N. Jb. Geol. Paläont. Abh. 277/2 (2015), 209–224
Stuttgart, August 2015

Article

Last millennial environmental reconstruction based on a multi-proxy record from Laguna Nassau, Western Pampas, Argentina

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With 5 figures and 1 table

Abstract: We present a multi-proxy record from Laguna Nassau (LN), a shallow lake which developed in a blowout depression in the semi-arid sandy lowlands of the Western Pampas of Argentina. This multi-proxy stacked record reveals the evolution of an incipient water body subjected to warm and dry conditions from ~900 to 770 cal yr BP, an interval that is coeval with the Medieval Climatic Anomaly (MCA) period. Vegetation was dominated locally by *Typha*, and regionally by the Espinal, represented by *Celtis*, along with psammophytic-halophytic communities in sand dunes and lowlands. After that, variable water-depths and unstable conditions occurred in the water body in relation to dry and humid climatic phases until ~200 cal yr BP, likely related to a transition from warm and dry conditions, corresponding to the MCA, to a colder and wet climatic setting during a period concurrent with the Little Ice Age (LIA). This water body evolved into a shallow lake since then, with a more stable and higher water level, and regional vegetation characterized by the Espinal and psammophytic-halophytic communities mantling and stabilizing the nearby sand dunes. This evolution suggests complex hydrological responses of LN likely associated with its sensitivity to climatic variability. Our results highlight important contrasts in hydrologic balance during the MCA and LIA along the western and northeastern Pampas, suggesting important shifts mainly in the South-American Summer Monsoon at centennial timescales over the last millennium.

Key words: Western Pampas, Argentina, blowout depression, late Holocene, multi-proxy record, climate change, paleoenvironments, dune field, Medieval Climate Anomaly, Little Ice Age.

Introduction

The Western Pampas is part of the low-relief Argentine Pampean Plain that is mantled by widespread late-Quaternary aeolian sandy sediment and dune fields (Tripaldi et al. 2013), and characterized by playa lakes (Salinas), low depression flats and more than 200 water-filled blowout depressions (deflation pans). It is a key region for the study of climate processes and dynamics due to its proximity to the eastern limit of the Arid Diagonal (AD). The AD is a narrow strip (band) developed in successive arid series of land, characterized by maximum aridity (very low precipitation), variable width, and noticeable latitudinal development, which interrupt the continuity of humid zones according to a combination of factors (e.g. relief, continentality) that are arranged from north to south over different atmospheric circulation zones (Bruniard 1982). The AD represents a boundary or transition between the two dominant sources of moisture from the Atlantic and Pacific oceans (Mancini et al. 2005 and references therein; Piovano et al. 2009).

www.schweizerbart.de
DOI: 10.1127/njgpa/2015/0502
0077-7749/2015/0502 $ 4.00

The Western Pampas has, therefore, the potential to record the spatial fluctuations of the overlapping areas of the southern hemisphere west-wind drift with the South-American tropical circulation over time. In particular, the water-filled blowout depressions constitute a useful source for reconstructing Late Quaternary environmental evolution and climatic variability because they provide both geomorphologic archives, concerning the formation of large-scale wind patterns, and lake sediment archives of the environmental and ecological changes, which contain numerous biological and geochemical proxy-indicators (e.g. pollen, charcoal, metallic elements, and salts, among others).

The information from these archives is important due to the scarcity of high resolution climate reconstructions across the Pampean plain spanning the last millennium and the fact that reconstruction of the past environmental variability has been hampered by this paucity of complete and well-dated paleoclimate archives (Piovano et al. 2009). Putting these environmental archives in a more regional context could better contribute to answer some basic questions about the occurrence, timing and frequency of climate fluctuations in the past, and to understand latitudinal paleo-circulation dynamics and the hydroclimatic response since the Late Pleistocene and particularly throughout the Holocene (Piovano et al. 2009).

In addition, reconstructing detailed past climatic patterns for the last millennium is essential for data/model comparisons for the southern part of South America, encompassing the climatic periods known as the Medieval Climatic Anomaly (MCA) and the Little Ice Age (LIA). These reconstructions can provide insights into the underlying mechanisms of climate variability and forcing imprints, which may shed light on the inter-hemispheric linkages of the climate system (teleconnections) as was found for the severe droughts of the 1930s that occurred in the Great Plains of North America and in the Western Pampas of South America (Tripaldi et al. 2013).

Several studies have been carried out in the Western Pampas, particularly in playa lakes, sandy plains and paleodune fields (e.g. González Díaz 1981; Iriondo 1999; Cioccale 1999; Tripaldi & Forman 2007; Calmels & Casadío 2004; Zárate & Tripaldi 2012, Rojo et al. 2012; Tripaldi et al. 2013; Forman et al. 2014). These studies have generated important information about aeolian processes, geology, geomorphology, and stratigraphy, which have contributed to understanding the effect of the large-scale wind patterns and climate change over time, particularly during the Holocene. However, our knowledge of Holocene paleoenvironments and moisture availability in west-central Argentina is still limited (Forman et al. 2014).

On the other hand, the combined and integrated data from different specialties (e.g. palynology, micropaleontology, archaeology) is necessary to better understand the complex landscape-scale interactions of hydro-ecologic, climatic factors and anthropogenic activities like agriculture and sheep/cattle grazing. The Western Pampas have been subjected not only to droughts and aeolian activity throughout the Holocene, with episodes well documented during the early-mid 20th century (Tripaldi et al. 2013), but also to flood events, sometimes intensified by cultivation activities (Viggliz o et al. 2009). Anthropogenic effects on the Western Pampas include landscape denudation, the decline of native grasslands (Demaría et al. 2003) and the endangerment of the pampas deer (Dellafiore et al. 2003)

Holocene multi-proxy records (e.g. pollen and non-pollen palynomorphs, charcoal, molluscs, ostracodes, and diatoms) contained in sedimentary archives in shallow lakes from blowout depressions of the Eastern (humid) Pampas have been analyzed in the last decade (e.g. Stutz et al. 2002, 2010). In contrast, records from similar systems in the Western (dry) Pampas have scarcely been studied and almost no biogenic fossil material has been neither recovered from sediments nor analyzed for paleoecological purposes.

The aim of this investigation is to reconstruct the paleoenvironmental conditions for the last ~900 years based on the integration of palynological and charcoal records along with geochemical analyses. This is the first multi-proxy record constructed from sediments from a water body in a blowout depression of the Western Pampas.

Study area

Location and geomorphologic - hydrologic context

Laguna Nassau (33°57'29.90" S – 65°21'55.55" W), formed in a blowout depression, is located in the semi-arid sandy lowlands of the Western Pampas (Fig. 1a-i), which cover the southern half and eastern regions of San Luis province, in the west-central Argentina (28°-38° S and 65°-70° W; Fig. 1). It is one of the many permanent water bodies (shallow lakes) distributed over the sandy plain of south-central San Luis prov-

