Paleoenvironmental reconstruction of the semi-arid Chaco region of Argentina based on multiproxy lake records over the last six hundred years

Flavio Cesar Speranza^{a,e,*}, Santiago Giralt^b, Liliana Concepción Lupo^{c,d}, Julio José Kulemeyer^{c,e,f,g}, Elizabeth de los Ángeles Pereira^{c,d}, Bernat Claramunt López^{h,i}

^a Instituto Nacional de Tecnología Agropecuaria, RN N° 34 Km 1286, Yuto 4518, Jujuy, Argentina

^b Institute of Earth Sciences Jaume Almera (ICTJA-CSIC), C/Lluís Solé i Sabarís s/n, 08028 Barcelona, Spain

^c Instituto de Ecorregiones Andinas (INECOA), CONICET, Universidad Nacional de Jujuy, Av. Bolivia 1239, San Salvador de Jujuy 4600, Jujuy, Argentina

^d Laboratorio de Palinología, Cátedra de Ecología General, Facultad de Ciencias Agrarias, Universidad Nacional de Jujuy, Alberdi 47, San Salvador de Jujuy 4600, Jujuy, Argentina

^e Cátedra de Ciencias de la Tierra, Facultad de Ciencias Agrarias, Universidad Nacional de Jujuy, Jujuy, Argentina

^f Cátedra de Suelos, Facultad de Ingeniería, Universidad Nacional de Jujuy, Italo Palanca 10, San Salvador de Jujuy 4600, Jujuy, Argentina

^g InDyA, Conicet-UNJu, UNT, Pcia. de Jujuy. Av. Gral. Martijena S/N, Palpalá, Jujuy, Argentina

^h CREAF, Universitat Autònoma de Barcelona, Edifici C (Facultat de Ciències), Barcelona, Catalonia

ⁱ Unitat d'Ecologia, Departament de Biologia Animal, Biologia Vegetal y Ecologia, Universitat Autònoma de Barcelona, Edifici C (Facultat de Ciències), Barcelona, Catalonia

ABSTRACT

In this paper, we analyze the paleoclimatic and paleoenvironmental evolution of Laguna Yema in semi-arid Chaco region of Argentina over the past six hundred years. High resolution multiproxy studies of lake sediments utilize analyses of lithology, mineralogy, geochemistry, palynology, and are constrained by radiocarbon and gamma spectrometry dating. Laguna Yema sediments were mainly composed of well stratified fine sediments (silts and clays), with variable proportions of quartz, clays (illite) and feldspar (microcline and albite). Twelve light and heavy geochemical elements were registered. Most elements (Al, Si, K, Ti, Fe, Rb, Ba, and Br) are associated with illite and albite. Different material transport processes related to the changes in aridity and humidity of the basin were identified using the main mineralogical origins of geochemical elements. Palynological records indicate cycles of contraction and expansion of the lake, with an increase in concentration of *Alternanthera aquatica* during wet periods (expansion of lake), and an increase in *Ambrosia*, *Poaceae* and fern spores during dry periods (contraction of lake). These changes are linked to fluctuations in moisture conditions in the Subandean Mountains and semi-arid Chaco regions, in response to interactions between the South American Monsoon System (SAMS) and the South American Low Level Jet (SALLJ), which send warm and humid air to northern Argentina. In a regional context, the Laguna Yema records are in accordance with the analyses of the temporal and spatial pattern of moisture distribution for the last six centuries.

1. Introduction

Holocene paleoclimatic studies provide important information on the long-term climatic trends required to generate and test hypotheses about climate patterns and to validate climate models (Hernández-Almeida et al., 2015; Mann et al., 2008; Ortega et al., 2015; Rial et al., 2004; Zorita et al., 2003). One common way to conduct paleoclimatic studies is through the high-resolution

multiproxy characterization of lacustrine sediments (Bradley, 2015; Gornitz, 2009). Lakes are among the best and most sensitive continental indicators of environmental changes (Battarbee, 2000; Fritz, 1996), and research provides evidence that lacustrine sediments can be used to reconstruct high-temporal resolution of past precipitation (e.g. Cheng-Bang et al., 2012; Kalugin et al., 2007), land management (e.g. Reavie et al., 2017; Sayer et al., 2012; Striewski et al., 2009), and environmental or limnological conditions of the lake (e.g. Bennion et al., 2005; Bigler et al., 2009; Chen et al., 2009).

Environmental changes that provoked modifications of drainage basin dynamics are precisely recorded in lake sediments (Fierro et al., 2016; Giralt and Julià, 2003). These modifications include disturbances in the river flow that feed the lake and variations in the amount of sediments and transport processes. Increases in river flow are related to increases in precipitation, which generate greater erosive power for the transport of materials and, consequently, an increase of terrigenous input into the lake (Amsler et al., 2007; Brea and Spaletti, 2010; Coppus and Imeson, 2002). Changes in the basin's floristic assemblages are also recorded in the lake sediments, and are analyzed through pollen studies of the lake stratigraphy (Bennett and Willis, 2001; Lupo et al., 2006, 2008). Finally, lake sediments also exhibit physical and chemical variations of lake water masses which, in turn, induce changes in the geochemical composition (Giralt et al., 2008; Piovano et al., 2002; Sáez et al., 2009), indicating changing nutrient inputs due to runoff variations (Giralt et al., 2008) or other allochthonous components (Martín-Puertas et al., 2011).

One of the challenges of using sediment records as an environmental archive is the complexity of identifying and differentiating the interacting external forces (e.g. climate, tectonics, geomorphological activity, changing regional vegetation, anthropogenic influence) from the internal forces (e.g. aquatic biota) (Cohen, 2003). Fierro et al. (2016) and Giralt et al. (2008) identified sediment transport process using redundancy analysis (RDA) with mineralogical and geochemical

samples, as well as Principal Component Analysis (PCA) with high resolution geochemical composition data. Additionally, the analyses of the palynological composition of the stratigraphic column of lacustrine sediments allow for a multidisciplinary approach to the series of environmental changes and help clarify situations in paleoenvironmental analysis. Examples include the presence of pollen types that indicate humidity variations, i.e.: Juncaginaceae, Cyperaceae, aquatic plants, fungi and ferns (Argollo and Murguiart, 2000; Fierro et al., 2016; Lupo et al., 2006); anthropogenic influences related to cattle grazing, e.g. Amaranthaceae/Chenopodiaceae (Pereira, 2014); and consequences of fires, e.g. decrease in tree pollen and increase in Poaceae pollen (Lupo et al., 2006).

