 1999; Hammarlund *et al*., 2004). The results of the isotopic analysis of San Bernardino Ciénega suggest specific changes associated with vegetation (ie, succession from $C_4/C_3$ grassland to aquatic macrophytes) and hydrology (ie, the degree to which the ciénega is wet or dry, and possibly surficial water stagnation). At San Bernardino Ciénega, prehistoric recharge of the groundwater system likely reflects wetter-than-normal winter precipitation (Minckley and Brunelle, 2007).

Flooding is inferred by the four negative excursions in the $\delta^{13}C$ values through the section (Figure 3). These excursions are suggestive of events that may have preferentially mobilized the surface of the ciénega and buried in-stream vegetation, similar to processes observed in the modern channel of Rio San Bernardino. This interpretation would be consistent with the magnetic susceptibility data, which do not have coincident peaks for these events. The largest excursion in $\delta^{13}C$ (after 2500 cal. yr BP), within the sands and marls of the unconformity, suggests a single or series of floods of sufficient magnitude to destabilize the ciénega surface, at least locally. The coincidence of the largest negative deviation within the unconformity leads to the interpretation that the other negative deviations represent similar events of lower local magnitude.

As noted by Meyers and Teranes (2001) and Santisteban *et al*. (2004), the use of $LOI_{550}$ and $LOI_{950}$ measurements as quantitative estimates of TOC and TIC, respectively, is prone to significant error. Variation in lithology and organic content are the two primary factors that account for differences between direct measurements of TOC and TIC and estimates from $LOI_{550}$ and $LOI_{950}$ measurements. Our results confirm these findings and demonstrate that for low concentrations of organic and inorganic carbon the error between absolute quantities of carbon determined using these methods can be significant. However, as shown in Figure 4, the general trend in TOC and TIC values within a sediment profile can be approximated using the $LOI_{550}$ and $LOI_{950}$ measurements, which suggests that these measurements are better used as a qualitative rather than quantitative proxy for variation in organic matter composition and preservation. This impression is supported by the lack of recovery of significant peaks in TOC by $LOI_{550}$ measurements in the organic-poor, lowermost section of the sediment record and the overestimate of TIC by $LOI_{950}$ measurements between 110 and 52 cm depth (Figure 3). Though the overall trend is preserved, these outliers attest to the reduced sensitivity of the $LOI_{550}$ and $LOI_{950}$ methods.

# Conclusion

Sedimentary isotope and elemental analysis from ciénega sediments provides information on temporal changes in the dominance of terrestrial and aquatic vegetation. These distinctions are important because they reflect changes in climatic conditions that control effective moisture, evaporation rates and the presence/absence of standing water. The $\delta^{13}C$ and C:N isotope analysis supported the hypothesis that conditions in the San Bernardino Ciénega shifted from more arid conditions ~4000 years ago to wetter conditions towards the present. Carbon isotope data suggest a shift from $C_4$ grass dominance (drier conditions) to algae (wetter conditions) over this time. C:N ratios exhibit a shift from higher terrestrial input to mostly aquatic-dominated conditions towards the present. Our multiproxy approach thereby provides clear evidence of consistent change from drier conditions to wetter conditions on the San Bernardino Ciénega. The examination of desert wetlands provides valuable information on how ciénegas function, which is critical for the preservation and restoration of these important desert water resources and habitats.

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