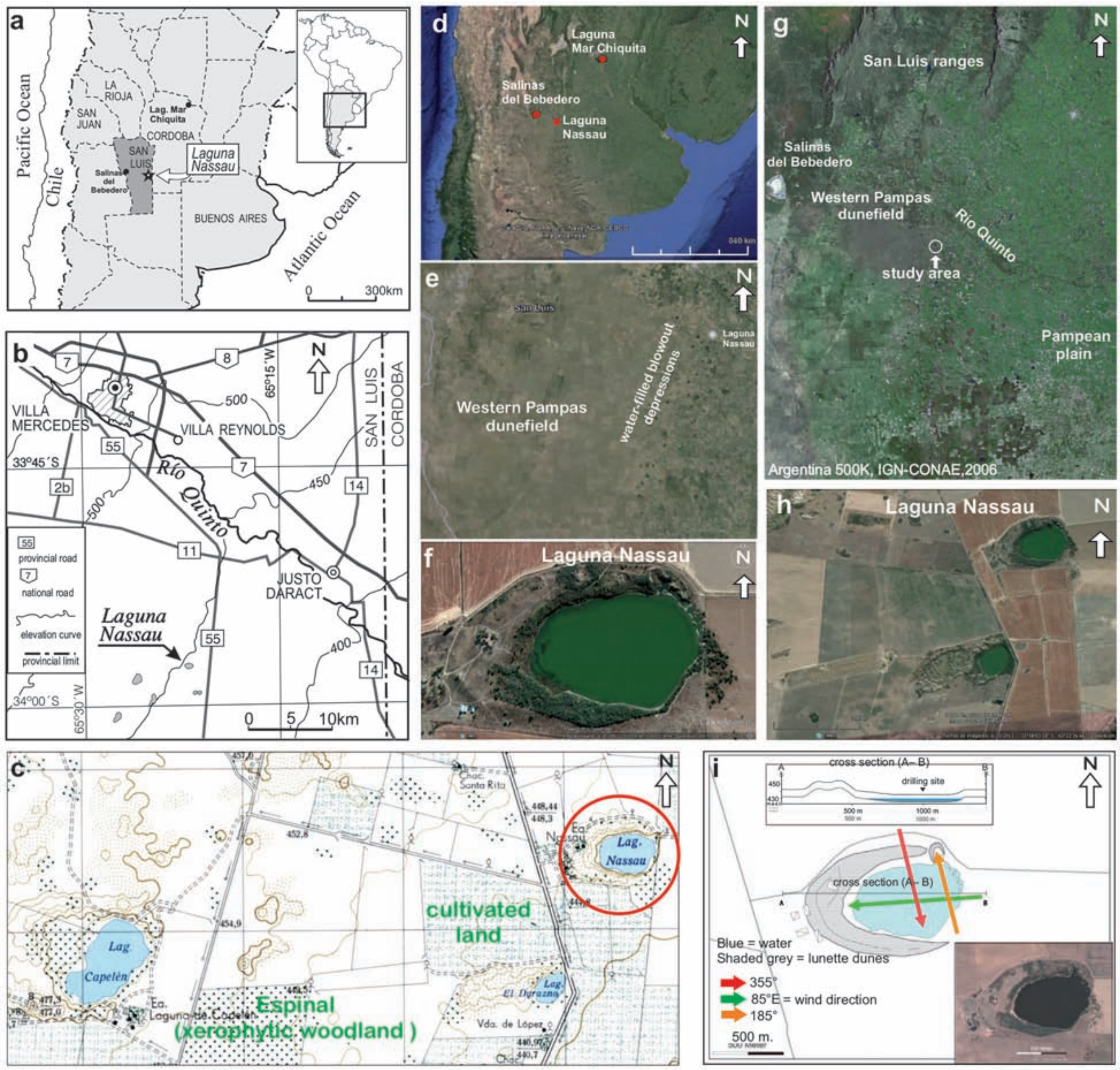

Fig. 1. a, b – Location map of the study area, **c** – Topographic map; **d-h** – Images of west-central Argentina and Laguna Nassau, and **i** – Cross section at Laguna Nassau and diagram of dune lunettes and arrows indicating the prevailing wind direction that formed each dune.

ince. This sandy plain contains a paleodune field that exhibits diverse aeolian bedforms and landforms, such as well-vegetated stabilized dunes, and aeolian sands that show different degrees of deflation and aeolian reworking in the form of blowouts, parabolic and barchanoid dunes (Tripaldi et al. 2013).

At present, Laguna Nassau is a water body that developed on a geomorphologically inactive blowout depression, although active blowout/dune – systems in the surrounding area show formation due to wind directions from 85°, followed by wind directions from 175° that generated one smallish lunette dune in the north eastern part (Fig. 1i, 2a, c). After that, winds from 355° enlarged the dune and increased its convexity. Soils here have a low capacity to retain water due to their high permeability, and the variable groundwater depth (0-25 m) and salinity (Peña-Zubiate et al. 1998; Colazo 2012). The region has an incompletely integrated surficial drainage system with numerous endorheic basins (Tripaldi et al. 2013), and no river or stream channels are evident (Viglizzo et al. 2009).

In particular, Laguna Nassau is located close to the Río Quinto basin and its overbank area, which is approximately 22 km to the west of Río Quinto, and about 16.5 km to the southwest at its closest. Geologic, tectonic and climatic conditions have been the forcing agents over the geomorphologic dynamics of the river basin. In the upper and central parts of the Río Quinto basin, important structural controls are driven by dendritic-angular drainage patterns or by sudden changes in the river course; whereas the lower part is completely filled and presents a distributary model (Quintana-Salvat & Romero-Nelson 1993). Generally, the lowlands around the Río Quinto basin have a groundwater table near the surface, and during periods of the high rainfall regime, water ponds on the surface and floods the most depressed areas. The rise of the groundwater table plays a fundamental role in the dynamics of water bodies, which become active only when the groundwater table reaches specific levels and promotes water interplay among depressions (Quintana-Salvat & Romero-Nelson 1993).

Vegetation

According to Cabrera (1971, 1976) a xerophytic woodland called Espinal is the characteristic vegetation of the Western Pampas; the dominant genera include *Prosopis* and *Acacia*, along with *Celtis*, *Schinus* and *Geoffroea decorticans*. More specifically, according to Anderson et al. (1970), the study area can be described as a sandy region with grasslands and *Geoffroea decorticans* islands. On the other hand, the study area is in the western portion of the phytogeographical district named *Psammophytic Espinal* (Lewis & Collantes 1973), characterized by a steppe covering the sand-dunes, where the more common grasses include species of *Stipa*, *Poa*, *Panicum*, *Sporobolus* and *Chloris* genera, along with herbs and shrubs of the Asteraceae family (*Senecio* and *Hyalis argentea*, among others). The neighboring sectors of the study area belong to the *psammophytic district* of the Interior (inner) Pampas (León & Burckard 1998) and it has been considered to be the western limit of the Pampa Grasslands (León & Anderson 1983). The grasslands were used for alfalfa cultivation at the beginning of the 20th century but now it is predominantly grazed grassland (Peña-Zubiate et al. 1998). Nevertheless, there are still relict undisturbed patches of the native grass *Sorghastrum pelitum* (León &Anderson 1983).

Local vegetation is represented by species of Chenopodiaceae, *Cortaderia*, *Schoenoplectus* and *Typha*. These species are found on the borders and shallow zones of the water body and brackish soils. In particular, *Typha* populations tolerate perennial flooding, poor soil conditions, and moderate salinity (Clewell 1985); therefore, they are normally present in marshes, ditches and lowlands surrounding the Laguna Nassau area.

Climate

The climate type in the Köppen climate classification system for the west-central Argentina, including the Western Pampas, is BWk, which defines a *desert middle latitude climate*. This climate has been considered to be arid to semi-arid with features that are very sensitive to low-frequency fluctuations that generate a pronounced east to west precipitation gradient (Compagnucci et al. 2002). The mean annual precipitation ranges from about >1000 mm in the Eastern (humid) Pampas to <300 mm at the Andes piedmont (Forman et al. 2014 and references therein). The low-level atmospheric circulation is involved to a certain extent in weather patterns and in the regime of precipitation over west-central Argentina (Compagnucci et al. 2002). Precipitation is concentrated in the spring and summer months, often being associated with the summerly intensification of the South American Summer Monsoon as the southernmost effect of humid air masses transported by the Atlantic anticyclone and the low-level meridional Chaco Jet (Compagnucci et al. 2002; Garreaud et al. 2009). A critical synoptic-scale element for the influx of moisture to west-central Argentina is the pressure gradient between a thermal orographic low east of the Andes and the subtropical South Atlantic anticyclone, which increases during the austral summer and results in the northeasterly flow and net influx of moisture from the Atlantic Ocean and Bolivian sources (Compagnucci et al. 2002).