While there is a growing number of paleoenvironmental studies in South America (Marchant and Hooghiemstra, 2004; Neukom and Gergis, 2011; Villalba et al., 2009), there are still important regions that have not been studied in detail. Research in these regions complements existing understanding (Lupo et al., 2007; Morales et al., 2015a, 2015b; Neukom et al., 2010; Oxman et al., 2013; Piovano et al., 2002; Valero-Garcés et al., 2003; Villalba et al., 1992, 1998) and, most importantly, fills spatial gaps with high-resolution proxy records (Baker, 2000; Coltrinari, 1993; Markgraf, 1998; Markgraf et al., 2000; Vuille et al., 2012). The semi-arid Argentine Chaco is one of these large regions. The relevance of the region lies in its significant biodiversity (Anonymous, 2005; Kuemmerle et al., 2017; Redford et al., 1990) and the fragility of the system, which has historically been modified by human activity (Morello et al., 2005) including exploitation of forest resources without management policies (Braier et al., 2004; Kleinpenning and Zoomers, 1989). It is also currently threatened by the regional expansion of agriculture (Baumann et al., 2016; Gasparri, 2016; Volante et al., 2016). The aim of this paper is to provide new insights about the environmental and climatic evolution of the semi-arid Chaco region of Argentina, using multiproxy records of lacustrine sediments.

2. Study area

2.1. Gran Chaco Americano

The studied area is located in Laguna Yema, Formosa Province, Argentina, at 155 m above sea level (masl), in The Gran Chaco Americano (Fig. 1). The Gran Chaco Americano occupies an area of approximately 580,000 km², from latitude 16° to 33° South and longitude 56° to 66° West. The climate is characterized by seasonal monsoons, with more than 80% of rainfall occurring between November and March (Minetti, 1999). The mean annual rainfall and mean annual temperature displays a strong longitudinal gradient. Based on this gradient and topography, the Gran Chaco is divided into four sub-ecoregions: Humid Chaco (where the annual precipitation values range between 1200 and 750 mm), semi-arid Chaco (750 to 500 mm), arid Chaco (500 to 300 mm) and Chaco Serrano (700 to 500 mm), with a differential topographical situation (Secretaría de Ambiente y Desarrollo Sustentable de la Nación, 2011). Laguna Yema is located in the semi-arid Chaco, with a mean annual temperature that varies between 20 and 22 °C, a mean summer temperature of 28 °C and a mean winter temperature 15 °C. The dominant vegetation is xerophilous semi-deciduous forests and savannas.

2.2. Lake catchment

The Laguna Yema Basin is a vast area of 122,000 km², with maximum altitudes of 5900 masl in the Eastern Andes. The basin is T-shaped. The Upper Basin is characterized by high erosion, a dendritic drainage system of streams and an anastomosing main channel, while the lower basin is differentiated by a meandering river system. The geology is characterized by a sequence of Tertiary mountain chains consisting of numerous rock types, dominated by sedimentary rocks (shale) and metamorphics (phyllite), providing a large amount of quartz and illite in a hydrographic network

(Iriondo and Paira, 2007). The Chaco Plain is dominated by surficial Quaternary sediments, mainly fine sand (98% quartz, 2% feldspar) and associated illite, formed from Eolian sediments (Iriondo, 1993; May et al., 2008; Servant et al., 1981).

The main river that feeds into Laguna Yema, the study locality, is the Teuquito River. This river is a detachment of the Teuco/Bermejo River, one of the most important river systems of Northern Argentina, which has a mean annual flow of approximately 340 m³/s (Secretaría de Energía, 1994) and a solid discharge of over 89.4 million tons/year (Brea and Spaletti, 2010; Soldano, 1947). The section within the Chaco Plain is characterized by high lateral mobility. This is related to the low slope, the high sediment load and the textural characteristics of the sediments transported (Orfeo, 1995).

2.3. Laguna Yema

The lake, located at 24°21'S–61°20'W, is relatively circular; it occupies an area of about 1.3 km², an approximate water volume of about 25,600,000 m³, and a maximum water depth of 3.5 m. According to our measurements, the lake is monomictic and the lake water remains completely mixed throughout the year, with a slight thermocline developing during the austral winter (14.72 °C at the lake water surface and 14.62 °C at the lake water bottom). The summer water temperatures range between 25.75 °C at the lake water surface and 25.17 °C at the lake water bottom. The pH of the lake water ranges between 8.27 and 8.54 in summer and between 7.90 and 8.63 in winter. The water chemistry is dominated by Ca⁺⁺ among the cations and by Cl⁻ among the anions. The water conductivity is rather low (264.7 mS cm⁻¹) and the dissolved oxygen values range between 79% at the lake water surface and 65% at the lake water bottom. In 1984, the northern shores of Laguna Yema were partly overgrown and a number of embankments were constructed. This overgrowth caused a lake surface enlargement owing to the inundation of the adjacent areas and a rise in the

lake water level. The main output occurs via a 89.5-km-long irrigation canal with a carrying capacity up to 10 m³/s. Furthermore, a channel was constructed to divert water from the Teuco River to the Teuquito River to increase the water volume of the latter. Today, the majority of the water entering Laguna Yema is water diverted from the Teuco River.

3. Materials and methods

In July 2008, four replicated cores following a NW-SE transect (Fig. 2) were retrieved using a gravity UWITEC core sampler (LY1.1 and LY1.2 at 24°20'S–61°20'W, LY2.1 and LY2.2 at 24°20'S–61°21'W, LY3.1, LY3.2 and LY3.3 at 24°21'S–61°20'W, and LY4.1 and LY4.2 at 24°21'S–61°19'W). The cores had a length which varied between 185 mm and 410 mm, and were sealed in the field to prevent water losses and possible disturbances during transport to the laboratory. The cores were stored in the Institute of Earth Sciences Jaume Almera (ICTJA-CSIC), in a cool chamber at +4 °C until opened, at which point they were sectioned longitudinally into halves: one was saved as archive material, and the other one was sampled for paleoenvironmental and paleoclimatic purposes.

3.1. Lithology and mineralogy

A detailed lithological description of the cores was carried out to characterize the main textural and sedimentological features of the sediments. The mineralogical composition of the sediments was determined on samples every 5 mm. These samples were dried at 60 °C for 24 h, and manually ground using an agate mill. Mineralogy was determined using a Siemens D-500 automatic X-ray diffractometer under the following conditions: Cu Ka, 40 kV, 30 mA, and graphite monochromator. The identification of minerals was made using the software connected to the diffractometer, and the

quantification of the different mineralogical species present in the crystalline fraction was carried out following standard procedure (Chung, 1974).

