



## A 700-year multiproxy reconstruction on the Argentinian Pampas inferred from the sediments of Laguna Blanca Grande

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### ABSTRACT

The Pampean region is a crucial area to obtain sensitive paleoclimatic lacustrine archives due to the presence of shallow environments in a territory non impacted by humans until the last centuries. In this study, we provide a paleoecological reconstruction for the last ca. 700 years based on a multiproxy lacustrine record from Laguna Blanca Grande, in Olavarría (Buenos Aires, Argentina). Our inferences, which were based on sedimentary properties, diatom, cladoceran and ostracod assemblages, offered interesting information about hydroclimatic variability and nutrient increase. Changes in relative abundances on diatoms, specifically on *Aulacoseira granulata* and *Aulacoseira granulata* var. *angustissima* and fragilarioids, were used to infer shifts in nutrient conditions. The remainder proxies together indicated small lake level changes. Reconstructed hydroclimatic conditions in Laguna Blanca Grande are consistent with previous paleoecological inferences indicating a humid phase around ca. AD 1450 and progressive drier conditions ca. AD 1530–1900. A flood gate construction and an increase of nutrients in the lake revealed a higher human pressure due to population increase and land-use changes during the last century. Further studies on taxonomy and autecology of microcrustaceans are needed to effectively unlock the information contained in biological proxies from Sudamerican records.

### 1. Introduction

The Pampean plains are fertile and vast lowlands that cover more than 750,000 km<sup>2</sup>, which include some regions in Argentina, Uruguay, and the southernmost states of Brazil (Politis, 2008; Viglizzo et al., 2001; Zarate, 2003). The interannual rainfall variability in this region is related to the sea surface temperature over the western South Atlantic, the intensity and position of the South Atlantic Convergence Zone (SACZ) and the South American summer monsoon (SASM) (Barros et al., 2000; Garreaud et al., 2009), which explains the migration of moisture and precipitation patterns in subtropical plains producing rainy

conditions during the austral summer. In addition to the intrannual variability, the region is strongly influenced by interannual phenomena such as the El Niño Southern Oscillation (ENSO). As a result of these different modes of climatic variability, the Pampean lakes have shown important lakes level changes during the Holocene, as demonstrated in Laguna Mar Chiquita (Cuña-Rodríguez, 2018; Coianiz et al., 2014; Piovano et al., 2014; 2009; 2004; 2002), Lagunas Encadenadas del Oeste de Buenos Aires (Córdoba, 2012, 2014), Lake Nahuel Rucá (Stutz et al., 2010), Lake Lonkoy (Stutz et al., 2012), Lake La Barrancosa (Plastani et al., 2019), Lake Adela (Dangavs and Mormeneo, 2012), Laguna del Monte (Dangavs and Pierrard, 2013), Lake La Brava (Irurzun et al.,

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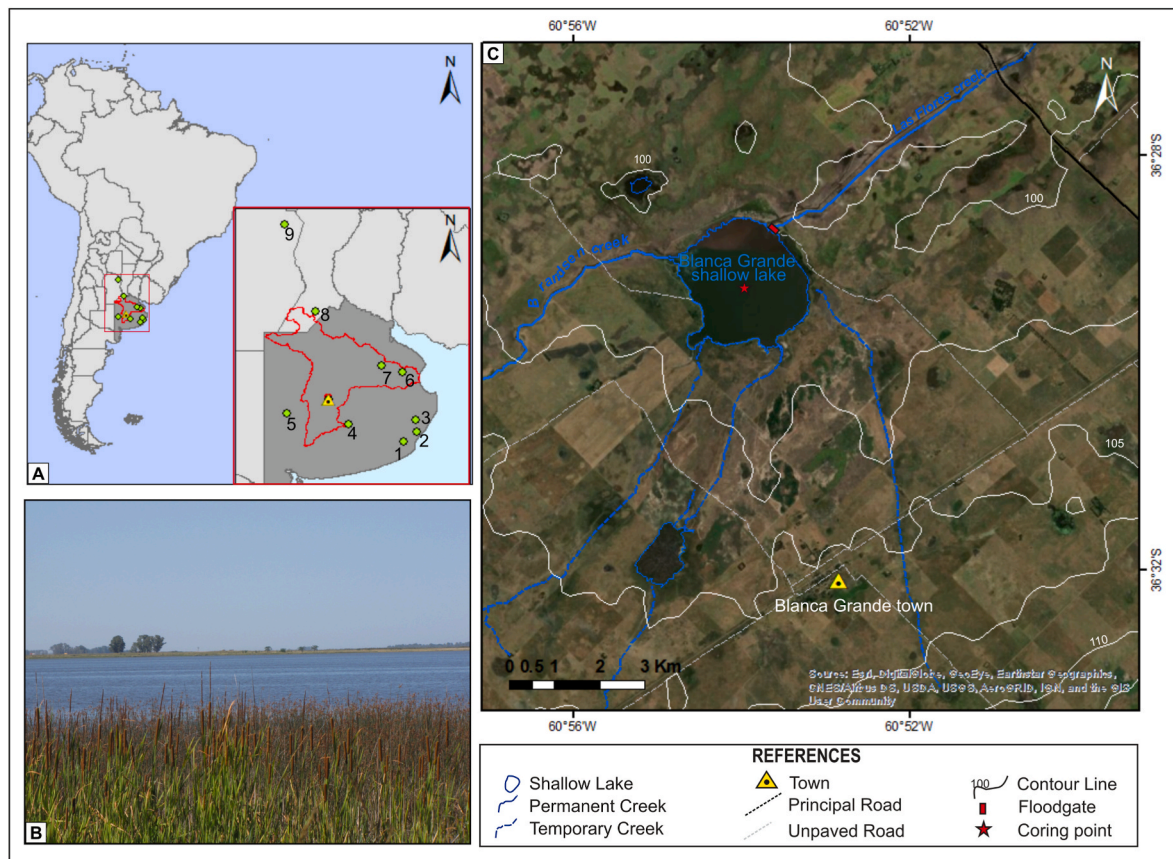
2014; Laprida et al., 2014) and Lake Melincué (Guerra et al., 2015, 2017) (Fig. 1). Despite the existence of some paleohydrological reconstructions, multiproxy inferences in the southern Pampas (classification according to Iriondo, 1994) are still needed to provide additional information on the timing and relationship of local hydrovariability with large-scale climatic events (Guerra et al., 2017; Lüning et al., 2019). Moreover, understanding the interaction of past climatic changes with limnological features is also crucial to face future challenges such as the synergic effect of climate warming and eutrophication on local/endemic biodiversity (Kopprio et al., 2010). This is particularly meaningful when taking into account the socioeconomical implications and ecosystem services of these lakes, considering that they play an important role as reservoirs of endemic biodiversity, flood control, recreation, tourism and climate change mitigation (Iwan et al., 2017).

In this study we used a lacustrine record based on diatoms, cladocerans and ostracods from Laguna Blanca Grande (Buenos Aires, Argentina) to provide new paleoecological information from southern Pampas (Fig. 1) and also to help to understand the temporal-spatial features of hydrological changes and the role of human activities in the last centuries. We hypothesize that this sequence may contain a relatively good signal of past natural conditions and climate variability since this region was not highly impacted by humans for a longtime. Documentary and historical sources (e.g., Djenderedjian, 2012; Mayo, 2000; Pedrotta et al., 2012) indicated that only sparse native populations inhabit La Pampa until the end of the 19th century. Migration and farming conversion did not take place until the beginning of the 20th century. Hydroclimatic variability as well as the recent human impact might have been recorded in our sediment record.