Summer rainfall variability (October-March) shows interannual to multidecadal fluctuations over a vast area of subtropical Argentina, including the Western Pampas; and statistical significant oscillations of quasi-periods in the bands 18-21, 6, 4 and 2 years can be found along the region and intra-regionally (Compagnucci et al. 2002) This variability in precipitation in western Argentina indicates hemispheric climate control linked to changes in sea surface temperatures,

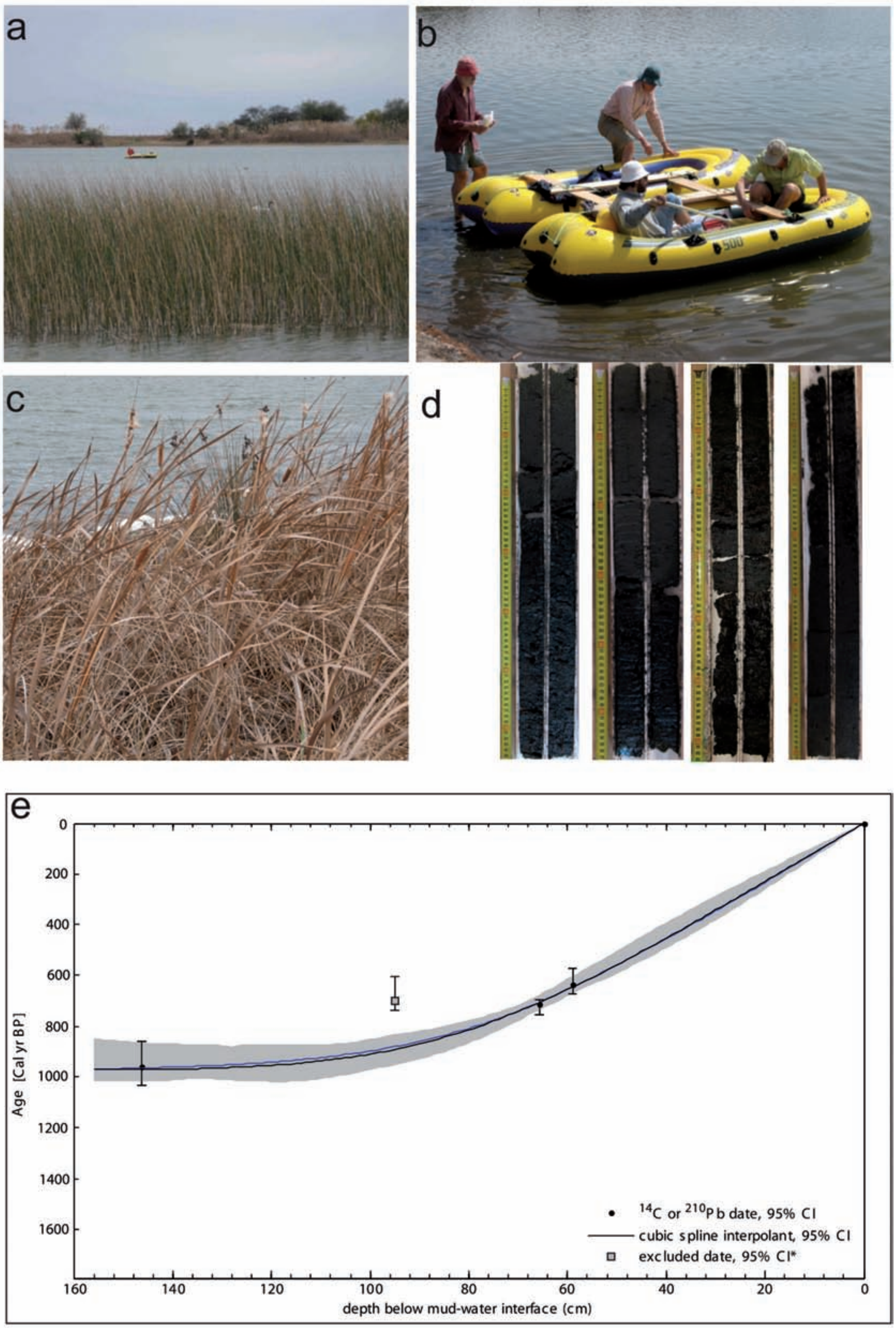

Fig. 2. a – Laguna Nassau; **b** – Two rubber boats connected and stabilized with wooden boards for the sampling; **c** – *Typha* populations at the border of Laguna Nassau, **d** – Sediments from longitudinal core sections, **e** – Age model developed for the composite core.

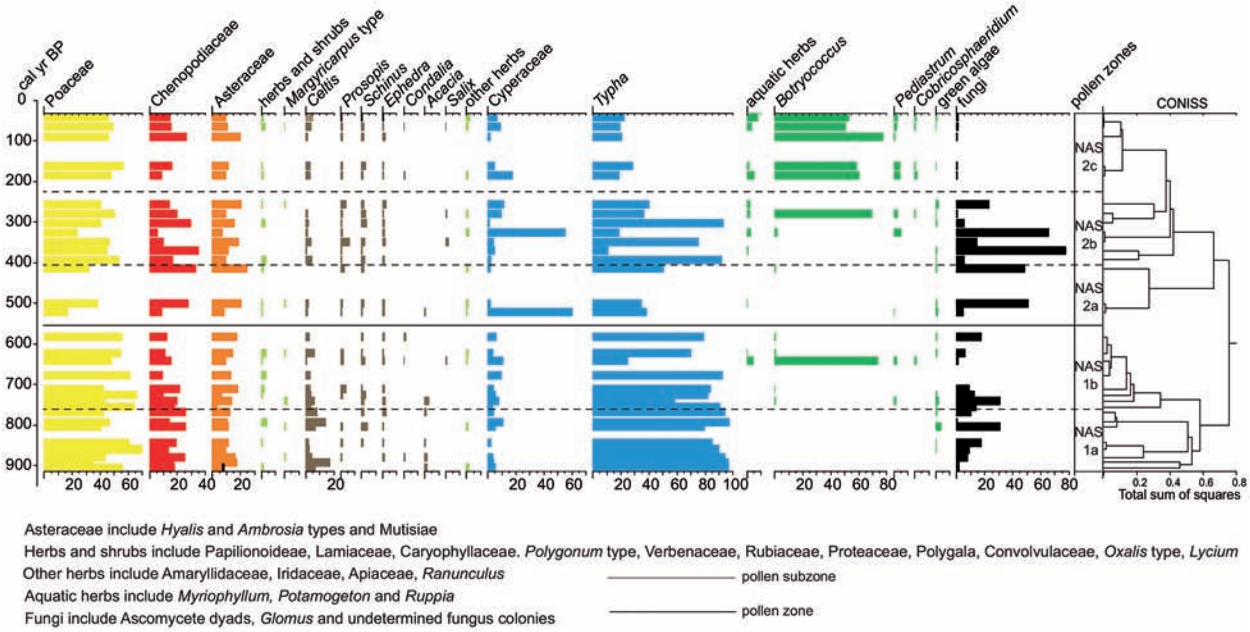

Fig. 3. Palynological diagram and Cluster Analysis. Dashed and bold horizontal lines correspond to the pollen zone divisions, which represent the main the changes along the records, and each zone corresponds to one time interval.

particularly in the equatorial Atlantic Ocean (Agosta & Compagnucci 2012).