3.2. Geochemistry

High-resolution geochemical profiles of the sediments were obtained using the non-destructive Avaatech X-ray fluorescence (XRF) Core Scanner from the University of Barcelona (UB). Sediments were characterized using a Rh tube at 10 kV (exposure time of 10 s with no filter for the elements Al, Si, S, K, Ca, Ti, and Fe), 30 kV (30 s with Pd-thick filter for Br, Rb, Sr, and Zr), and 50 kV (40 s with Cu-filter for Ba) to obtain chemical profiles that are as statistically significant as possible. Measurements were made every 0.3 mm and expressed in counts per second (cps). The database of core LY3.3 was composed of 12 variables and 1293 samples, and core LY4.1 was made up of 12 variables and 930 samples. Sediments were digitized using high resolution camera equipment attached to the Avaatech X-ray Fluorescence (XRF) core scanner. The gray-colour curve was obtained using the software ImageJ (Schneider et al., 2012) and gray values were calculated every 0.07 mm.

3.3. Palynology

Palynological stratigraphic analyses were carried out for 28 samples, selected according to the facies identified in the lithological analysis. Each sample has a thickness of 5 mm. The processing of samples was carried out using standard palynological techniques for Quaternary pollen (Fægri and Iversen, 1989). We used *Lycopodium clavatum* as a control (Stockmarr, 1971) to calculate concentrations (spore/gram of sediment). The subsamples were visually analyzed with an optical microscope, counting and identifying a minimum number of 300 pollen grains per sample. The identification of the pollen types was carried out by comparison with the reference collection of the

Palynology Laboratory of the Faculty of Agricultural Sciences of the National University of Jujuy (PAL-JUA) and pollen atlases (Markgraf and D'Antoni, 1978; Pire et al., 1998; Pire et al., 2002; Salgado, 2006; Wingenroth and Heusser, 1984). The names of the pollen types were established according to the criteria of De Klerk and Joosten (2007) and Joosten and De Klerk (2002). Relative frequencies (%) were calculated for the pollen count. Pollen types that had a representation of total grains lower than 2% were excluded from the analyses. The spores were excluded from the total sum of the count due to over-representation presented by this group and therefore was expressed in concentration values (absolute frequency). Palynological data were analyzed using Tilia v2.1.1 (Grimm, 2011).

3.4. Climate analyses

To analyze the cross-correlation between sedimentological and climatic data we used two types of climate databases: regional and local. The regional climatic precipitation data was extracted from the reanalysis data CRU TS v4.01 - high-resolution gridded datasets (Harris et al., 2014), containing information from 1900 to 2015. Local climate data were taken from weather stations, which covered from 1934 to 1990 (Bianchi et al., 2005). To perform the cross-correlation analyses, data were processed to be comparable by temporal resolution. The climatic precipitation data of both databases (high-resolution gridded datasets and local climate data) have a monthly resolution. These monthly values were summed to obtain annual precipitation values, since the pattern of seasonality of rainfall was maintained for both databases and for all years. To avoid over-representation in cross-correlations, mainly due to the presence of very low frequencies, we eliminated the trends of the common part of the sedimentological data with the rainfall data using the algorithm “Detrended” from the RSEIS package (Lees, 2009) in R statistical software (R Core Team, 2013). Accordingly, cross-correlation analysis was conducted on river flow values at hydrometric stations (Subsecretaría de Recursos Hídricos, 2004).

3.5. Statistical analyses

The statistical analyses were conducted using R statistical software together with the packages *gclus* (Hurley, 2004) for clustering purposes, *tseries* for time series analysis (Trapletti and Hornik, 2009), and *vegan* (Oksanen et al., 2005) for redundancy analysis (RDA) and principal component analysis (PCA). RDA was carried out to simplify the many variables of the XRF datasets, that likely represent similar aspects of the geochemical composition of the sediments. The mineralogical compositions of the sediments were used as a constraining matrix given that each mineralogical species represents a “compendium” of geochemical elements. Thus, RDA was used to identify the possible origins of the light and heavy elements obtained by XRF, and to characterize sedimentary processes, e.g. different types of transport (Giralt et al., 2008; Martín-Puertas et al., 2011). In this analysis, the XRF dataset was resampled to 5 mm in order to have the same sampling resolution as the mineralogical data.

3.6. Chronology

The chronological framework of the sedimentary sequences was based on 6 AMS ^{14}C samples that were analyzed in the Poznan Radiocarbon Laboratory, Poland (Table 1). The radiocarbon dates were calibrated using SHCal13 (Hogg et al., 2013; Niu et al., 2013; Reimer et al., 2013) through the online software CALIB 7.1 (<http://calib.org/calib/calib.html>), selecting the calibrated median age and the age range with highest relative area under the probability distribution of 2-sigma calibration. Post-1954 CE radiocarbon dates present serious drawbacks and for this reason calibration was done with the online software CALIBomb with Southern Hemisphere Zone 3 compilation (<http://calib.org/CALIBomb/>) (Hua et al., 2013; Reimer et al., 2004). Additionally,

gamma ray spectrometry analysis (isotope ^{210}Pb) was carried out to adjust the age model of the upper core LY3.3 (Table 2). Measurements were made every 1 cm in the upper 8 cm of core.

4. Results

4.1. Lithology

The lithological correlation diagram of the cores (Fig. 2) allowed us to select the core LY3.3 as the most complete of the lacustrine distal sedimentation processes, and the core LY4.1 as the most complete of the lacustrine proximal sedimentation processes. Three lithological units were defined on the basis of the main textural and sedimentary features present in the cores (Fig. 2). From the bottom to the top of the sequences these units are:

- Unit 1: located between the base of the cores and 26.4 cm (for core LY3.3), and 8 cm (for core LY4.1), this unit is made up of massive dark grayish brown (10YR 4/2) silts, fine sands and silty clays. Locally, it can present mottled textures.
- Unit 2: Only visible in core LY3.3, located from 26.4 to 16.3 cm. It is composed of mottled brown (7.5YR 5/3) silty clays and a number of layers of sand. At the uppermost part of this unit there is an 8 mm-thick layer of dark brown (7.5YR 3/2) clay.
- Unit 3: Located in the uppermost part of both cores, it is made up of massive very dark brown (7.5YR 2.5/2) clay with abundant plant debris.