## 2. Site description

The Argentinian Pampean region comprises an extensive plain (~500,000 km<sup>2</sup>) covering the center-east of the country. The geological setting is characterized by loess-like deposits covered by Quaternary aeolian sediments, composed of massive to poorly stratified sandy silt, partially reworked by fluvial action and with common carbonate accumulations of unknown origin (Muhs, 2013; Rubio et al., 2019; Zarate, 2003; Zárate and Tripaldi, 2012a). The climate of southern Pampas is subtropical semiarid, characterized by mean annual temperature of 14.4 °C, with mean values of 2 °C in the coldest months (June–July) and 29 °C in the warmest (August). Mean annual rainfall is about 901 mm (mean values 1988–2010, National Meteorological Service from the Olavarría meteorological station). The geomorphology of this region -low slope and absence of geographical features- allows the development of wetlands and shallow lakes in the most depressed areas of the plain. Most of the lakes are small (<500 ha), shallow (~4 m), eutrophic and polymictic (i.e., without thermal stratification) (Geraldini et al., 2011; Laprida, 2008; Quirós and Drago, 1999).

Laguna Blanca Grande (Fig. 1; 36°29'12,99"S, 60°53'45,91"W) is located between Olavarría and San Carlos de Bolívar, Buenos Aires Province, Argentina. It is an almost round lake with a 450 ha basin, an average depth of 80 cm and a maximum of 180 cm. It receives water from the Brandsen Creek, in a permanent regime, and from three temporary watercourses. Water flows from the lake into the Arroyo Las Flores, where there is a sluiceway to regulate the level. This gate was probably built around the 1950s in a context of water management actions around Lagunas Encadenadas del Oeste to prevent the impacts of floods and droughts in the region (Monachesi and Albaladejo, 1997).



**Fig. 1.** Location map of the study site. A) Location of the study site in South America, showing the location of the main paleolimnological studies in the region: 1) La Brava (Iruzun et al., 2014); 2) Lakes Nahuel Rucá and 3) Lonkoy (Stutz et al., 2010, 2012); 4) Lake La Barrancosa (Plastani et al., 2019); 5) Lagunas Encadenadas del Oeste (Córdoba, 2012); 6) Lake Adela (Dangavs and Mormeneo, 2012); 7) Laguna del Monte (Dangavs and Pierrard, 2013); 8) Lake Melincué (Guerra et al., 2015) and 9) Laguna Mar Chiquita (Piovano et al., 2002) B) Photograph of the lake and C) Satellite image of the lake showing the inlets and outlets.

Lake shows alkaline waters (pH = 8.7) and total nitrogen values ca. 81.3 mg/l (Hassan, 2011). Conductivity is ca. 0.6 mS/cm and hardness is ca. 227 mg/l (Hassan et al., 2011). The order of major ion concentration is  $\text{HCO}_3^- \gg \text{SO}_4^{2-} > \text{Cl}^-$  and  $\text{Na}^+ \gg \text{Mg}^{++} > \text{K}^+ > \text{Ca}^{++}$  (Colautti and Remes-Lenicov, 2003). Modern diatom assemblage is composed of *Aulacoseira granulata*, *Staurosira longirostris*, *Cyclotella meneghiniana*, *Hippodonta hungarica*, *Pseudostaurosira brevistriata* (Hassan et al., 2011; Hassan and De Francesco, 2018). Zooplankton is composed of the rotifers *Keratella tropica*, *Notholca* sp., *Asplanchna girodi* and *Polyarthra vulgaris*, the cladocerans *Bosmina* sp. and *Macrotix laticornis* and the copepod *Notodiaptomus incompositus*. This is the main source of food of the Argentinian silverside (*Odontesthes bonariensis*), which also inhabits this lake (Colautti and Remes-Lenicov, 2003). Today, recreational fishing and tourism are some of the main activities around the lake. However, at regional scale, Olavarría has a diversified economy with important contribution of agriculture, stockbreeding and industry related to mining activities (Olavarría, 2010).

### 3. Materials and methods

#### 3.1. Coring, sampling and chronology

Sediment cores were recovered with a Livingston piston corer from the deepest part of the lake (0.6 m) in December 2013. Two parallel and overlapping cores (LBG-A and LBG-B) were taken from the lake at a distance of 3 m from one another. Core LBG-A was 77 cm in length while core LBG-B was 102.5 cm in length. Core LBG-A extended from the mud-water interface to a depth of 77 cm. After the correlation of the cores, it was decided not to analyze the upper part of the core LBG-B, from the mud-water interface to 37.5 cm, and perform the analysis only from 37.5 cm to the bottom of the core (65 cm length). This strategy ensured an overlap of ca. 40 cm between the two cores. Sediment cores were wrapped in plastic film, placed in PVC tubes and stored in a cool room at 4 °C until further processing. Core description was carried out following the methodology described in Schnurrenberger et al. (2003) and the Munsell color chart (Munsell Colour Company, 1975). The stratigraphic column was built using the lithological patterns suggested by the US Geological Survey (2006). Color and main physical properties such as composition, structure, or degree of humification were the initial basis to establish a correlation between both cores. Then, the correlation was confirmed by analytical measurements and biological proxies. Based on this correlation, four bulk sediment samples along the whole length of the composite record were selected for AMS  $^{14}\text{C}$  analysis at the CHRONO Center laboratory at Queen's University Belfast, UK. Radiocarbon dates were calibrated using the ShCal13 database (Hogg et al., 2013) and the 95.4% distribution (2s probability interval) was considered to build the age-depth model.

As one of the samples did not accomplish the principle of superposition, an age-depth Bayesian model was built using only three samples. The age-depth model was built using the package Bacon (Blaauw and Christen, 2011) in R 3.4.2 software R Development Core Team, 2019. The curve was adjusted with a Gaussian model and included the starting condition that the surface was  $-63$  as a  $\pm 0$  cal years BP. Using these settings, over 7000 iterations were run using a Markov chain Monte Carlo (MCMC) method to estimate the unknown parameters in the age-depth model. Although carbonate accumulations of variable morphology and genesis are common in the loess sequences (Muhs, 2007), Fontana (2007) showed that reservoir effect was negligible in a Pampean shallow lake in the same geological setting. Therefore, no correction for reservoir effect was applied in the model.

#### 3.2. Analytical and biological methods

Volumetric subsamples of  $1\text{ cm}^3$  were taken at 5 cm intervals for organic matter, granulometry and biological analysis (diatoms, cladocerans and ostracods). For granulometric analysis, samples were

dispersed in distilled water after organic matter and carbonates were dissolved with  $\text{H}_2\text{O}_2$  and HCl, respectively, and analyzed by laser diffraction (Mastersizer Malvern, 2000). The samples with granulometry  $> 250\ \mu\text{m}$  were sieved. Results were integrated into the GRADISTAT V 4.0 program (Blott and Pye, 2001). The granulometric analysis was performed at the Marine Geology Laboratory at the Instituto Argentino de Oceanografía, Argentina. Organic matter was determined by weight loss on ignition (LOI) at 550 °C for 4 h. Subsequently, the  $\text{CO}_2$  mass evolved from carbonate was determined by LOI at 950 °C for 2 h, and the carbonate content was calculated by multiplying the weight loss by 1.36 (Heiri and Lotter, 2001). LOI analysis was carried out at the Centro de Investigaciones en Ciencias de la Tierra (CICTERRA - CONICET - UNC).