The Laguna Nassau location falls between 500 and 600 mm isohyets (Peña et al. 1998); and between 23 °C and 8 °C isotherms, which correspond to January (austral summer) and July (austral winter) mean temperatures, respectively (Colazo 2012). Seasonal wind data (wind drift potentials) indicate persistent winds from the northeast and more northerly components in the winter and the fall (Tripaldi & Forman 2007). Specifically, the seasonal wind data (1995-2009) from Villa Reynolds (approximately 25 km northward from Laguna Nassau) revealed considerable variation in prevailing wind direction and velocity, reflecting seasonal changes in synoptic-scale circulation and local topographic effects; and a resultant drift direction (RDD) to the SW-WSW (RDD: 225-255°) (Tripaldi et al. 2013).

Materials and methods

Sampling

We obtained six overlapping cores of the entire sedimentary sequence from the Laguna Nassau deepest sector, which is at 3.8 m water depth. Based on their correlation and stratigraphic completeness, we selected 4 cores to produce a 146 cm composite core and stacked record. The core extraction was performed from a drilling platform that consisted of two rubber boats connected and stabilized with wooden boards, and by using a UWITEC corer. The sediment cores were extracted from the pistons and placed in plastic tubes. One of the cores was retrieved at 0 cm depth, that is, at the sediment-water interface in the lake bottom, whereas the other three cores were taken at 8, 56 and 86 cm depth. Those depths were selected for creating partial overlap between contiguous cores in order to correlate them and produce a composite core, taking into account the sampler-length. Two cores were sampled for palynological analysis at the University of Cologne. These two cores and an additional one were analyzed for charcoal. In both cases (palynological and charcoal analyses), sampling was carried out continuously at 2 cm intervals. Sediments from all cores were predominantly composed of lacustrine homogeneous darkish mud (Fig. 2d). No modern surface pollen and charcoal sampling from land sediments surrounding Laguna Nassau were performed. However, the uppermost 8 cm from the top of the composite core correspond to 20th century, and AD 2006 is the most recent year.

Palynological analysis

Standard palynological techniques were applied for pollen analysis, which includes the use of KOH, HCl, HF and acetolysis processing (Faegri & Iversen 1989). Identified non-pollen palynomorphs (NPP) included spores of bryophytes (*Phaeoceros*, *Anthoceros*), colonies of algae (*Botryococcus*,

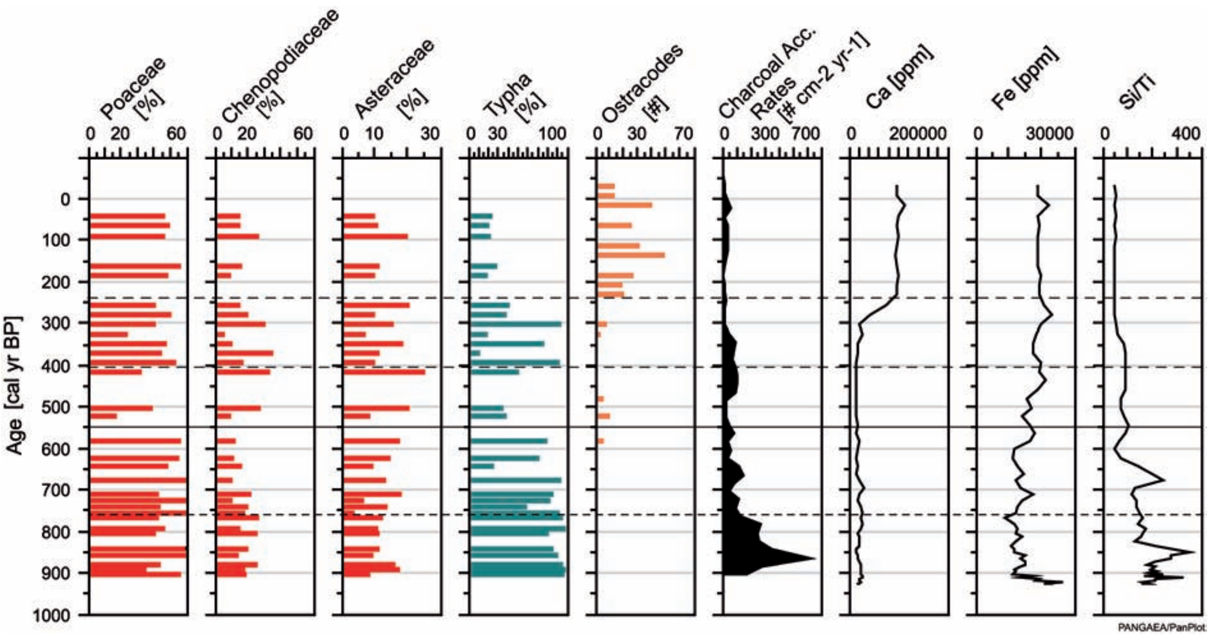

Fig. 4. Multi-proxy record plot: main pollen taxa, ostracodes, charcoal accumulation rate, Ca and Fe concentrations and Si/Ti ratio. Dashed and bold lines, same as for Fig. 3.

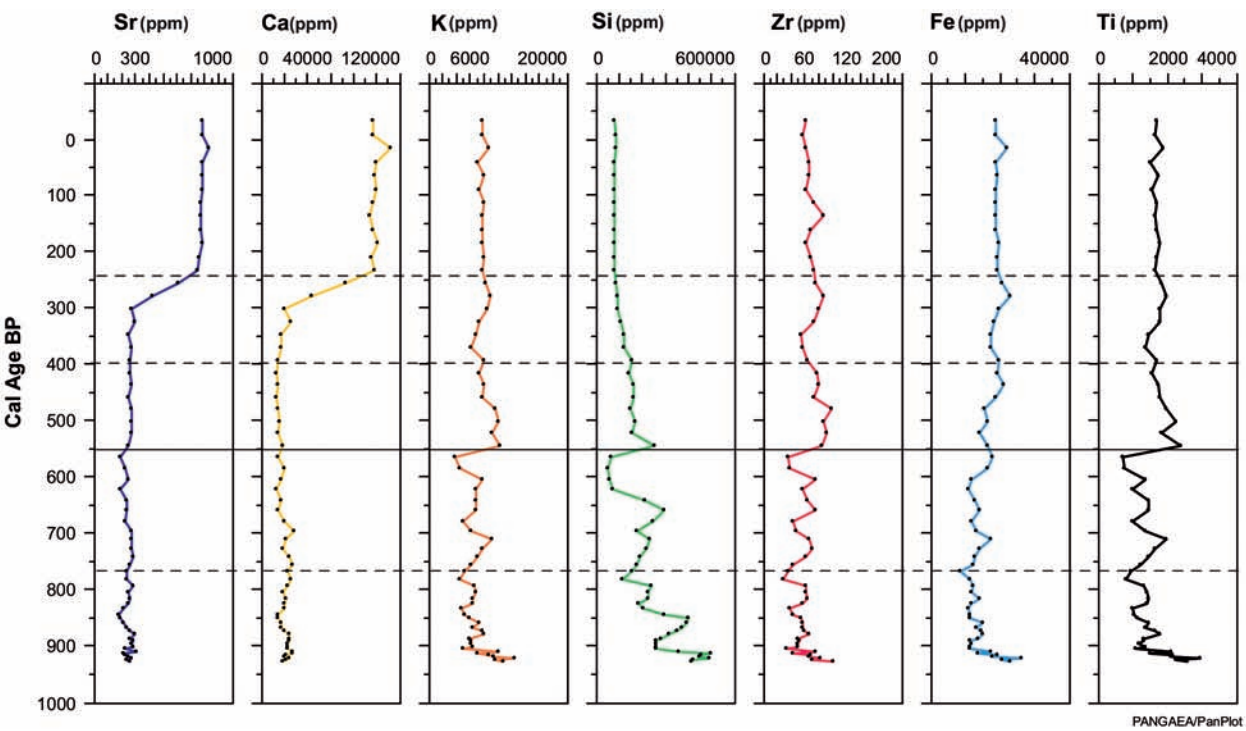

Fig. 5. XRF elemental curves over time. The meaning of dashed and bold lines is explained in Fig. 3.