4.2. Chronology

The calibrated age values of samples (Table 1) showed no reversal in core LY3.3, however, we found an inconsistency in the AMS date of core LY4.1, probably due to sedimentary reworking

processes. We calculate the sedimentation rate in the core LY4.1 using only the sample dated LY4.1.AMS1 and the same calculation was carried out using the radiocarbon sample LY4.1.AMS2. These rates were compared with the sedimentation rate of the core LY3.3. This analysis between both cores allows us to assume LY4.1.AMS1 to be a correct sample. Gamma spectrometry using ^{210}Pb provided dates for the first 8 cm of depth of core LY3.3 (Table 2). To perform the age model in core LY3.3, the gamma ray spectrometry (^{210}Pb) and radiocarbon dates were combined. Only ^{210}Pb dates were considered for the uppermost part of core due to the greater accuracy of this method in recent ages, discarding the radiocarbon dating sample LY3.3.AMS1. The model was constructed by linear interpolation (Fig. 3). Since we found no visible changes in lithology, the age of the base of core LY3.3 was calculated as 1455 CE from linear extrapolation, assuming that the sedimentation rate does not show considerable changes. On this chronological basis, in the core LY3.3, the lithological Unit 1 dates from 1455 to 1640 CE, Unit 2 from 1640 to 1765 CE, and Unit 3 from 1765 to 2008 CE.

4.3. Mineralogical and geochemical composition

In terms of mineralogical components, Laguna Yema sediments were mainly composed of variable proportions of quartz, clays (illite), and feldspar (microcline and albite) (Fig. 4). The behavior of illite and microcline proportions are inversely proportional to the quartz percentage in the three units identified, but the albite did not show a behavior related to the other minerals. The geochemical series of both cores (Fig. 5) showed tendencies towards significant levels of elements Al, Si, S, Ca, Br, and Zr. Levels of Al, Si, and Zr, declined progressively towards the top of the core. Contrastingly, S, Ca, and Br exhibited a gradual increase towards the top. This less evident trend also occurred for Sr. Three mineralogical and geochemical Units (light and heavy elements) with homogeneous behavior were defined by stratigraphically constrained cluster analysis in core LY3.3

and two units in LY4.1, which correspond to the lithological units previously described. In both cores (Fig. 4 and Fig. 5), the units in the sequences are, from bottom to top:

- Unit 1: The lowest average Quartz proportion of total core was 69% in LY3.3, and 59% in LY4.1. On the other hand, in this unit we found the highest average illite and feldspar percentages. Most of the elements (Al, Si, Ti, Fe, Rb, and Ba) showed an increasing trend in counts from the base to the top of the unit. The S, K, Br, and Sr elements showed the lowest average counts of the core.
- Unit 2: Only identified in the core LY3.3. Characterized by containing the highest average percentage of quartz (77.4%), with a reduction of the other minerals, especially the microcline. In the geochemical composition, there was an upward trend in Ca and S.
- Unit 3: The quartz, illite and albite showed similar proportions with respect to the average values of the core. In opposition, the microcline percentage increased with respect to the other units. The geochemical composition was characterized by having the highest average counts of S, Ca, and Br, and the least counts of Al and Si; and, to a lesser extent, of K, Ti, Zr, and Ba, of total core.

The results indicate a correspondence between mineralogical and geochemical variations among the units of both cores. Likewise, mineralogical and geochemical stratigraphically constrained clusters manage to differentiate the units in similar depths.

4.4. Sedimentology statistical analysis

Redundancy Analysis (RDA), constructed from geochemical elements and using mineralogical compositions as a constraining matrix, allowed us to define three main “families” of variables in accordance with their possible mineralogical origins (Fig. 6):

Family A: This family is present in both cores. Most light and heavy elements (Al, Si, K, Ti, Fe, Rb, Ba) and the gray curve are associated with the illite, and to a lesser extent to the albite. The main constituents of the clays (illite and albite) are Al and Si, and the other chemical elements are contained among the octahedral layers of clay, because they have a very large ionic radius. Both terrigenous minerals (illite and albite) are associated with Br, which can be used as a robust proxy to estimate the total bulk organic matter (Ziegler et al., 2008). This association suggests that the same sedimentary process caused their entry and distribution into the lake.

Family B: This family was also present in cores LY3.3 and LY4.1 and was displayed opposite the previous one. The mineral that defines this family is quartz and it is associated with S (core LY3.3) and S, Ca, Br, and the gray curve (core LY4.1). The presence of S in this family could be interpreted as indicative of sulfides or pyrite. The latter mineral was found in the sediment in quantities less than 5%, so it was not possible to detect it using XRD. The presence of organic matter indicators in core LY4.1 (Br and Ca) associated to S might reinforce the presence of pyrite formed by the bacterial decomposition of the organic matter in anaerobic environments.

Family C: This family is only present in core LY3.3. Sr, Zr, and Ca are associated with feldspar minerals. This core has more feldspar, especially microcline; therefore, its elements make a more significant contribution to the establishment of this family.

The presence of Family C in only core LY3.3 suggests that the terrigenous minerals were transported by different sedimentary processes (eolian vs. fluvial mechanisms). These different mechanisms have also been highlighted in other sedimentary sequences (Giralt and Julià, 2003; Rodó et al., 2002).

Principal Component Analysis (PCA) of cores LY3.3 and LY4.1 allowed for the identification of the main sedimentary processes that control the input, distribution and sedimentation of particles in the sediments at the bottom of the Laguna Yema (Fig. 6). The two first eigenvectors (EV) of core LY3.3 accounted for the 64.6% of total variance. The first eigenvector accounted for 42.2% of total variance whereas the second accounted for 22.4%. In the case of core LY4.1, the two first eigenvectors represented 79% of total variance, the first EV representing 57.2% and the second, 21.8%.

The first eigenvector of both PCAs is controlled by the contradiction of Family A, constituted of clays, and Family B, quartz elements and organic matters, indicating changes in the terrigenous - primary productivity of the lake. In the second eigenvector the relationship between Sr and Ca could indicate the presence of endogenic carbonates, resulting from variations in salinity, possibly related to lake level fluctuations. Additionally, forming the second axis, elements Rb and Fe are associated with illite clays. As the lake level fluctuations would affect both cores independently of their location within the lake, both PCAs show the same second distribution of EV elements.