For diatom and chrysophyte cyst analysis, samples were treated with sodium pyrophosphate ( $\text{Na}_2\text{P}_2\text{O}_7$ ) to deflocculate the sediment and to remove the clays. Then, 15 mL of HCl (35%) were added to wet samples to remove carbonates. Finally, samples were heated to a water bath for 2 h with  $\text{H}_2\text{O}_2$  to remove organic matter (Metzeltin and García-Rodríguez, 2003). They were washed with distilled water successively until reaching a neutral pH in between the three treatments mentioned above. Once cleaned, permanent slides were made using an Entellan® (refractive Index: 1.54) mounting medium. At least 400 diatoms valves per sample were identified in an optical microscope at  $1250\times$  magnifications with oil immersion. Relative abundances of taxa (included chrysophyte cysts) were calculated by dividing the number of valves and cysts from each species by the total count on each slide/sample. These analyses were carried out at the Geoscience laboratory from CURE-Rocha, Uruguay. Diatom species were identified using the appropriate keys (Frenguelli, 1941; Gómez and Bauer, 2000; Hasle and Syvertsen, 1997; Krammer and Lange-Bertalot, 1986, 1988, 1991a, 1991b; Metzeltin et al., 2005; Metzeltin and García-Rodríguez, 2003; Theriot et al., 1992). Ecological information on diatom taxa preferences was extracted from Denys (1991), Theriot et al. (1992), Van Dam et al. (1994), Gómez and Bauer (2000), Kociolek and Spaulding (2003), Rühland et al. (2003) Hassan et al. (2009) and Solak et al. (2012).

For cladoceran analysis,  $1\text{ cm}^3$  of sample was heated and stirred in 10% potassium hydroxide (KOH) for 30 min. Then, the sediment samples were sieved through a  $40\ \mu\text{m}$  mesh, following the procedure described by Szeroczyńska and Sarmaja-Korjonen (2007). The sieve residue was carefully transferred to a beaker. One tablet of *Lycopodium* spores was placed on a watch glass and a few drops of 10% HCl were added to dissolve the tablet. Afterward, the solution was poured off into the beaker and mixed well. Then, the sample was transferred into a test tube and centrifuged for 10 min at 3500 rpm. After centrifugation, the water was discarded, and a small quantity of ethanol was added and mixed. A slide was placed on a hot plate and liquefied glycerol jelly with some safranin drops were added. Then, a few drops of sample with ethanol was added and spread over the coverslip area. Finally, a coverslip was placed on the slide and pressed gently. Samples were identified under a LOMO/LUMAN fluorescence microscope at  $20\text{--}100\times$  magnification. Cladoceran identifications and ecological characteristics were obtained from the literature on south American cladocerans and from López-Blanco and Sinev (2016), Paggi (1998a), (1995) and Smirnov (1971). This analysis was performed at the Escuela Politécnica Nacional, Ecuador.

Sample preparation for ostracod analysis was carried out using the methodology proposed by Holmes (2001) and Danielopol et al. (2002). Samples were washed and sieved through a  $63\ \mu\text{m}$  mesh. The freeze-cooling technique was used for sample disintegration in fine-grained sediment, by adding sodium hexametaphosphate before freezing. Then, samples were dried at room temperature for 12 h, and the valves were picked out with a fine brush on a Nikon stereoscope (SMZ645) at  $50\times$  magnification. Identifications were based on taxonomic keys and specialized diagnosis (D'Ambrosio et al., 2015; Laprida, 2006; Ramón-Mercau et al., 2014). Absolute abundances were calculated from the number of adult valves of each species in 10 mL of sample. Additionally, charophyte oogonia, fish remains, gastropods and testate



amoebae were also identified. Ostracod analysis was carried out at the GIBPC laboratory from Universidad Pedagógica y Tecnológica de Colombia.

Stratigraphic diagrams showing the relative abundances of each proxy were performed using the *Psimpoll* 4.27 software (Bennett, 2009). The broken stick model was applied to determine the number of significant stratigraphic zones (Bennett, 1996). Major zones were identified using the optimal division information content for ostracods and the binary splitting by sums-of-squares for cladocerans and diatoms. Before performing the zonation analyses, ostracod data were transformed using square root to stabilize the variances and increase the importance of rare species. Diatom data were  $\log(x+1)$  transformed to give less weight to dominant and/or abundant taxa. Only the most abundant species were used for diatom analysis; those whose abundance was greater than 2% in at least 3 samples and considering that the percentage removed was less than 10% of the total abundance of each sample (Karst and Smol, 2000).

Detrended correspondence analysis (DCA) were applied to diatom data to estimate the degree of species turnover (Hill and Gauch, 1980). DCA has yielded good results for diatom analysis, allowing interpretation of records with different temporal scales and environmental gradients (e.g., Correa-Metrio et al., 2014; Hassan et al., 2012). The meaning of DCA axis 1 was inferred in terms of *a priori* knowledge of their distribution in modern environmental gradients (Bicudo et al., 2016; Hassan et al., 2009). Then, the axis scores DCA1 was plotted stratigraphically to provide a simplified picture of changes through time. DCA analysis was performed using “*vegan*” package (Oksanen et al., 2019) in software R 3.6.3 R Development Core Team, 2020.

## 4. Results

### 4.1. Sedimentology and physical characteristics

Physical properties and sedimentology analysis in cores LBG-A and LBG-B resulted in an overlap of ca. 40 cm. 66.5 cm in core LBG-A overlapped with 27.5 cm in core LBG-B, producing a composite sequence of 104 cm. This composite record was composed of dark-brownish sandy silt sediments with an increasing proportion of sand from top to the bottom part of the core. Eleven facies and six sedimentary units were distinguished, their colors varied from brown (10 YR 4/3) to dark brown (10 YR 4/29) (Table 1; Fig. 2). The mean values of organic matter throughout the first 75 cm of the sediment core were ca. 7% with a decreasing trend toward the top. A sharp shifting was observed ca. 75 cm (contact zone of Facies 8 and 9), where the organic matter content decreased towards the bottom of the core. Carbonate content was low, with mean values around 0.05% and increasing values in Unit 1.

### 4.2. Age-depth model

The chronological model based on three  $^{14}\text{C}$  radiocarbon dates (Fig. 3) yields an average sedimentation rate (SR) of 1.47 mm/yr for Laguna Blanca Grande sediment core. However, the model showed distinct sedimentation rates depending on the age (Fig. 3). From 99.5 to 40 cm, the SR was relatively higher but it slowed down from 40 cm to the top of the sediment core.

### 4.3. Diatoms

A total of 55 diatom taxa representing 34 genera were identified in the Laguna Blanca Grande sediment core. The most representative taxa belonged to seven genera (*Aulacoseira*, *Cyclotella*, *Thalassiosira*, *Nitzschia*, *Amphora*, *Staurosira*, and *Surirella*). *Aulacoseira granulata* (Ehrenberg) Simonsen and *Aulacoseira granulata* var. *angustissima* (O.Müller) Simonsen dominated the sediment record (Fig. 4). Other abundant species were also *Aulacoseira ambigua* (Grunow) Simonsen, *Aulacoseira muzzanensis* (Meister) Krammer and *Cyclotella meneghiniana* (Kützing).

**Table 1**

Lithological description and facies characterization of the composite core LBG.