Pediastrum, *Spirogyra*), *Glomus*, fungus dyads, and other colonial fungi. The total amount of palynomorphs counted varied between 180 and 2569 and was performed over the entire area of each sample slide. Pollen percentages were calculated in relation to the total pollen sum, excluding *Typha* due to its local signal. The NPP percentages were calculated in relation to the total pollen sum plus NPP sum. Pollen zones were determined by CONISS stratigraphical constrained Cluster Analysis (Grimm 2004). Pollen taxa selected for this analysis were Poaceae, Chenopodiaceae, Asteraceae and *Celtis*. The TGView program was used for plotting diagrams (Grimm 2004). CONISS cluster dendrograms are displayed on the right side of the palynological diagram, showing the pollen zones (Fig. 3). The multi-proxy graphic (Fig. 4) was displayed using PanPlot software by Pangaea® Data Publisher for Earth & Environmental Science (Sieger & Grobe 2013).

Charcoal analysis

The macroscopic Charcoal analysis was performed following the methods described in Whitlock & Anderson (2001). Samples of 1 cm^3 were placed in 5% KOH for 24-hours dispersion. They were then wet-sieved through stacked 125 µm and 250 µm sieves. Charred particles in the size classes 125-250 µm and >250 µm were counted separately under binocular microscope (25x and 16x magnification) using a gridded Petri dish. The charred particles were counted and converted to charcoal concentration (particles/cm^3). These data were translated into charcoal accumulation rates (CHAR; particles/cm^2/year) by dividing the concentration of each sample by its modelled deposition time (cm/year). The Char-Analysis Software (Higuera 2009) was used to resample charcoal concentrations to define equally spaced time intervals throughout the record. Ostracod shells, if present, were also counted throughout the sequence.

Table 1. Radiocarbon dates in years before present (^{14}C yr BP) and their correspondent calendar years (cal. yr. BP).

Lab #	Depth (cm)	Measured ^{14}C age	Measured error (±)	MCAgeDepth modelled age (cal yr BP)
Poz-43774	58	575	25	537-(603)-641
Poz-43718	92	715	30	572-(670)-707
Poz-43716	62	745	30	662-(683)-727
Poz-43774	158	1020	30	834-(940)-1014

XRF-analysis

This analysis was geochemically characterized by X-ray Fluorescence (XRF) using a Thermo-scientific Niton XL 3t XRF-analyzer at the German Archaeological Institute in Frankfurt and Cologne University, Germany. Here, we present the analyses for Strontium (Sr), Calcium (Ca), Potassium (K), Silicon (Si), Zirconium (Zr), Iron (Fe) and Titanium (Ti) in ppm unit.

Chronology

Three AMS radiocarbon dates were obtained from organic matter contained in the lacustrine mud. The results are presented in Table 1. All ages are reported in uncalibrated radiocarbon years before present (^{14}C yr BP) and were calibrated to calendar years before present (cal. yr BP). The calibration and the age model were performed by CALIB 6.1.1 and MCAgeDepth 0.1 software (Fig. 2e). According to this age model, the multi-proxy records range from approximately 930 to -56 cal yr BP (ca. AD 1025 to 2006).

Results

Description of multi-proxy records

According to Cluster Analysis, the palynological spectra can be divided in 2 pollen zones and 5 subzones; each division between contiguous subzones and zones representing vegetation change, the main one at ~770 cal yr BP and the other occurring at 585, 415 and 255 cal yr BP. These changes are mostly coincident with variations in values of charcoal particles and elemental concentrations (Figs. 3, 4, 5); all of which can be described as following:

NAS-1a: 900-770 cal yr BP (AD 1045-1182)
(112-78 cm depth)
This period is marked by the dominance of Poaceae, Chenopodiaceae and Asteraceae (highest values of 70, 26 and 17%, respectively) with some fluctuations in their values. In particular, *Celtis* presents very fluctuating and the highest values (up to 17%) of the whole sequence. *Prosopis*, *Schinus*, *Ephedra*, *Condalia* and *Acacia* are intermittently recorded. Cyperaceae presents values up to 10%, and *Typha* is up to 97%. Green algae are present with <5% while fungi increase up to about 30%, and decrease at the top.

The charcoal accumulation rate in this zone is the highest of the entire record, increasing from ~100 up to <600 particles/cm^2/year, followed by a decrease to similar values to previous. Regarding the elements, before ~905 cal yr BP, Sr and Ca present little fluctuations; whereas K, Si, Zr, Fe, and Ti show higher fluctuations and a decreasing trend. The Si/Ti ratio is also recorded with fluctuating values and a peak of >400 ppm.

NAS-1b: 770-580 cal yr BP (AD 1182-1367)
(78-56 cm depth)
This interval is characterized by more constant values of Poaceae, Chenopodiaceae and Asteraceae (mean of 54, 15 and 12%, respectively). *Celtis* decreases notably (highest values of 6%). In contrast, *Prosopis* increases slightly (up to 4%) whereas *Schinus*, *Ephedra*, *Condalia* and *Acacia* maintain similar records to the previous. Cyperaceae increases intermittently and *Ty-*

pha is recorded with fluctuating values, some of them being lower than those previously recorded (range of 25-93%). Aquatic herbs (*Myriophyllum*, *Potamogeton* and *Ruppia*) appear with values of <10 %, *Botryococcus*, *Pediastrum* and other green algae appear during this time, the first has a peak of 80%, while the second and third are registered as traces. Fungi fluctuate from <5 to 35%.

In this period, the charcoal accumulation rates decrease over time from values <200 to about 25 particles/cm^2/year. Sr and Ca present little fluctuations along this interval as previously. Ca and K, Si, Zr, Fe, and Ti show an increasing trend, reaching the highest peak at ~700 cal yr BP, followed by fluctuating values. The Si/Ti ratio is recorded with a peak of <400 ppm.

NAS-2a: 580-415 cal yr BP (AD 1367-1545)
(56-40 cm depth)
This short interval is marked by lower and highly fluctuating values of the main taxa, a Cyperaceae peak, and abrupt decrease in *Typha*, and 40% of fungi. Also, scarce ostracodes appear but then are no longer recorded, which coincides with a charcoal increase up to about 100 particles/cm^2/year. Sr and Ca values are very constant, with similar magnitude as in the previous zone. In contrast, K, Si, Zr, Fe, and Ti show fluctuating values and an increase at ~550 cal yr BP. Si/Ti ratio values present low variations.