4.5. Palynological analysis

Palynological analysis was carried out for core LY3.3. On the basis of current regional palynological studies, it was possible to identify fossil pollen types, reaching in some cases the species level (Ortuño et al., 2011; Pereira et al., 2018; Pire, 1985; Pire et al., 1998, 2002). These studies were the basis for the reconstruction of past vegetation. Different pollen types were grouped according to strata of terrestrial vegetation, aquatic plants and spores. The following groups were defined: Trees, Shrubs, Herbs, Aquatic, and Spores. The Trees Group is composed of 9 types of pollen, predominantly *Schinus* and *Schinopsis balansae*/*Schinopsis lorentzii*. The Shrubs Group is constituted of 8 pollen types, predominantly *Celtis*. The Herbs Group is made up of 15 types of

pollen, with major abundances of Amaranthaceae/Chenopodiaceae, Ambrosia, Poaceae, and Cyperaceae. The Aquatic Group is made up of *Alternanthera aquatica* and Juncaginaceae pollen types. *A. aquatica* has the highest percentage values of pollen in this group. The Spores Group is composed of Polypodium, Pteridophyta, and 3 unidentified spore types, the most abundant being the unidentified trilete spore. The relative frequencies of the pollen count are plotted on the pollen diagram in Fig. 7. Three units were identified by performing a stratigraphically constrained cluster analysis using the method of incremental sum of squares with the pollen count data, which partially coincide with the lithological Units:

Unit 1: High predominance of pollen grains from the Herbs Group, accounting an average of 90% of all pollen grains. The pollen Trees had an increasing trend that started approximately in 1530 CE. The relative frequency of Shrubs remained constant, showing an increase peak in 1600 CE. The Spores showed an increasing trend, reaching a peak concentration of 360 spores/g of sediment.

Unit 2: The unit started with the appearance of large amounts of pollen grains from the aquatic group (75% of total pollen), between 1665 and 1673 CE. From 1680 CE, a predominance of Herbs with an average of 89% of total pollen was identified. The Trees and Shrubs had a slight decreasing trend at the end of the phase. The same trend was quantified in the Spores, reducing its absolute frequency from 250 to 85 spores/g.

Unit 3: Between 1770 and 1835 CE, an increase in the pollen proportions of the aquatic was recognized, with an average of 62% of total pollen. From 1835 CE until 1862 CE, the proportions of Aquatic decreased significantly, increasing the proportions of the Herbs. The Aquatic showed an increasing trend since 1908 CE towards the top of the core, as did the Shrubs Group. The Trees Group did not have a clear trend in this unit, with average proportions of 3% of the total pollen.

5. Discussion

5.1. Paleoenvironmental interpretation

5.1.1. Sedimentological significance of ordination analysis (RDA and PCA)

The variations in the flow of the tributary rivers produce a difference in the transport of sediments from the Upper and Middle Basins to lowland areas (Laguna Yema), composed mainly of clay and quartz (Nadir et al., 1982). This process can be identified through redundancy analysis of mineralogical and geochemical data. The first eigenvector of our RDA determines the presence of illite on the negative extreme and the presence of quartz on the positive extreme (Fig. 6); this contradiction indicates different transport processes. Quartz, due to its larger size, heavier weight and generally rounded shape, needs more energy to be transported by water. Clays, however, require less energy to be transported due to their flat form, and they are usually transported by wind. Therefore, the first EV of the RDA can be interpreted as an index of changes in the aridity or moisture conditions of the lake basin. These changes in aridity could be directly linked to effective regional precipitation and/or local variations of evaporation from the lake. Increased rainfall in the basin of the lake could mean more runoff and increased flow from the Teuquito River (Fig. 9A), resulting in a greater influx of heavy minerals like quartz and also an input of organic material carried by the river and laminar flow from the shore of the lake. Conversely, low values of precipitation would mark arid conditions in the lake basin, reducing the regional plant coverage and facilitating the eolian erosion of the shallow sediments. This process will permit the deposit of lighter minerals such as clays into the lake (Fig. 9B).

When the lake water is at a normal level, mineralogical compositions are differential due to unequal position with respect to the mouth of the river where it flows into the lake (Teuquito River). When

there is an input of water, the substances that need more energy to be transported (quartz) are deposited near where the river feeds into the lake, and the material that requires less energy to be transported travels to more remote coastal areas the lake. For this reason, core LY3.3 (near the entrance) has a higher content of quartz and core LY4.1 (distal entrance) a higher content of illite (clays) (Fig. 9A). Contrarily, when the lake level is low due to reduced water input, it generates increased concentration of organic material and its subsequent deposit. At the same time, a decrease in the lake level brings about a reworking of the shore zone, and clays are transported towards the center of the lake while the coastal heavy material (quartz) remains in place. This phenomenon is reflected in core LY3.3 (near where the river flows into the lake) where the indicators of organic material are associated with clays, and in core LY4.1 (lake shore) where organic matter is closely linked to quartz (Fig. 9 A and B).

Similarly to the interpretation of redundancy analysis (RDA), the first eigenvector of PCA in both cores would be indicating changes in the aridity and moisture conditions of the basin. The values of the first eigenvector of the PCA of geochemical data were used to reconstruct a climatic signal (water availability), due to the advantage of higher stratigraphic resolution (sample every 0.03 mm) with respect to mineralogy.

The second EV was not taken into account for the final climate reconstruction due to its very little explained total variance.

5.1.2. Correlation of the reconstructed precipitation with climatological datasets

The interpretation of the first EV from the PCA allowed us to assume that this eigenvector shows positive values when the moisture conditions were greater and negative ones when the

environmental conditions were arid. Therefore, this vector must have a positive correlation with the precipitation series.

We tested the correlation between the annual values of the first two axes of PCA (EV1 and EV2) in both cores, with the annual average rainfall values of regional precipitation (CRU reanalysis data) and local precipitation (meteorological station data). The correlations with meteorological station data were significant with positive values for EV1, and maximum correlation values of 0.48 (Fig. 10 shows interpolation maps of correlation results). Thus, the Laguna Yema sediments register with greater consistency the precipitation generated in the Upper Basin, where there is a greater annual precipitation (1000 to 2000 mm), friable lithology, frequently with pronounced geological dips, which, combined with intense precipitations, give rise to a drainage network which is very active in the transport of materials to the piedmont and adjacent plains (Ferrero et al., 2015). In contrast, the semi-arid Chaco, with lower rainfall (500 to 700 mm), has an undefined drainage network, minimum slopes and sandy soils, so there are important inter-fluves without a surface drainage network, except for the paleochannel of the Bermejo and Pilcomayo rivers. The results obtained for the CRU reanalysis data showed low and non-significant correlations.