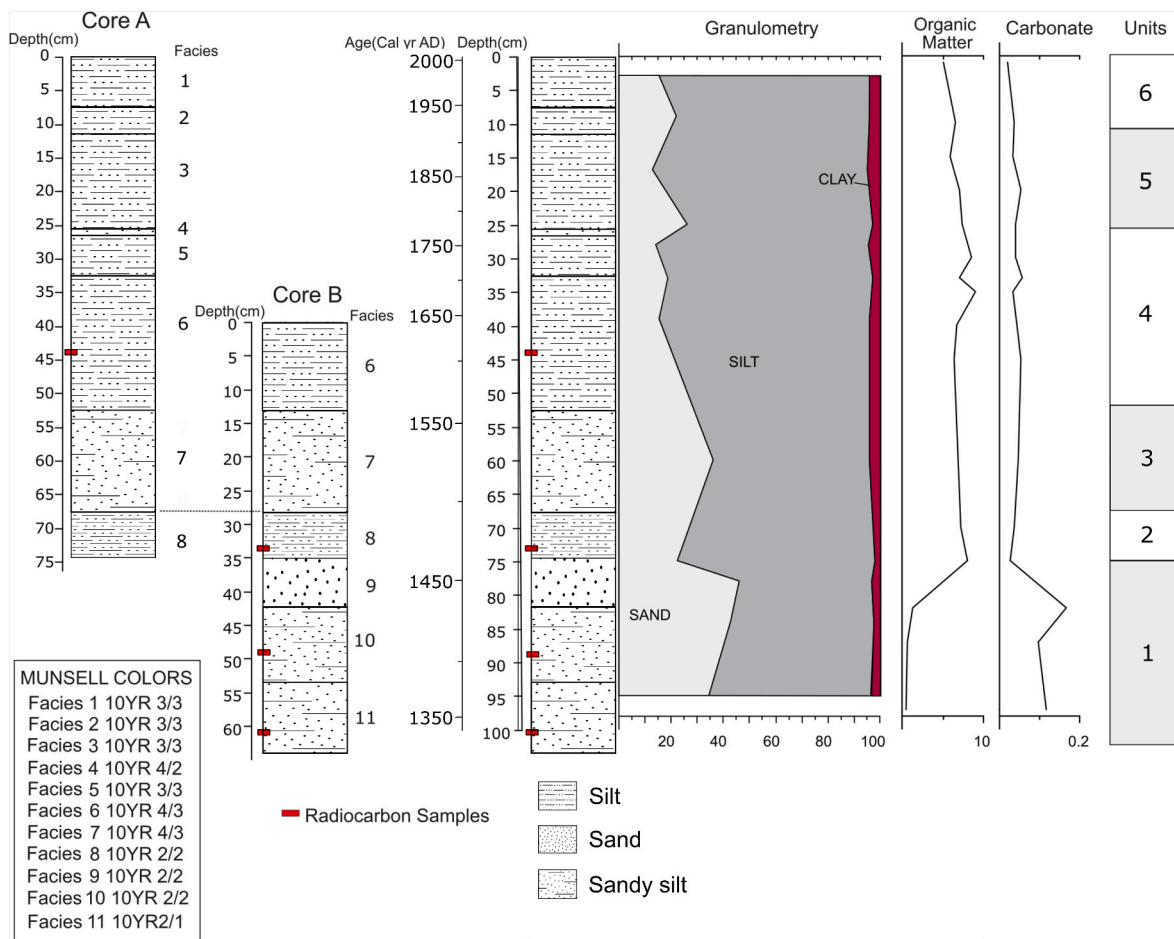
Facies	DEPTH (cm)	DESCRIPTION	SEDIMENTARY UNITS
Facies 1	0–7	Massive, very fine sandy coarse silt, dark brown color, saturated in water, rich in organic matter, abundant plant macro remains.	Unit 6
Facies 2	7–11	Very fine sandy very coarse silt, brown color, with massive structure. It has diffuse planar contact with the underlying unit.	
Facies 3	11–25.5	Massive, very fine sandy coarse silt, dark brown, with iron mottles. It has indistinct contact with the underlying unit.	Unit 5
Facies 4	25.5–26	Very fine sandy very coarse silt, dark grayish brown color, with massive structure. It has indistinct contact with the underlying unit.	Unit 4
Facies 5	26–31.5	Very fine sandy coarse silt, dark brown color, with massive structure. It has indistinct contact with the underlying unit.	
Facies 6	31.5–52	Very fine sandy very coarse silt, brown color, with massive structure. It has indistinct contact with the underlying unit.	
Facies 7	52–67.5	Very fine sandy very coarse silt, black color, with high bioturbation. It has a diffuse planar contact with the overlying unit.	Unit 3
Facies 8	67.5–75.0	Very coarse-silty fine sand, lightly laminated, with thin light brown sandy (1–2 mm) laminae interbedded in dark-organic bed, very dark brown color. It has a planar sharp contact with the overlying unit.	Unit 2
Facies 9	75.0–81.5	Very fine sandy very coarse silt. Presence of root remains, and light bioturbation, very dark brown color. It has a planar sharp contact with the overlying unit.	Unit 1
Facies 10	81.5–93	Very fine sandy very coarse silt with a higher proportion of silt than the overlying unit, brown-black color. It has a planar sharp contact with the overlying unit.	
Facies 11	93–104	Very fine sandy very coarse silt, black color. It has a diffuse planar contact with the overlying unit.	

Zonation analysis indicated the presence of four zones (DT-1, DT-2, DT-3 and DT-4). DT-1 zone (99.5–72 cm) was characterized by higher relative abundances of *A. granulata* and *C. meneghiniana*. In DT-2 (72–25 cm), the percentages of *A. granulata* decreased although they were still high. The two upper zones (DT-3 and DT-4; 24–10 cm and 9–0 cm, respectively) were associated with a relative increase of *A. granulata* var. *angustissima* in detriment of *A. granulata*. Besides, in the uppermost zone (DT-4), *Staurosira longirostris* (Frenguelli) Metzeltin, Lange-Bertalot & García-Rodríguez, *Staurosira construens* Ehrenberg and *Surirella rorata* Frenguelli increased their relative abundances.

DCA axes 1 and 2 of diatom samples were 1.52 and 1.16 standard deviations (SD) of species turnover in length. *A. granulata* var. *angustissima*, *S. longirostris* and *S. construens* had the highest scores on DCA Axis 1, while *A. granulata* and *A. muzzanensis* and chrysophytes, were associated with the lowest scores (Fig. 4).

### 4.4. Cladocera

A total of six Cladocera taxa were identified in Laguna Blanca Grande (Fig. 5); *Bosmina* Baird, 1846, which usually prefers pelagic environments and five littoral taxa *Chydorus sphaericus*-group, *Leydigia* sp. Kurz,



**Fig. 2.** Correlation and physical properties of the Laguna Blanca Grande sediment cores. From left to right: cross-correlation between LBG-A and LBG-B, dark red rectangles show the depth of radiocarbon samples; sedimentary facies; lithology; lithological description; granulometry; organic matter (LOI), carbonate content and sedimentary units of the resulting composite core LBG. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

1875, small *Alona* sp., *Alona* cf. *affinis* (Leydig, 1860) and *Pleuroxus* Baird, 1843 (Fig. 5). *Bosmina* was the dominant taxa throughout the sediment core with relative values ca. 70–90%. In the CL-1 zone (99.5–75 cm), *Bosmina* showed its maximum relative abundances. CL-2 (75–10 cm) zone was marked by higher relative abundances of *Chydorus sphaericus*-group, which together with the benthic *Leydigia* had a more continuous presence throughout the zone. However, both groups of cladocerans showed several changes along the whole zone, especially around 32 cm, where *Chydorus* increased at the expense of *Bosmina*. CL-3 (10–0 cm) was characterized by higher values of *Bosmina* and decreasing values of the benthic species.