NAS-2b: 415-255 cal yr BP (AD 1545-1705)
(40-26 cm depth)
In this zone, Poaceae, Chenopodiaceae and Asteraceae present mean values of 49, 23 and 13%, respectively. *Celtis* presents a decreasing trend (highest value <5%). *Prosopis*, *Schinus* and *Ephedra* keep values of <5%. Cyperaceae have values up to 20% and a peak of ~50%. *Typha* registers the highest fluctuations of the sequence (10-95%), and aquatic herbs are more frequent having comparable values to the previous section (<10%). *Botryococcus* is intermittently registered and has a peak of ~70%, *Pediastrum* is also discontinuously recorded with values of ~10%, and green algae maintain similar values to the previous zone, whereas fungi increase notably, reaching peaks of 80%.

The charcoal accumulation rate diminishes considerably to the lowest values of the record (<50 particles/cm^2/year). Ostracodes reappear in this zone and increase towards the end of this interval; which coincides with the increase in Ca. Similarly, Sr also increases. K, Zr, Fe, and Ti shows a small peak at ~300 cal yr BP, while Si displays a constant decreasing trend as does the Si/Ti ratio.

NAS-2c: 255-40 cal yr BP (1695-1909 AD).
(26-08 cm depth)
Poaceae, Chenopodiaceae and Asteraceae present more constant values (mean of 50, 16 and 12%, respectively); and *Celtis*, *Prosopis*, *Schinus* and *Ephedra* are recorded with values around 3, 1.5 and 1%. Cyperaceae is constantly present with values up to 20%. *Typha* registers the lowest values of the sequence (up to 28%) and aquatic herbs reach 10%. *Botryococcus* has values between 41 and 73%, *Pediastrum* values are only as high as 5%; green algae and fungi are recorded with very low values or as traces.

The charcoal accumulation rate is lower than 100 particles/cm^2/year. Ostracodes reach the maximum values (up to 50 individuals /sample), which coincides with the highest Ca (~25,000-30,000 ppm). Sr follows the same Ca pattern. K, Si, Zr, Fe, and Ti have very constant values as well as the Si/Ti ratio; however, Zr shows a small peak at ~150 cal yr BP.
In the last upper part of the zone, between 40 and -56 cal yr BP (AD ~1910-2006), the charcoal records and almost all element trends show little variation in their curves, except for a small peak at AD ~1930. On the contrary, Si and Zr remain practically constant, as well as the Si/Ti ratio. Ostracodes decrease to 15 individuals per sample. No palynological records are available after 40 cal yr BP (AD ~1910).

Discussion

The pollen spectra consist predominantly of three groups of taxa, (1) Poaceae, Chenopodiaceae and Asteraceae representative of the psammophytic and halophytic steppes (2) *Celtis*, *Prosopis*, *Schinus* and *Condalia* characteristic of the Espinal xerophytic woodland, and (3) *Typha*, Cyperaceae and aquatic herbs (*Ruppia* and *Potamogeton*), which reflect the local semi-aquatic and submerged vegetation. Also, the aquatic palynomorphs *Botryococcus*, *Pediastrum*, and other green algae (*Spirogyra* and *Scenedesmus*) were recognized and they are indicative of lake depth. The main fluctuations in the palynological spectra coincide with variations in charcoal accumulation rate and elemental concentrations, and provide evidence of the vegetation and environmental evolution at centennial scale for the last ~900 cal yr BP. This evolution can be described in time intervals with limits that were established according to the pollen zones resulted from Cluster Analysis (Fig. 4).

Paleoenvironmental reconstruction

The blowout depression upon which Laguna Nassau developed could have formed sometime during the Holocene or earlier, since the San Luis paleodune field exhibits evidence for repeated activation during the last glaciation, ~33,000-20,000 cal yr BP (Forman & Tripaldi 2007), and a nearly continuous sequence of aeolian sand sheet deposits spanning most of the Holocene (Forman et al. 2014). It is possible that the origin of the blowout depression resulted from the operation of the twin processes of salt weathering and aeolian deflation. It is likely that the groundwater table controlled the depth to which deflation occurred and contributed to salt weathering process (Goudie & Wells 1995).

Our chronology indicates that the lake level rise and the organic sedimentary deposition in the blowout depression – likely related to the variations in the groundwater table – were already taking place at ~900 cal yr BP. Similar variation trends of K, Si, Zr, Fe and Ti from sandy sediments beneath the organic mud, suggest the dominance of minerogenic clastic input at ~930 cal yr BP. In addition, Sr and Ca show little variation, which may be related to predominantly inorganic deposition. However, the Si/Ti ratio shows more variation than the elemental composition of the sediments, which may indicate aeolian input of Si-rich minerogenic material from outside the catchment and the concurrent input of Si from biogenic silica (Fey et al. 2009).

Between ~900-770 cal yr BP (AD 1045-1182)

According to our results, Espinal vegetation was already developing by ~900 cal yr BP. In fact, the highest percentages of *Celtis* recorded during this interval can be associated with temperatures warmer than today along with a dry or slightly moist, well-drained soil. It can also be associated with a groundwater table deep enough to permit the necessary underground growth and development of the root system of *Celtis* trees.

Concerning local vegetation, the stands of *Typha* likely would have been in shallow waters or low-lying wet zones of the blowout because the species of this genus commonly populate the margins of ponds or in water of <30-46 cm in depth (Vaccaro 2005). The dominance of *Typha* could be related to the onset of vegetational cover at the margins of an incipient water body, as they are typical of early-seral communities occurring early in the primary succession immediately or soon after disturbance in moist, wet habitats or debris flows (Carter 1984).

Typha is an aggressive invasive when freshwater and nutrients influxes occur, and they produce high litter biomass. They are composed of dense stands of live and dead biomass that may reduce plant diversity (Vaccaro 2005); thus, they might have superimposed the regional signal of Poaceae, Chenopodiaceae and Asteraceae, representing the psammophytic and halophytic communities.

The highest charcoal accumulation rates recorded during this time reflect fire events that can be directly related to high litter biomass of *Typha* populations as the fuel burned during drought periods. Indeed, fires also favor those populations for a rapid dispersion into newly burned sites by sprouts from rhizomes (Barry et al. 2002). The mortality of *Typha* species may have occurred when severe fires burned under drained marshes; thus, their burned populations might have played a key role in the fire events driven by semi-arid conditions.

Variations in *Typha*, an increase in Poaceae, the highest peak of charcoal accumulation rate, an increase in Fe and the highest Si/Ti suggest that dry conditions followed the beginning of the incipient development of the water body at ~860-800 cal yr BP, and emphasize the environmental instability in terms of the moisture (Figs. 4, 5). The variable trend in Si during this interval and the highest Si/Ti can be related to the biogenic silica availability from the biomass of the *Typha* and Poaceae, together with that of the Espinal species, e.g. *Celtis*. Sr and Ca are low, with little variation; instead, K, Zr Ti and Fe present similar variations, suggesting geochemical processes related to humid and dry events, as well as to the influx of biomass and aeolian sand into the system (Figs. 4, 5).

These dry and semi-arid conditions during this interval are coeval (synchronous) with the Medieval Climate Anomaly period, and may represent the response of the ecosystem to interannual to multidecadal summer precipitation variability.

Between ~770-580 cal yr BP (AD 1182-1367)

The decreasing trend of *Celtis* and the disappearance of *Acacia* suggest variations in Espinal cover and/or composition. In addition, variable percentages of Poaceae, Chenopodiaceae and Asteraceae reflect instability of the psammophytic-halophytic communities that developed on the sand dunes and flat areas surrounding the water body. The highly variable values of *Typha* indicate water depth fluctuations also supported by a peak of *Botryococcus*, the appearance of *Pediastrum* and aquatic herbs.

