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Environmental history for the last two milennia in the central Argentinean Pampa plain: A paleolimnological approach

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ENVIRONMENTAL HISTORY FOR THE LAST TWO MILENNIA IN THE CENTRAL ARGENTINEAN PAMPA PLAIN: A PALEO-LIMNOLOGICAL APPROACH

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Abstract. The Central Pampa plain (36°–37° S; 60°–61° W) presents numerous shallow lakes subjected to climatic dynamics and anthropogenic impacts during the Late Holocene, but few were analyzed. New studies are essential to provide an integral and regional analysis of these lakes evolution. In this context, a multi-indicator analysis including sedimentary and palynomorph (pollen and non-pollen) indicators was performed to reconstruct the paleoenvironmental evolution of Blanca Chica shallow lake during the past 1700 years. Four main lake condition stages were identified. Natural forcing dominated the period prior to 1880 CE, followed by a scenario characterized by the combined action of anthropic and natural forcings. Between 260–800 CE, laminated sediments and phytoplankton dominance point to a high-level, turbid, nutrient rich lake during a wet period. Between 800–1600 CE, massive sediments, increasing halophytic vegetation and decreasing phytoplankton indicate a lower water-lake level in a dry context. This drought scenario was intensified between 1660–1830 CE as suggested by massive mottled sediments, submerged macrophytes remains and filamentous chlorophytes. A shift to wetter conditions is indicated for 1830–2015 CE, by a perennial, turbid, eutrophic, high-level lake with massive organic sediments. The onset of agriculture and cattle was shown by a raise in pollen taxa (*i.e.*, 1830) and increased sedimentation rates related to soils erosion which suggested intense anthropic activity. The change in the aquatic communities and sedimentology for the last 30 years allowed considering a shift to high anthropogenic impact combined with an increase in precipitation which generated an accelerated eutrophication of the lake.

Key words. Shallow lake. Eutrophication. Late Holocene. South America Palynology. Sedimentology. Natural forcing. Human activities.

Resumen. HISTORIA AMBIENTAL DE LOS ÚLTIMOS DOS MILENIOS EN LA LLANURA PAMPEANA CENTRAL ARGENTINA: UN ENFOQUE PALEOLIMNOLÓGICO. La llanura pampeana central presenta numerosos lagos someros sujetos al impacto climático y antrópico durante el Holoceno tardío, pero solo pocos fueron estudiados. Nuevos aportes son fundamentales para analizar la evolución de estos lagos. En este contexto, se realizó un análisis multi-indicador incluyendo los sedimentológicos y los palinomorfos (polínicos y no polínicos) para reconstruir la evolución de la laguna Blanca Chica durante los últimos 1700 años. Se identificaron cuatro etapas del lago, donde los cambios antes de 1880 CE resultaron de forzantes climáticos y después, por una combinación entre variabilidad climática y actividades antrópicas. Entre 260–800 CE, un lago caracterizado por un nivel alto, turbio, rico en nutrientes, con sedimentación laminar y dominancia fitoplanctónica, indicó un período húmedo. Entre 800–1600 CE, sedimentos masivos, aumento de vegetación halófila y disminución del fitoplancton indicaron niveles bajos del lago, en un contexto seco. Para 1660–1830 CE, estructuras moteadas masivas, macrófitas sumergidas y clorofitas filamentosas sugirieron menor precipitación y niveles bajos del lago. Entre 1830–2015 CE, se infirió un lago alto perenne, turbio, y eutrófico, que sugiere un ambiente más estable en un contexto más húmedo. Además, se registró intensa actividad antrópica, reflejada en la aparición de taxones de polen relacionados con la actividad agrícola y ganadera y en el aumento de la tasa de sedimentación relacionada con la denudación de suelos para la agricultura. El cambio en las comunidades acuáticas y en la sedimentología durante los últimos 30 años indicó un cambio hacia mayor impacto antrópico y mayores precipitaciones, generando una acelerada eutrofización.

Palabras clave. Lago somero. Eutrofización. Holoceno tardío. Palinología de Sudamerica. Sedimentología. Forzantes naturales. Forzantes antrópicos.

HIGH-RESOLUTION paleolimnological studies based on multiple indicators, such as biological and physical ones, constitute important tools to reconstruct the evolution of lacustrine systems and to evaluate their responses to multiple forcing (Birks & Birks, 2006). The analysis of multiple indicators (*i.e.*, sedimentary facies, pollen and non-pollen palynomorphs, plant macrofossil remains and associated fauna, fossil pigments, diatoms, among others) provides different evidences related to different levels of the water bodies trophic stages and about the lake physical functioning. Thus, these allow to "build" a more complex picture to better understand the nature and causes of environmental change (Davidson *et al.*, 2018). When reconstructions are carried out in a network of similar systems (multi-site analysis), paleoenvironmental inferences can be extrapolated to generate reconstructions in a regional context. The comparison and the integration of natural records allow refining previous paleoenvironmental/climatic reconstructions to evaluate similarities and differences in the timing, functioning patterns and sedimentary processes. This in turn allows to assess the multi-scale response of lakes to changes, first at the local scale (human activities such as livestock, agriculture and urbanization, land use change) and then at the regional scale (climate change under global change scenario).