5.1.3. Hydrological analysis

The measurements of the hydrometric stations installed on the main tributary rivers of Laguna Yema are closely related to the amount of water precipitated in the Upper and Middle Basin. The correlation analysis between the annual precipitation data and the mean annual runoff data of five spatially contiguous meteorological and hydrometric stations (Fig. 10), showed significant values between 0.36 and 0.51 (Table 3). The Peña Alta hydrometric station is located in the Upper Basin of the Laguna Yema, and the remaining stations are located in the Middle Basin. High precipitation normally increases the flow of rivers, which, in turn, provokes erosion, mass movements, and an

increase in the proportion of materials transported by the rivers, indistinctly clays or quartz. This behavior of the transport of materials is displayed in the sedimentation rate of Laguna Yema (Fig. 11), where periods of higher humidity register an increase in sedimentation rate and vice versa. This is more evident during the last period (1920–2008), with a positive correlation between the water availability reconstruction (geochemical signal summary - EV1 of PCA) and the sedimentation rate, calculated with higher resolution via chronological reconstruction by gamma-ray spectrometry.

5.1.4. Palynological interpretation

The moisture and aridity conditions in the basin and, consequently, changes in water volume of the lake, were also recorded in the palynological analysis. According to the behavior of the relative frequency of pollen grains in the samples, two distinguished pollen groups were identified (Figs. 7 and 8). One was a series formed by pollen associations of *Amaranthaceae/Chenopodiaceae*, *Ambrosia*, *Poaceae* (Herbs group), and trilete spore of ferns (Spore group), whose patterns are directly proportional to one another; the other formed by the Aquatic group (*Alternanthera aquatica*) has an indicator inversely proportional to the previous series. The above-mentioned pattern indicates an expansion and a retraction of the lake. When the lake expands, there is an increase in the development of *Alternanthera aquatica*, promoted by an influx of nutrients from the basin due to the increased flow of the river that feeds the lake (Fig. 9A). In addition, favorable conditions are generated for the development of this aquatic vegetation due to the presence of dead standing trees located inside the lake that causes a decrease in waves, partially reduces wind speed and allows free-floating aquatic vegetation to become fixed (Lallana et al., 2007). When the lake experiences a regression (Fig. 9B), the coastal zones increase in surface area and become more humid, generating favorable conditions for the development of herbaceous vegetation and correspondingly, the appearance of colonizing species such as ferns (Torres et al., 2016; Williams et al., 2011), ultimately generating a greater amount of spores. In addition, the shore is closer to the core, so it will have a

higher concentration of pollen grain and spore. The positive relationship between pollen concentration in *Alternanthera aquatica* and Juncaginaceae (Aquatic plants) with water availability reconstruction of sedimentary signal (Fig. 8) is likely due to the fact that a higher value of moisture, interpreted as an increase of water entering the lake, generates favorable conditions for the development of this type of vegetation. In contrast, Poaceae, Ambrosia, Amaranthaceae/Chenopodiaceae (Herbs group) pollen types and trilete spore have an inverse relationship, because an increase in aridity of the basin provokes an expansion of surface area of the shoreline, with an increase in the development of herbaceous vegetation due to higher humidity in this area. According to our interpretation, the pollen types Amaranthaceae/Chenopodiaceae, Ambrosia, Poaceae, trilete spore, and *A. aquatica* correspond to the local pollen signal. They are closely related to the environmental conditions of the surrounding lake and its expansion and retraction. On the other hand, the pollen group of shrubs and trees and possibly the remaining pollen types of herbs correspond to the regional pollen signal (Pereira et al., 2018). The aridity and humidity conditions were also partially recorded by the regional pollen signal. The pollen types *Bulnesia*, *Prosopis* (Trees), and *Celtis* (Shrubs) have a proportional relationship with the water availability states, showing an increase in pollen proportions during humid periods. The reduced relation between the total pollen types of the Trees group and water availability could be due to the fact that this type of association requires more years for their population dynamics to be modified; therefore they have a reduced sensitivity for reflecting short-term climatic oscillations. A decrease in the total pollen proportions of this group is showed in Unit 3, because tree species had a reduction in density due to intensive selective forest harvesting for railroad station and posts starting in the mid-nineteenth century (Morello et al., 2005), coexisting with the tannin industry that started around 1875 (Zarrilli, 2000).

The presence of livestock in the area dates back to the end of the 17th century (Gelman and Barsky, 2012), but an impact on the pollen records was not identified, probably because historically, the management type was extensive (low stocking rate) and mainly for subsistence (Valenzuela, 2002).

5.2. Paleoenvironmental implications and regional reconstruction

The Laguna Yema record allows the inference of changes in humidity conditions and regional environmental changes for the last 553 years. The location of each sample with respect to the new vector space defined by the PCA of geochemistry (Fig. 6) indicates a specific position regarding the humidity and aridity conditions in the basin. Plotting the samples of the x coordinates allows us to reconstruct the availability of water in the Laguna Yema basin. In order to obtain a regional view of the evolution of the humidity states in the last 553 years, we used a portion of temporal and spatial reconstruction of December/January/February average precipitation anomalies (Neukom et al., 2010), lake level reconstruction of Laguna Mar Chiquita (Piovano et al., 2002), standardized tree-ring chronology series of dendrochronological studies in the Southern (Rio Bolsas) and Northern (Arrasayal) Upper Basins of Laguna Yema (Villalba et al., 1992, 1998), and Annual (January–December) Vilama-Coruto lake area reconstruction (Morales et al., 2015b), which are plotted in Fig. 11. These archives were selected because they have an annual resolution and are located near the semi-arid Chaco region, at E of the South American Diagonal Arid. Through consolidation of this paleoclimatic information, three main periods were characterized:

From cal. age 1455 to 1640 CE: the sedimentological records of Laguna Yema have characteristics of a relatively humid period at the beginning. The palynological records show a reduction of the spores in this first wet phase. From 1500 to 1640 CE, an arid period, with the lowest values recorded of the sedimentologic signal, started. The pollen associations *Ambrosia*, *Poaceae*, and trilete spore show high relative frequencies during this stage. *Ambrosia* shows the maximum value

of the core in 1563 CE, and trilete spore has its maximum value in 1631 CE. Conversely, the proportion of *Alternanthera aquatica* is reduced. These phases of initial moisture and an arid phase at the end of the period coincide with the records of Mar Chiquita lake water levels (Piovano et al., 2002). The Vilama-Coruto lake area reconstruction (Morales et al., 2015b) shows similar humid/arid periods with the Laguna Yema records until 1595. Afterwards, Morales et al. (2015b) observed a period of humidity and aridity oscillations. The paleoclimatic precipitation of Neukom et al. (2010) shows humidity and aridity oscillations, mainly between 1590 and 1640 CE.