#### 4.5. Ostracods

Four species of ostracods were recorded in the Laguna Blanca Grande sediment record (Fig. 6): *Limnocythere cusminskyae* Ramón-Mercau et al. 2014, *Cyprideis salebrosa* Bold, 1963, *Heterocypris incongruens* Ramdohr, 1808 and *Ilyocypris ramirezi* Cusminsky and Whatley, 1996. The number of individuals per sample never exceeds 400 and the maximum abundance was 40 ind/mL (Fig. 6). *Limnocythere cusminskyae* and *H. incongruens* were the main taxa of the assemblage. *L. cusminskyae* dominated over 90% of the assemblages and represented 85% of individuals throughout the core. In fact, six out of the 23 samples contained monospecific populations of *L. cusminskyae*, which were dominated by females. *Ilyocypris ramirezi* was only found in two samples, while only juvenile valves from *C. salebrosa* were found in five depths.

The preservation of the valves throughout the composite sequence was heterogeneous, with both well preserved and broken specimens.

OST-1 (104–75 cm) was characterized by the presence of gastropods, fish scales, charophytes, *L. cusminskyae* (<25 ind/mL), *H. incongruens* and juveniles from *C. salebrosa*. In OST-2 (75–63 cm) and OST-4 (51–39 cm), ostracods were absent. The top of OST-3 (63–51 cm) was mainly composed of articulated shells of *L. cusminskyae* (<40 ind/mL) with some valves of *H. incongruens*. In OST-5 (39–7 cm), gastropod remains, fish scales and testate amoebae were recorded, while ostracods were again abundant (<30 ind/mL). *Limnocythere cusminskyae* was the dominant species, representing 85% of the assemblage, followed by *H. incongruens* (13%), while *I. ramirezi* and *C. salebrosa* represented the remaining 2%. In OST-6 (7–0 cm), ostracods were less abundant than in the previous zone. Only specimens of *L. cusminskyae* with ruptured and disarticulated valves together with testate amoebae and fish remains were recovered (Fig. 6).

## 5. Discussion

The biological assemblage in Laguna Blanca Grande is typical of shallow, eutrophic and alkaline freshwater systems from the Pampean region (Hassan, 2011; Laprida, 2006; Paggi, 1998b; Plastani et al., 2019; Smol, 1985). Biological proxies coupled with sediment properties' changes suggested a shift in nutrients and hydroclimatic conditions during the last centuries. Diatom assemblage was marked by high relative abundances of *A. granulata*, which is replaced by the variety

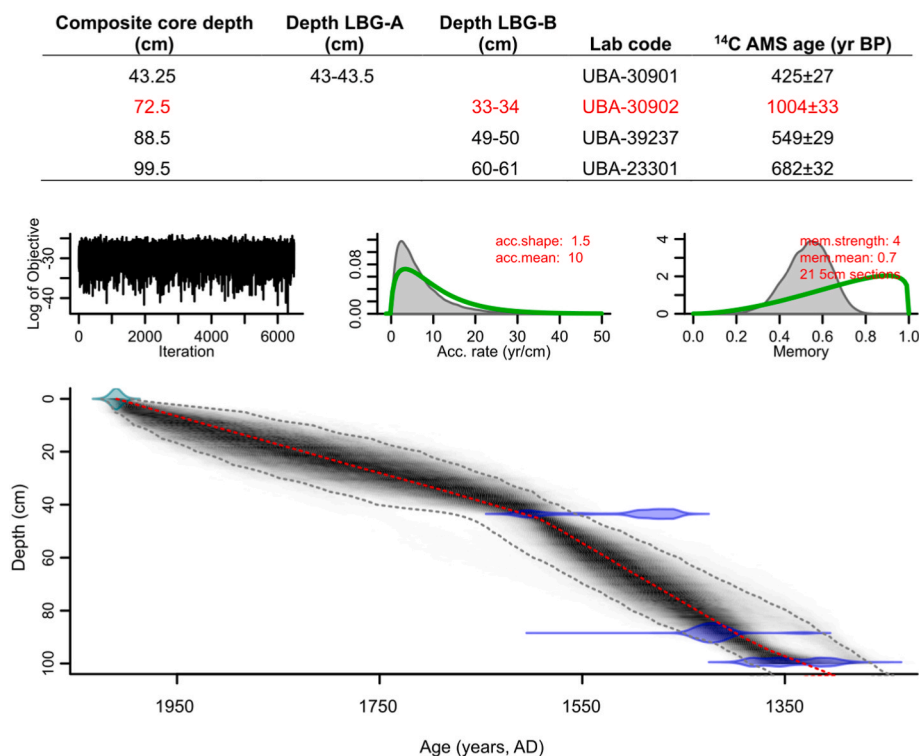


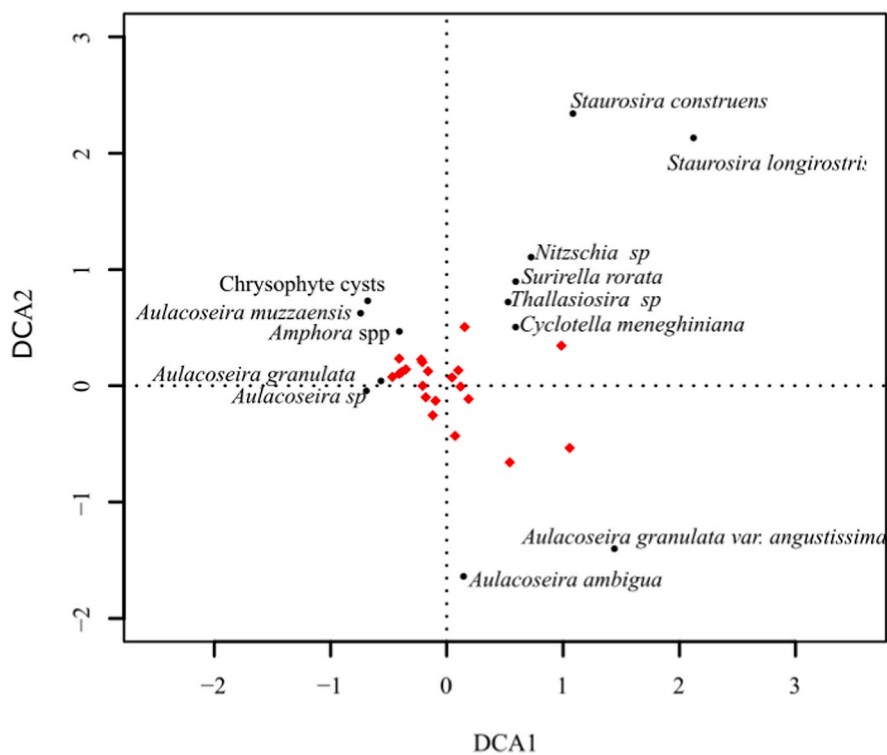
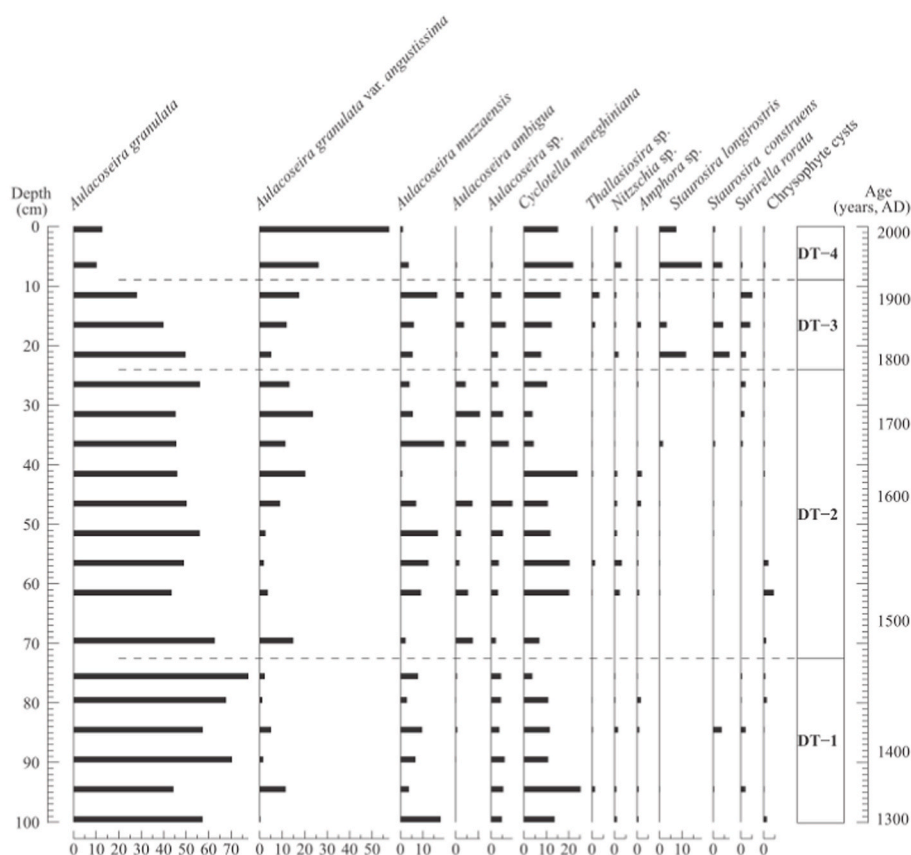
Fig. 3. Chronological model for Laguna Blanca Grande sequence based on three AMS <sup>14</sup>C dates. The upper panel shows a table with the radiocarbon dates on Laguna Blanca Grande analyzed at 14CHRONO Center for Climate, the Environment, and Chronology School of Geography, Archaeology, and Paleoecology at the Queen's University Belfast (UBA code). Calibrated dates showed in the table were obtained in OxCal applying the ShCal13 calibration curve. Material dated: bulk sediment. The sample not used in the model is indicated in red. In the bottom panel, the Bayesian age model showing the calibrated <sup>14</sup>C dates (transparent blue) and the age-depth model (darker greys indicate more likely calendar ages; grey stippled lines show 95% confidence intervals; red curve shows single 'best' model based on the weighted mean age for each depth) (Blaauw and Christen, 2011). (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