A decreasing trend in charcoal accumulation rates and Si/Ti, and the variable pattern of Fe suggest changing environmental conditions. A generally decreasing, yet oscillating trend in charcoal accumulation rates suggest more variable and less frequent fire events, which coincide with *Typha* fluctuation patterns, thus reinforcing that litter biomass from *Typha* was the fuel for fires. The increase of fungi and the appearance of scarce ostracodes reflect more frequent humid environmental conditions than before. The nearly constant values of Sr and Ca, except for a small peak in the latter, coincide with the appearance of ostracodes. Ca is often viewed as a signature of increased warming, (Muynck et al. 2013; Wang et al. 2012) but it may also possibly be related to increased acidity (acid rain) where dissolution of local limestone could increase Ca levels in a pond or lake. Aeolian inputs of $CaCO_3$ from dust and/or wood ash – $CaCO_3$ is a major component – may also be considered.

A charcoal peak at ~650 cal yr BP is coincident with a peak in Si/Ti, which may imply the biogenic origin of Si. The Zr and Si, however, vary in the same direction and may be related to clastic sedimentation (Avramidis et al. 2014); whereas the variations in K may be associated with the clay composition but also to the wood ash. In summary, humid/wet events became more frequent during this period, reflecting complex hydroecologic variability, coeval with the Medieval Climate Anomaly.

Between ~580-415 cal yr BP (AD 1367-1545)

This short period is characterized by the continuity of environmental variations in terms of moisture and water depth, and probably with less constant warm conditions as suggested by the decreasing trend of *Celtis* and its subsequent absence towards ~415 cal yr BP. This variability in moisture is shown by the psammophytic and halophytic communities, the taxa of which (Poaceae, Chenopodiaceae and Asteraceae) show quite variable patterns. In addition, the local *Typha* decrease is likely associated with an increase in water depth that forced *Typha* stands to move to shallower littoral zones of the water body. Cyperaceae registered a 60% peak and the charcoal accumulation rate presents a small peak only at ~450 cal yr BP. The Fe shows an increase, which could be associated with a higher degree of oxidation, which in turn means frequent water level changes. The Si/Ti ratio and most of the elements, particularly Sr and Ca, are recorded with fewer oscillating values than before, suggesting more stable geochemical water body conditions, related perhaps to more allochthonous input.

The environmental variations in terms of moisture and water depth during this interval in Laguna Nassau could be related to the transition from predominantly warm during the Medieval Climate Anomaly to much cooler conditions during the Little Ice Age, driven by the shifting South American Summer Monsoon.

Between ~415-255 cal yr BP (AD 1545-1705)

The Espinal vegetation is represented by the reappearance of *Celtis*, with values showing a decreasing trend, and by *Prosopis*, *Schinus* and *Ephedra*, with nearly constant values and a small increase. These spectra could be reflecting the modern Espinal distribution and composition as a response to a change in environmental and climatic conditions (e.g. lower temperature forcing northeastward displacement of subtropical species such as *Celtis*). In addition, Poaceae, Chenopodiaceae and particularly Asteraceae, with relatively higher and constant values, might be reflecting landscape stabilization due to the more vegetation cover.

Locally, this interval is characterized by a higher variability than before in terms of hydroecological conditions, mostly evidenced by the *Typha* oscillating values. Nevertheless, a trend towards increased water depth, related to the influence of a wetter environment is suggested by the sudden reappearance of ostracodes and *Pediastrum*, and by the Cyperaceae and *Botryococcus* peaks; and the abrupt decrease in charcoal accumulation rate after ~300 cal yr BP. Also, reduced uptake of water by vegetation (reduced evapotranspiration) during cooler times may have contributed to ponding process and higher water levels. The notable increase and changing pattern of Sr and Ca can be related to the appearance of ostracodes occurring at this time, when small peaks in K, Zr, Fe and Ti are recorded; all of which may be related to variable geochemical characteristics of the water body. However, Si is fairly constant, which could be implying its partially biogenic origin. The wetter and probably colder environmental conditions during this interval correspond to the Little Ice Age period.

Between ~255-40 cal yr BP (AD ~1600-1900)

The Espinal vegetation is characterized by slightly higher values of *Celtis* and lower values of *Prosopis* whereas taxa composing the psammophytic and halophytic communities present similar values to the previous time. Despite the small variations in the relative proportions of Espinal taxa, more stable environmental conditions can be inferred, because of the low and fairly constant charcoal accumulation rate. A deeper water body is indicated by the relative values of aquatic herbs, *Botryococcus* and *Pediastrum*; also by the *Typha* decrease, and the increased numbers of ostracodes. A deeper stable water body may be responsible for the very little variation in the concentration of almost all elements. The Zr small peak ~150 cal yr BP can be attributed to the high resistance to weathering and the minimal mobility in the environment. The interaction of Zr with aquatic plants, which have a rapid uptake of soluble Zr, can also affect the availability of this element.

In this interval, the evident development of the water body can be associated with the expansion of the overbank zone and the rise of the groundwater table, which, in turn, is influenced by water availability in the catchment area of the Río Quinto basin (Quintana-Salvat & Romero-Nelson 1993; Cioccale 1999; Viglizzo et al. 2009).

No palynological records are available after ~40 cal yr BP. A small charcoal peak coincident with peaks in Sr, Ca, K, Fe and Ti, however, can be related to the drought event in the paleodune field during the first half of the 20th century, evidenced by geomorphological studies and historical documents (Tripaldi et al. 2013). No human impact has be recognized in our study; however, in the early 20th century, cultivation expanded to lands adjacent to the Western Pampas, reflecting the availability of pristine land (Tripaldi et al. 2013 and references therein).

Overall, the multi-proxy record shows the evolution of Laguna Nassau, which was characterized by unstable and highly variable depth, but with a trend from an incipient low level water body to a deeper and permanent shallow lake.

Paleoclimatic interpretation and regional context

At ~900 cal yr BP, the ponding process and organic deposition in the blowout depression, where Laguna Nassau developed, may reflect climatic amelioration in comparison with most of the earlier Holocene times, particularly from ~12,000 to 1,000 years BP, when pervasive, nearly continuous and ubiquitous sand-sheet deposits covered the Western Pampas, and many aeolian systems were active (Forman et al. 2014, and references therein). This sand-sheet deposit was favored by considerably drier conditions and sparse vegetation of the arid Monte type, which today is mostly developed in the western region of San Luis province. This vegetation facilitated formation of the sand sheet, allowing accumulation of particles by obstruction of wind (Forman et al. 2014).

The climatic amelioration suggested by the ponding and organic deposition, can be associated with warm and humid conditions for the period 1400-800 cal yr BP, corresponding to the Medieval Climatic Anomaly when a climatic improvement in the central region of the country is registered by an incipient soil development, expansion of the fluvial and lacustrine systems, and formation of swamps in depressions (Iriondo 1999; Cioccale 1999). Also, in the Sandy Aeolian Plain or Pampean Sand Sea located at 33-38°S, 59°20'-67°W (Iriondo 1999), partial erosion of the landforms occurred in all dune fields, and large deflation depressions were transformed into permanent lakes due to rising of the groundwater table (Cioccale 1999).

However, the frequent fire events along with the highest *Celtis* percentages in the Laguna Nassau pollen record suggest a semi-arid climate and indicate that drier and warmer conditions than today predominated in the area from ~900 to at least ~770 cal yr BP. A recent reconstruction of air temperatures for southern South America indicates the presence of a prolonged (decades long) period of elevated summer temperature occurring in the thirteenth and early fourteenth centuries (Díaz et al. 2011), during the MCA climatic event.