From cal. age 1640 to 1765 CE: the sedimentology reconstruction of the precipitation of Laguna Yema shows a long period of intermediate water availability, with an a slight increase in humidity between 1655 and 1680 CE, which was also recorded in the pollen with the increase in *A. aquatica* proportion and decrease of herbs. In 1680 the pollen types *Amaranthaceae/Chenopodiaceae*, *Poaceae* and *Ambrosia* have high proportions, probably due to the retraction of Laguna Yema. The paleoclimatic precipitation of Neukom et al. (2010) and The Río Bolsas dendrochronology series (Villalba et al., 1998) also show an intermediate water availability, with peaks of maximum humidity around the years 1705, 1730 and 1750 CE (paleoclimatic precipitation), and 1728 and 1756 CE (Río Bolsas), possibly temporal out of sync with the Laguna Yema moisture record. The Mar Chiquita (Piovano et al., 2002) and Vilama-Coruto records (Morales et al., 2015b) coincide with an intermediate water availability, without periods of increased humidity.

From cal. age 1765 to 2008 CE: the availability of water oscillates in the sedimentological and palinological signal in Laguna Yema records, showing a humid phase at the beginning of period until 1835, with a high proportion of *A. aquatica*, due to the expansion of Laguna Yema. Two intervals of maximum humidity around 1765 to 1780 and 1805 to 1835 CE were recorded in the sedimentological signal. From 1835 until 1855 we record a period of aridity, with a higher percentage of pollen associations of *Poaceae*, *Ambrosia*, and *Amaranthaceae/Chenopodiaceae*, when

the humidity level gradually began to increase until 1945 CE. This complex Hydrological evolution during LIA (Little Ice Age) was also noted in previous work (Valero-Garcés et al., 1999).

The 20th century is characterized by a period of greater humidity in the basin of Laguna Yema, with a significant increasing trend of sedimentological signal, from 1945 to 2008 CE. An increase in the *A. aquatica* and a decrease in the proportions of the pollen associations Poaceae, Ambrosia, and Amaranthaceae/Chenopodiaceae due to lake expansion were recorded at this stage. The Laguna Mar Chiquita record, unlike the Laguna Yema records, shows oscillations in water availability at the beginning of period until 1835. From 1835 to 2008, the signals of both paleoclimatic records coincide. In the same way, the tree growth index of Ríos Bolsas and Arrasayal (Villalba et al., 1992; Villalba et al., 1998), and the paleoclimatic precipitation (Neukom et al., 2010) have coincidences in the availability of water throughout this period with the Laguna Yema records. However, they do not record the wet period corresponding to 1805–1835 CE, showing a slight reduction in humidity. In the Yala lakes (24°06'S, 65°28'W) and Laguna Seca (22°21'S, 63°52'W), which are located in the upper basin of Laguna Yema, an increase in humidity was recorded in 1960 CE as well as 1974 CE to the present (Lupo et al., 2006; Fierro et al., 2016). The Vilama-Coruto records also show a period with variable water availability (Morales et al., 2015b), but the humidity/aridity states are inverse with respect to Laguna Yema records, especially from 1945 to 2008, with a notable decrease in humidity conditions over the years.

Laguna Yema shows an increase in the sedimentation rate and the paleoclimatic signal (EV1 of the PCA of geochemistry) from 1980s to the present, coinciding with the building of a reservoir by creating embankments on the natural lake shores, and the construction of a feeding channel to increase flow of the Teuquito River.

Laguna Yema is located in the East of the South American Arid Diagonal, described by Bruniard (1982) and Piovano et al. (2009), where the main source of moisture is the Atlantic via the atmospheric circulation system. The moisture fluctuations registered in Laguna Yema seem to be the local response to the processes occurring on a regional scale. The archives of the Puna/Altiplano located in the South American Arid Diagonal generally offer hostile signs for the plain region (Piovano et al., 2009). Thus, Morales et al. (2015b) in the Vilama-Coruto Lake System (Lat 22°40'S) show contrast throughout the wet and dry phases, especially from 1765 to the present. The integrated studies of pollen and diatoms at Laguna Pululos (Lat 22°30'S) also indicate a contradiction to our analysis of the moisture conditions, particularly from 1660 to 1945 CE (Morales et al., 2015a; Lupo et al., 2007), but coincide with an increase in moisture from 1945 CE to the present. Palynological and sedimentological studies in Quebrada de Lapao (23°23'S – Oxman et al., 2013), show dissimilar results to ours, with a humid period between 1500 and 1700 CE, and an arid period from 1700 to 1800 CE. In Laguna El Peinado (Lat 26°30'S), Valero-Garcés et al. (2003) recorded the first periods of aridity and moisture coinciding with Laguna Yema (1500 to 1830 CE), with a discrepancy beginning in 1830 CE.

The contrast identified is the effect of two atmospheric circulation systems with different sources of humidity: the South American Monsoon System (SAMS), transporting tropical and amazonic humidity from the Atlantic to east of the South American Arid Diagonal as well as the humidity coming from South Atlantic and the Pacific westerlies, both of which are transported and distributed in the South American Arid Diagonal (Mancini et al., 2005; Schäbitz and Liebricht, 1998). Changes in the intensity of the westerlies are considered as the main cause for rainfall variability in the high Andes around 27°S (Grosjean et al., 1997). The Laguna Yema records indicate that there were fluctuations in the humidity conditions during the Little Ice Age (LIA) in the Subandean Mountains and semi-arid Chaco, showing two periods of humidity (1455 to 1500 and 1655 to 1680 CE). This interpretation contrasts with paleohydrologic reconstructions that suggest arid conditions during

cold periods (LIA) along the subtropical lowlands (Córdoba et al., 2014; González, 1994; Piovano et al., 2002). This indicates that other climatic factors could be contributing to conditions in the studied area. These climatic factors probably include moisture responding to an interconnection between the South American Monsoon System (SAMS) and South American Low Level Jet (SALLJ), which caused warm and humid air advection towards Paraguay, northern Argentina, and southern Brazil (Garreaud et al., 2008; Vera et al., 2006).

6. Conclusions

The Laguna Yema records presented in this work constitute the first high-resolution multiproxy study of the semi-arid Chaco region. We characterized the climatic oscillations, especially in terms of moisture and aridity, that have controlled the sedimentary processes of the Laguna Yema basin for the last 553 years through interpretation of the pollen associations and differentiation of the principal sedimentological processes related to transport energy. Higher humidity conditions in the basin generate an increase in water erosion through surface runoff, transporting heavier minerals such as quartz as well as facilitating the development of aquatic vegetation due to the addition of organic matter and favorable anchoring conditions. Higher aridity conditions generate a decrease in transport energy, with the water transport of clays. In addition, regional vegetation coverage is reduced, allowing wind to have a higher capacity to mobilize lighter materials. Accordingly, retraction of the water body generates favorable conditions for the development of herbaceous vegetation and ferns on the lake edges.