*angustissima* in the upper part of the record. Given the different ecological preferences of these varieties for nutrient conditions (Bicudo et al., 2016; Kilham and Kilham, 1975; Stoermer et al., 1985; Turkia and Lepistö, 1999), this is interpreted as changes in trophic state. Bicudo et al. (2016) and Turkia and Lepistö (1999) found that *A. granulata* has a lower weighted average optimum for nitrogen and phosphorous than the variety *angustissima*. Moreover, the increase of *A. granulata* var. *angustissima* in our sequence also occurs together with an increase of *C. meneghiniana*, which is favored by high organic and turbid waters with limited light penetration (Hassan, 2013). These inferred changes in nutrient conditions are further evidenced by the DCA axis 1, which reflected the turnover of *A. granulata* by the variety *angustissima* in the upper part of the record and showed negative scores dominating before 1750 AD (Fig. 6). This inferred change in nutrient availability was not followed by an increase in organic matter, as shown in Fig. 2. In many lakes, a large fraction of organic matter is decomposed under high concentrations of oxygen and resuspension of sediments generated by wind (Meyers and Ishiwatari, 1995). These conditions are more frequent in polymictic lakes, like the Pampean lakes, where the entire water column is mixed over the year or even daily. Mixing would produce an oxic environment at the bottom, increasing the rates of decomposition of organic matter by microorganisms in the upper part of the record. Furthermore, the nutrient increase might have triggered the observed shift in species composition but not a biovolume increase, as also noted in other paleoecological studies (e.g. López-Blanco et al., 2011).

However, the remaining biological and sedimentological proxies did not register a distinct change in the nutrient state, but they may indicate small oscillations in lake levels. The interpretation of cladoceran assemblages has limitations derived from the restricted knowledge of taxonomical and autecological characteristics in this part of the world. The assemblages showed the dominance of *Bosmina* sp., which generally has pelagic preferences. Regarding nutrient availability, *Bosmina* has eurioic preferences since it has been recorded both in oligotrophic (López-Blanco et al., 2011, 2020) and eutrophic environments (George, 1974; Lotter et al., 1998; Solis et al., 2018). The main components of the cladoceran littoral-benthic community might have been favored either

under lower lake levels and/or under an increase in the trophic conditions. *C. sphaericus* and *Alona* are ubiquitous taxa with a great capacity for colonization, they can benefit from both nutrient enrichment and shallower conditions (Alonso, 1996; Smirnov, 1971). However, when plotting planktonic/benthonic ratio from cladoceran assemblages and comparing with ostracods, sedimentological data and other regional reconstructions, all together were concordant with small changes in hydrovariability (Fig. 7). Ostracods show a response to conductivity changes and thus, to small lake level changes. Four zones (OST-1, 3, 5 and 6) were characterized by the dominance of *L. cusminskyae*, which is highly tolerant to alkaline conditions and oligohaline waters (Laprida, 2006; Marquez et al., 2016) and suggest a higher solute concentration at shallower levels. These biozones were intercalated by OST-2 and OST-4, where the absence of ostracods may indicate unstable conditions for ostracod colonization.

At the bottom of the sediment core (99.5–72 cm; ca. AD 1335–1472) (DT-1; CL-1; OST-1), less eutrophic conditions are inferred by higher values of *A. granulata*. The sediment here was composed of dark brown sandy coarse silt (Unit 1), poor in organic matter. The highest proportion of sand fraction in this unit, as well as the highest sedimentation rate, suggest important fluvial input that might have increased the lake level. The dark brown color associated with low organic matter content indicates relatively strong reducing conditions and a deposition in a perennial lacustrine environment (Wu and Li, 2004). The highest sedimentation rate calculated from the age-depth model in this section (Fig. 3) and the higher values of *Bosmina* and *A. granulata*, which was also related to high river flow conditions (Hötzel and Croome, 1996; Nogueira, 2000; Wang et al., 2009), are also compatible with considerable sediment input due to the high water inflow in Laguna Blanca Grande. Higher lake level reconstructed in the lower LIA (ca. AD 1270–1340) in Laguna Blanca Grande agrees well with the idea of a more humid phase inferred from Botuverá Cave (Bernal et al., 2016, Fig. 7) and with more humid conditions during the preceding period, the Medieval Climatic Anomaly (ca. AD 900–1300) (Cioccale, 1999; Iriondo and Kröhling, 1995). At the regional scale, this inference is concordant with the high-level stands described in Lagunas Encadenadas del Oeste



**Fig. 4.** In the upper panel, the relative abundance of diatom species and Chrysophyte cysts in LBG sediment core. Diatom zones (DT1-4) are based on the indicated cluster constrained analysis. In the bottom panel, a DCA ordination of (black circles), showing presenting the ecological space occupied by samples (red diamonds). (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)