Regionally, geomorphic and stratigraphic records from one of the driest and westernmost dune fields, Médanos Negros, located in La Rioja province (Fig. 1) show dune reactivation around 900 cal yr BP associated with dryness and subsequent desiccation (Tripaldi & Forman 2007). In the northern Pampas, in Laguna Mar Chiquita (Fig. 1), a highstand has been recorded at 1,100 cal yr BP, while droughts are poorly resolved due to the occurrence of several sedimentary hiatuses (Piovano et al. 2009 and references therein). From this integration we infer that probably climatic conditions during the MCA were not uniform at regional scales, and included dry and wet phases occurring in a multi-decadal to centennial scale. The MCA climatic conditions have been related to a significantly weakened South American summer Monsoon

(SASM), with the mean location of the Inter-tropical Convergence Zone (ITCZ) acting as modulator of the SASM intensity on multi-decadal to centennial time scales (Vuille et al. 2012). The influence of a weakened SASM could have been extended to the Western Pampas, as its southernmost limit, with consequence of variations on the Laguna Nassau water level.

From ~770 to ~200 cal yr BP, the Laguna Nassau record suggests that climatic variability prevailed and was characterized by progressively more frequent wet and humid events, with almost no fire events between ~300 and 200 cal yr BP. This climatic variability at Laguna Nassau coincides, chronologically, with the cessation of sand accretion by 800 to 200 years ago in different sections of the San Luis paleodune field, associated with wetter conditions and the succession of Espinal vegetation (Forman et al. 2014).The highest hydroecological variability inferred from our results, particularly between ~600 and 500 cal yr BP can be associated with the transition from dry and warm to wet and colder climatic conditions, but always under a predominantly semi-arid climate. This transition could indicate a shift from MCA to LIA climatic conditions. Regionally, in Salinas del Bebedero (Fig. 1) two highstands (+10 and +6 m over the Salinas floor) took place at 550 and 334 cal yr BP, respectively; punctuated by a dry episode between them (Piovano et al. 2009).

During the last 200 years, a deeper, more stable water body at Laguna Nassau is coeval with the cessation of sand accretion, suggesting more humidity than before. However, during the first 30 years of the 20th century, small peaks of the charcoal accumulation rate reflect some fire activity, which is in agreement with documented historical drought (Tripaldi et al. 2013). Regionally, the stratigraphic sections from the San Luis paleodune field expose a complex sequence of aeolian sands and paleosols at ~95-60 cal yr BP suggesting aeolian mobilization alternating with wet and more stable phases (Tripaldi et al. 2013). In the northern Pampa plains, the paleo-hydrological record from Laguna Mar Chiquita indicates dry conditions since ~AD 1770 with the occurrence of short-lived humid pulses during the second half of the 19th century, AD 1850-1870 (Piovano 2009). In Salinas del Bebedero, historical documents appear to indicate a high lacustrine stage (+5/+6 m over the Salinas floor) from the 18th to the 19th century associated with late LIA times (Piovano et al. 2009 and references therein), which is concurrent with the deeper water phase of Laguna Nassau. The lacustrine stage in Salinas del Bebedero may have been triggered by large amounts of seasonal meltwater from Andean fluvial system as was proposed for the Last Glacial period (Piovano et al. 2009). Likewise, this situation in Laguna Nassau could have occurred when meltwater in the catchment area of the Río Quinto Basin, uphill in the San Luis ranges (Sierras de San Luis), increased the water supply and raised the groundwater table.

Our results and interpretations are partially in agreement concerning the cold and arid conditions proposed for the Pampean plain during the LIA (e.g. Piovano et al. 2009) since we inferred colder but not extremely arid conditions after ~400 cal yr BP. In fact, we interpret a trend toward more humid conditions or at least with enough water supply by the increase in depth and water level stabilization of the Laguna Nassau water body, and by the diminished fire activity in comparison with the first half of the last millennia. Nevertheless, our inferences regarding a wet phase can be partially coherent with the intensified climatic oscillations and succession of extreme drought and flood events proposed by Cioccale (1999). Indeed, the LIA period in the central region of Argentina was not a homogeneous event: it was formed by two cold pulses, separated by an intermediate period of more benign conditions, similar to or more humid than at present (Cioccale 1999). During the LIA, the mean state of the SASM was strengthened, due to a further southward displacement of the ITCZ, which can be interpreted as a thermodynamic adjustment to allow for enhanced northward heat transport required to balance Northern Hemisphere cooling (Vuille et al. 2012).

An east-west connection in the central region of Argentina may play an important role in the different climatic conditions during MCA and LIA, and confirm de model proposed by Iriondo (1999) that established inverse correlations among different South American plains (Cioccale 1999). During the LIA, in the west, Salinas del Bebedero Lake reached a high level, while the Mar Chiquita Lake, in the east, became a swamp skirted by salinas and dunes in the east. This means that, in the west of the region, the fluvio-lacustrine systems were larger during cold events (LIA) and shrank during warm events (MCA). In contrast, the fluvio-lacustrine systems in the eastern region diminished during cold events and increased their extent during warm episodes (Cioccale 1999). The response of Laguna Nassau water body has some similarities with the response of Salinas del Bebedero, which is coherent with its location in the Western Pampa region.

Furthermore, according to Piovano et al. (2009), two groups of climate records – on both sides of the Arid Diagonal – can be distinguished regarding their hydrological response during dominant warm or cold climatic phases. The first group includes records from the Pampean region and the second group includes archives of the Patagonian climate, as well as the Salinas del Bebedero. The complex hydrologic variability of Laguna Nassau makes it difficult to clearly categorize its response in either of these groups. This ambiguity can be due to the sensitivity of Laguna Nassau from its proximity to the border of the Arid Diagonal. Nevertheless, the changes in the water depth of Laguna Nassau over time are comparable to those of Salinas del Bebedero.

The different interpretations about timing and frequency of humid/wet pulses and intensification of dry periods can be attributed to local environmental variations but also to different levels of chronological resolution. For instance, periods of dryness are not chronologically well-constrained; therefore, it is unknown if there were multiple decadal-to-century scale droughts that propagated dune movement (Forman et al. 2014).

Conclusions

The multi-proxy record from Laguna Nassau water body shows multi-decadal to centennial environmental and vegetation changes, as well as complex hydro-ecological variations; and evidenced the evolution from an incipient and unstable water body towards a deeper and stable shallow lake during the last ~900 years, which encompass the MCA and the LIA climate periods.

From the comparison of our records with other records from the west-central Argentina, we conclude that the environmental, hydrological and climatic conditions during the MCA and LIA were not uniform and included dry and wet phases with different timing at the regional scale. Regionally, Laguna Nassau has a response to climatic variation more similar to Salinas del Bebedero than to Laguna Mar Chiquita, supporting the east-west differences in responses on the Pampean Plain and the influence of location with respect to the Arid Diagonal.

However, more high-resolution records are still needed for clearly establishing trends and timing of wet and dry phases for the last millennia and to establish patterns of response to variations in the atmospheric circulation within the South American context.

Acknowledgements

We give cordial thanks to Amalia González who elaborated the map figures, to Knut Rassmann (German Archaeological Institute, Frankfurt) to Markus Forbriger and Felix Henselowsky (Geographical Institute, Cologne) for their help and support with the XRF analyses. We thanks Dr L. Rojo and the anonymous reviewer for their comments and suggestions. We are very grateful to Joanne Ballard for her comments and contributions, and for the English revision, also revised by Sophie Lehmann. Funding by the Hohmann Foundation (Gesellschaft für Erdkunde, Cologne, Germany) to Wilfried Schulz is greatly acknowledged.

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Manuscript received: May 19th, 2014.
Revised version accepted: February 12th, 2015.

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