The reconstructed moisture for Laguna Yema and meteorological variables showed that the main source of water is in the Upper Basin (Subandean Mountains), because this area receives higher water recharge due to rainfall, has mountains with a steep slope and friable surface materials that are eroded and then transported through a well-developed drainage network.

The developed climate model is consistent with several regional paleoclimatic studies located at E of the South American Arid Diagonal, letting us identify four main phases: i) a moisture at the beginning and arid phase at the end of period from 1455 to 1640 CE; ii) followed by an intermediate water availability phase from 1640 to 1765 CE, with an increase between 1655 and 1680 CE; iii) later, the period between 1765 and 1945 CE which has an oscillating pattern with alternating phases of moisture and aridity, and ends with a trend to increase water availability (1945 to 2008 CE).

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FIGURES

Fig. 1. Laguna Yema map location based on the Digital Elevation Model of Farr et al. (2007). The lake is located in Formosa Province, Argentina, within the semi-arid Chaco Sub-ecoregion of the Gran Chaco Americano Ecoregion.

Fig. 2. Lithological and stratigraphic correlation diagram. The cores are positioned with respect to the location according to the lake diagram. Stratigraphic correlations are based on lithological criteria to characterize the main textural and sedimentological features of the Laguna Yema sediments.

Fig. 3. Chronological framework of Laguna Yema constructed using ^{14}C AMS and isotope ^{210}Pb dates. The solid line represents the chronological age-depth model based on calibrated median age, and horizontal bars are the confidence error.

A

B

Fig. 4. High-resolution photograph (enhancement by balancing hues), lithological stratigraphy, mineralogy (expressed as a percentage on total dry weight), gray-colour curve and stratigraphically constrained cluster of (a) core LY3.3 and (b) core LY4.1 of the Laguna Yema sediments.

Fig. 5. High-resolution geochemical stratigraphy of (a) core LY3.3 and (b) core LY4.1 of the Laguna Yema records. Light elements (Al, Si, S, K, Ca, Ti and Fe) and heavy elements (Br, Rb, Sr, Zr and Ba), measured by XRF core scanner, are expressed as counts per second (cps). Stratigraphically constrained clusters are included that allowed delimiting mineralogical units.

Fig. 6. (a) Redundancy Analysis (RDA). Geochemical data constrained by mineralogical data at 5 mm of resolution of core LY3.3 and LY4.1. The vectors are twice the length of the corresponding chemical elements, whereas the vectors of the minerals are half the length, in order to facilitate analysis and understanding. The circles mark the main “families”, suggesting their possible origin (for further details see text). (b) Principal Component Analysis (PCA) of geochemical data at full resolution (0.035 mm) of core LY3.3 and LY4.1. Plot of samples (numbers) and the variables (arrows) in the plane defined by the first two eigenvectors.

Fig. 7. Stratigraphic pollen diagram. The pollen groups in relative frequencies (%) and the spore group in absolute frequency are expressed. Stratigraphically constrained cluster analysis by the method of incremental sum.

Fig. 8. Stratigraphic pollen diagram summarized in the pollengroups and Laguna Yema water availability reconstruction.

Fig. 9. Representative scheme of changes in lake water levels and association of sedimentological and palynological records in Laguna Yema ecosystem.

Fig. 10. Graphical interpolation of the correlation values between annual mean precipitation of each meteorological station and first eigenvector values (EV1) of the PCA of geochemistry. The isohyets from the average annual precipitation data of the meteorological stations are plotted.

Fig. 11. Palaeoenvironmental archive located in the Chaco region and Laguna Yema basin. From left to right: a) Sedimentation rate of Laguna Yema; b) Water availability reconstruction (first eigenvector of geochemistry PCA) of Laguna Yema; c) Lake level reconstruction of Laguna Mar Chiquita (Piovano et al., 2002); d) Portion of Temporal and spatial reconstruction of December/January/February average precipitation anomalies (Neukom et al., 2010); e) and f) Tree ring standardized growth index of dendrochronological studies in southern (Rio Bolsas) and northern (Arrasayal) upper basin (Villalba et al., 1992, 1998); and g) Annual (January–December) Vilama-Coruto lake area reconstruction. Annual lake area expressed as Z score of the 1975–2007 lake area mean, based on the nine individual lakes (Morales et al., 2015b). Heavy dark line show smoothed series with a centered 10-year moving average.

TABLES

Sample	Lab. ID	Depth (cm)	Uncalibrated ^{14}C age (2σ) (yr BP)	Calibrated age (cal.yr CE)		
				Median	Age range	Relative area under probability distribution
LY3.3.AMS1	Poz-31168	0	111.12 $\pm$ 0.36 pMC	1998	1997–1999	0.905
LY3.3.AMS2	Poz-31167	9	50 $\pm$ 50 BP	1870	1803–1937	0.719
LY3.3.AMS3	Poz-33778	24	275 $\pm$ 35 BP	1659	1622–1679	0.514
LY3.3.AMS4	Poz-33777	37	440 $\pm$ 35 BP	1481	1435–1512	0.74
LY4.1.AMS1	Poz-31170	7	101.78 $\pm$ 0.35 pMC	1999	1998–2000	0.891
LY4.1.AMS2	Poz-31169	27	100.15 $\pm$ 0.37 pMC	1999	1999–2000	0.837

Table 1: ^{14}C AMS radiocarbon ages measured in Laguna Yema cores.

Depth (cm)	Calibrated age (cal. yr CE)
0	2008 $\pm$ 0
1	1999 $\pm$ 2
2	1992 $\pm$ 4
3	1985 $\pm$ 6
4	1974 $\pm$ 12
5	1962 $\pm$ 20
6	1949 $\pm$ 32
7	1928 $\pm$ 62
8	1891 $\pm$ 182

Table 2: Gamma-ray spectrometry. ^{210}Pb age model from core LY3.3.

		Hydrometric stations					Sig. (2-tailed)
		San Felipe	Pozo Sarmiento	Peña Alta	Aguas Blancas	Caimancito	
Meteorological station	Coronel Mollinedo	0.51					0.055
	Embarcación		0.49				0.001
	San Salvador de Jujuy			0.36			0.042
	Aguas Blancas				0.45		0.021
	Yuto					0.51	0.002

Table 3: Pearson correlation analysis between annual precipitation and mean annual runoff of spatially contiguous meteorological and hydrometric stations.