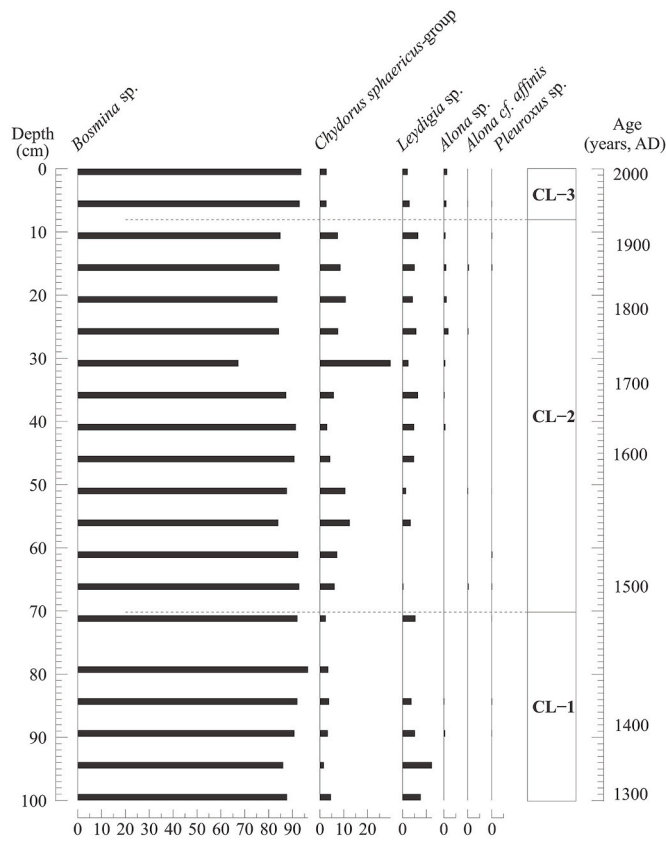


Fig. 5. Relative abundance of the cladocerans in Laguna Blanca Grande sediment core. Cladocera zones (CL1-3) are based on the indicated cluster constrained analysis.

(Laprida et al., 2009), Laguna Mar Chiquita (Coianiz et al., 2014; Piovano et al., 2002) and Lake Melincué (Guerra et al., 2015) (Fig. 7).

From ca. 72–9 cm (ca. AD 1472–1930) (DT-2) decreasing proportions of *A. granulata* in favor of *A. granulata* var. *angustissima* indicated variable conditions in terms of nutrient enrichment. Documentary sources show that indigenous societies were already present in the Pampean region 1000 years ago (Mazzanti, 2003). However, most of the native inhabitants were small and nomadic groups of hunter-gatherers and the population situated southern to Rio Salado was very scarce until the eighteenth century (Aldazabal, 2002). In AD 1828, historical documents situated the military fort of Blanca Grande during the “Previous Seasons to the Desert Conquest” very close to the lake for a very short time (Crivelli, 2013). Before Laguna Blanca is already mentioned in some historical documents from AD 1770–1790 (Floury-Dagorn, 2013), but there is historical and documentary evidence of the presence of sparse native population whose main activity was stockbreeding (Pedrotta et al., 2012). This period of variable nutrient enrichment was probably combined with small lake level oscillations with a tendency towards shallower conditions at the end of this period. Laminated dark brown silty fine sand (Unit 2) that changes to black sandy silt highly bioturbated with higher organic matter content (Unit 3) suggests a deposition by suspension in a low energy environment, which is concordant with the absence of ostracods (OST-4, OST-2) and with higher *Bosmina* abundances at relatively higher levels. The decrease in sand content indicates limited fluvial input in comparison with the previous period, which is supported by a lower SD in the chronological model (Fig. 3). The fine clastic lamination could respond to variations in the water and sediment inputs into the lake. In Unit 5, the sediment was composed of dark brown sandy coarse silt with iron mottles indicating intermittent oxidized conditions, which suggests that they were mainly deposited on a very shallow lake with high mixed conditions or

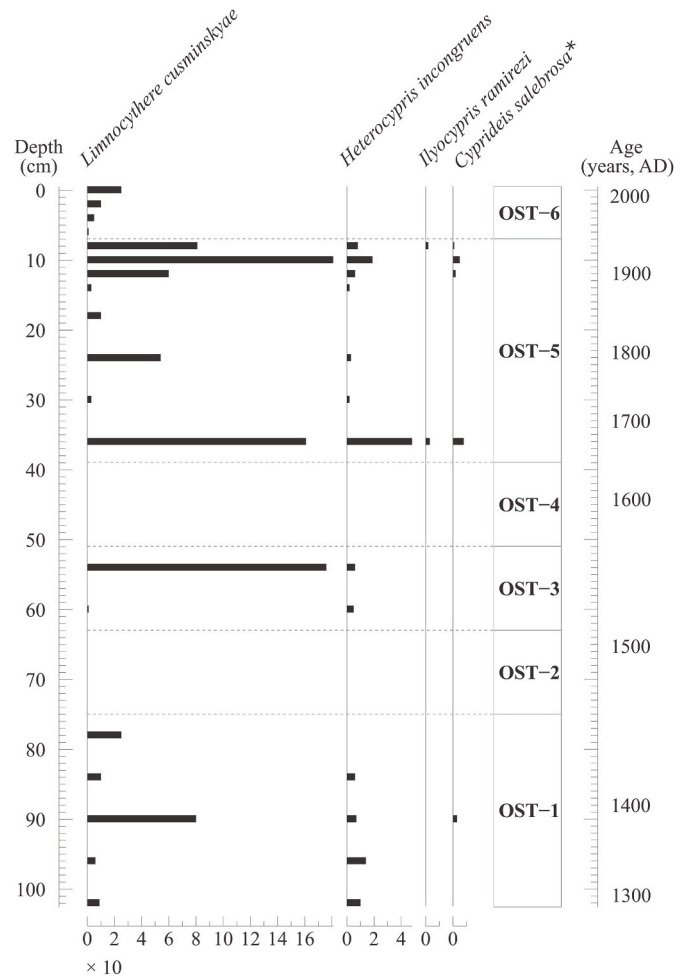
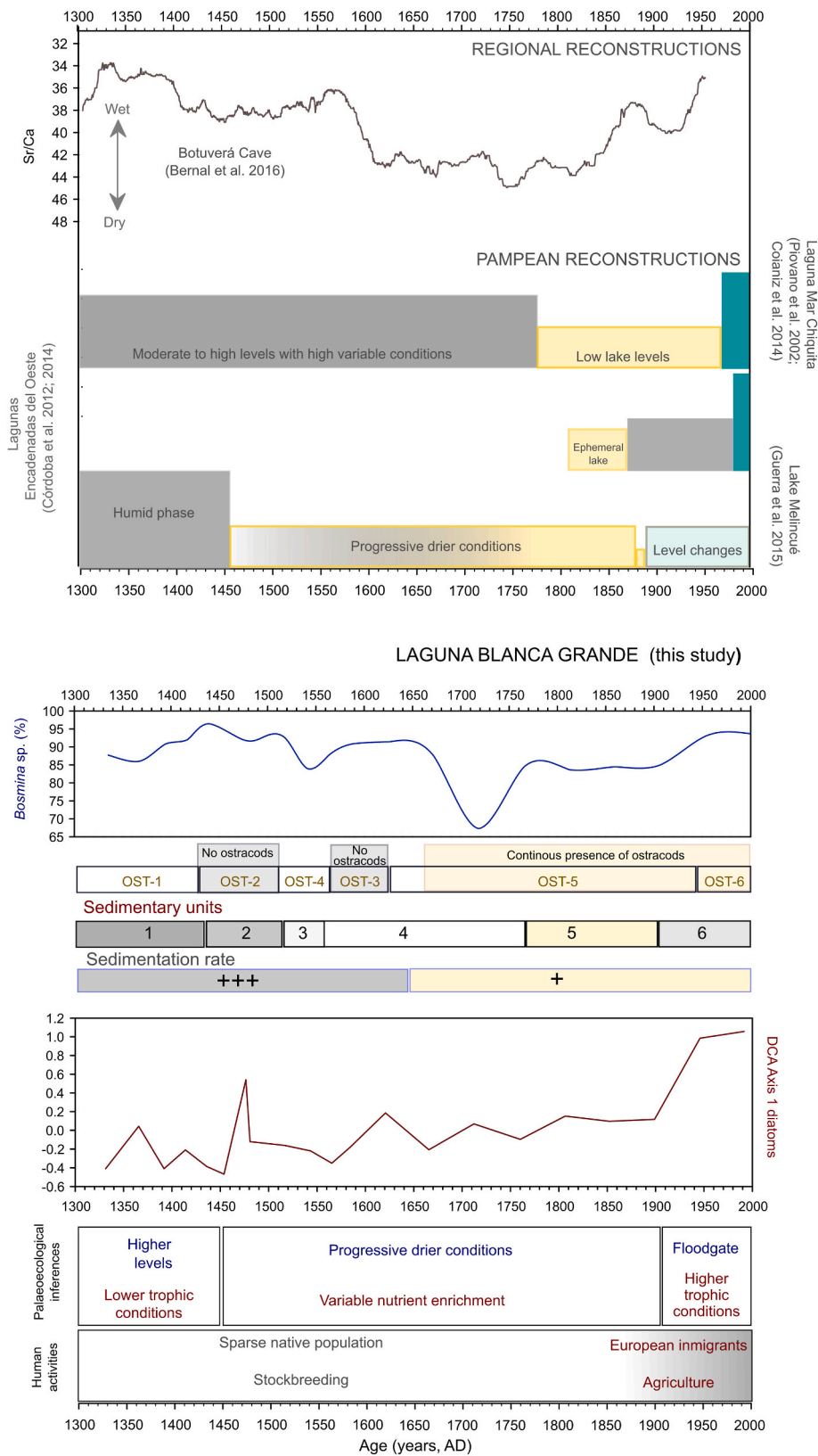


Fig. 6. Absolute abundance of ostracods in Laguna Blanca Grande sediment core. \*Only juveniles were recorded. Zonation was defined using optimal division information content after applying a square-root transformation on the data set.

temporary subaerial exposure. Ostracods also showed the highest total values and a more continuous presence, supporting the idea of decreasing lake levels. In particular, *L. cusminskyae* dominated the assemblage, which, together with *H. incongruens*, might also indicate oscillations in lake levels and subsequent conductivity variations (Kihn et al., 2017; Laprida and Valero-Garcés, 2009; Marquez et al., 2016). Lake level fluctuations with a progressive reduction of level from 1340 AD to 1900 AD are ascribed to drier conditions and frequent extreme events registered in the Pampean region during the LIA (Córdoba, 2012; Córdoba et al., 2014; Guerra et al., 2017; Laprida et al., 2009; Piovano et al., 2009).

Nutrient enrichment is inferred in the upper part of the sediment record (from 9 cm; AD 1925) by higher relative abundances of the diatoms *A. granulata* var. *angustissima* and by the establishment of *S. longirostris* and *S. construens* (Dixit et al., 1992). Hassan et al. (2014) also interpreted a shift from *Aulacoseira* spp. by fragilarioid taxa as a nutrient increase caused by the development of intensive farming activities. The Pampean Region experienced large scale deforestation since the end of the 19th century due to agriculture and railroad construction, which favored soil degradation (Dussart et al., 2011; Melo, 2004). Locally, colonists from Russia and Germany were established in Olavarría from AD 1878 within a national strategy to inhabit the Pampean region. Intensification of the farming activities to obtain wheat, potatoes, corn and vegetables transformed the original landscape (Pedrotta et al., 2012).





**Fig. 7.** Comparison of proxies from the Laguna Blanca Grande sequence and selected local and regional palaeoclimate reconstructions in South America and the Pampean region. In the upper panel regional and Pampean reconstructions. In the lower panel compilation of the biological and sedimentological proxies together with historical/documentary data of anthropogenic activities in Laguna Blanca Grande. From upper to lower part of this panel: *Bosmina* sp. (%), ostracod biozones, sedimentary units, sedimentation rate, loadings from diatom DCA axis 1, paleoecological inferences about hydroclimatic variability/nutrient enrichment and historical data of land occupation and uses.

In the uppermost part of the sequence (7.5 cm; from ca. 1940), higher and relatively steady values of lake level with episodes of high energy are inferred. The sedimentary properties of Unit 6 and by the presence of disarticulated ostracod valves indicated events of higher mechanical disturbance. However, this inference in our record did not

agree with regional reconstructions, which recognized changes in hydrovariability. A regional increase of precipitation in AD 1940 was detected in instrumental records (Garreaud, 2009; Guerra et al., 2017; Pasquini et al., 2006). Similar hydroclimatic tendencies were also recognized in different paleolimnological records from the Pampean

plain (Córdoba et al., 2014; Fontana, 2005; Laprida and Valero-Garcés, 2009; Piovano et al., 2009; Stutz et al., 2014). However, at a local scale, intensive periods of flooding and droughts in the western part of the Buenos Aires province led to agriculture losses and hydrological works (Monachesi and Albaladejo, 1997). The sluice gate construction in the 1950s might have effectively controlled lake levels in Laguna Blanca Grande and might be the origin of Unit 6 and the disarticulated valves of ostracods.

Although our paleoecological reconstruction agrees well with previous inferences, historical documents and instrumental records, the timing of the reconstruction in the upper part of the record (from the last  $^{14}\text{C}$  date to the top of the core) should be considered with caution because the age control points here are sparse. A higher number of independent  $^{14}\text{C}$  tie points or a  $^{210}\text{Pb}$ - $^{137}\text{Cs}$  chronology in the upper part of the sediment would provide a more accurate chronology for the recent human impact.

## 6. Conclusions

Overall and despite the low resolution of this sedimentary record, our paper contributes to increasing the spatial resolution in the Pampean plain in terms of both humidity and nutrient enrichment, as well as to understand the role and trends of natural variability versus anthropogenic impact in the last centuries. Human activities started in this region around ca. AD 1800 with the official foundation of the first towns (Pedrotta et al., 2012) but anthropogenic impacts were not evident until the twentieth century, when agricultural expansion (Monachesi and Albaladejo, 1997) led to nutrient enrichment and the establishment of a new diatom assemblage dominated by *A. granulata* var. *angustissima* and by fragilarioid taxa. The main periods of hydrological variability, notably the humid phase (ca. AD 1450) and progressive drier conditions mirror previous reconstructions in the region. Recent alterations of the hydrological cycle (ca. AD 1950) are consistent with further anthropogenic impacts in Laguna Blanca Grande, already shown by the nutrient enrichment. High-resolution studies would improve our understanding of complex climatic patterns operating in this zone. However, further studies on taxonomy and autecology are needed to refine the paleoecological interpretations based on biological proxies and to effectively unlock the information contained in its sediment records.

## Credit author statement

**Charo López-Blanco:** investigation, formal analysis, methodology, writing-review & Editing; **Gloria Alejandra Rodríguez-Abaunza:** investigation, formal analysis, methodology, writing-review & Editing; **Carina Seitz:** investigation, formal analysis, methodology, writing-review & Editing; **Laura Pérez:** investigation, formal analysis, methodology, writing-review & Editing; **Carolina Cuña-Rodríguez:** investigation, formal analysis, methodology, writing-review & Editing; **Sonia L. Fontana:** funding acquisition, conceptualization, review, validation, supervision.

## Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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