The large number of lakes across the Pampa plain of Argentina (Quirós, 2005; Iriondo *et al.*, 2009; Piovano *et al.*, 2025) offers a unique opportunity to develop paleolimnological studies. The increasing research carried out in recent years demonstrated the potential of pampean lakes as paleoenvironmental archives and in evaluating the timing of changes in order to discuss the influence of climatic and anthropogenic (stressors) forcing operating in the region at different time-scales (from the Last Glaciation Maximum (LGM) to the Climatic Warm Period (CWP) (*e.g.*, Stutz *et al.*, 2002; Laprida & Valero-Garcés 2009; Piovano *et al.*, 2009; Stutz *et al.*, 2010, 2012, 2014; Córdoba *et al.*, 2014; Laprida *et al.*, 2014; Guerra *et al.*, 2015; Plastani *et al.*, 2019; López-Blanco *et al.*, 2021; De Francesco *et al.*, 2022; among others). Most of these studies are mainly focused in environmental reconstructions at the millennial scale but do not often provide a detail of the changes occurred during the last millennia, at centennial and/or decade time-scales. In addition, several limnological studies performed in the region covered short periods of time (< 20 years) (Allende *et al.*, 2009; Diovisalvi *et al.*, 2010; O'Farrell *et al.*, 2011; Mancini *et al.*, 2013; Sánchez *et al.*, 2015, 2017, 2023; Cano *et al.*, 2016; Schiafno *et al.*, 2019; Quiroga *et al.*, 2021; Izaguirre *et al.*, 2022), but eutrophication and climate change occur on longer time scales (centuries-decades).

Currently, there is a lack of general agreement about the hydro-climatic evolution patterns overall the entire Pampa plain during the last part of the Late-Holocene. In particular, three global climatic events with different regional expression have been recognized in the Pampa plain during the last millennium: a dominant warm phase, namely the Medieval Climatic Anomaly (MCA) (950–1350 CE) associated to positive hydrological phases; a predominantly cold phase denoted the Little Ice Age (LIA) (1500–1850 CE) (Cioccale, 1999; Piovano *et al.*, 2009; Bird *et al.*, 2011; Thompson *et al.*, 2013), associated to dry phases (Cioccale, 1999; Prieto & García Herrera, 2009; Bird *et al.*, 2011; Thompson *et al.*, 2013); and more recently the Current Warm Period (Thompson *et al.*, 2013), characterized by predominantly humid conditions. Although these events are considered global climatic phenomena, reconstructions based on lacustrine records across the sub-regions of the Pampa plain depict a non-uniform pattern in their occurrence, expression and timing.

This contribution is focused in the central-southern Pampa plain (35°–37°20′ S; 58°–61°10′ W), which is characterized by the presence of numerous eutrophic shallow lakes that were subjected to climate dynamics and anthropic impact during the late Late-Holocene. Shallow lakes in the central-southern Pampa plain are highly sensitive to variations in precipitation, temperature and anthropic activities, which alter and modify their structure and functioning (Diovisalvi *et al.*, 2010). Land-use change has also deeply induced to soil-erosion and modified the delivery of sediments into closed lakes (Quirós *et al.*, 2006). This is a poorly studied area that needs to be better inspected to integrate with the few paleolimnological reconstructions. López-Blanco *et al.* (2021) reconstructed the hydroclimatic variability and nutrient increase of a shallow lake of the central Pampa plain (Blanca Grande lake) during the last 700 years. Sánchez Vuichard *et al.* (2021) identified the main forcing factors behind the changes in the structure and dynamics of Cabeza de Buey lake communities for the last 600 years. Guerra *et al.* (2015) reconstructed the hydrological and environmental evolution of Melincué lake during the last millennium. Through the integration of the information from the analysis of multiple sites, it will be possible to create a database of the functioning of the shallow lakes of the central-southern Pampa plain, necessary to compare in the future with other subregions of the Pampa plain and evaluate the response to forcings on a regional scale.

This study is based on pollen, non-pollen palynomorphs (NPPs) and sedimentological information from a core taken at Blanca Chica lake to identify environmental changes in the lake evolution caused by natural and anthropogenic drivers during the late Late-Holocene. As aforementioned, its location from which there are few data of this nature makes Blanca Chica lake a compelling study site for better understanding the past responses to human activities and climate shifts in the central southern Pampa plain.

Study site

The Pampa plain of Argentina contains important wetlands (Kandus *et al.*, 2008) characterized by numerous shallow lakes (Geraldi *et al.*, 2011). Blanca Chica lake is located in the center of the southern Pampa plain (Fig. 1). The general setting of the area is an extensive plain dissected by several fluvial systems, giving way to a moderately undulating landscape with some low hills. Subordinate aeolian landforms are represented by some deflation basins and dunes, developed during the Late Pleistocene (Zarate & Tripaldi, 2012). In particular, the Blanca Chica lake (36° 50′ S; 60° 28′ W) is a shallow (up to 2 m water depth) and small (160 ha) lake. Present-day limnological features characterize it as a turbid (Secchi Disc

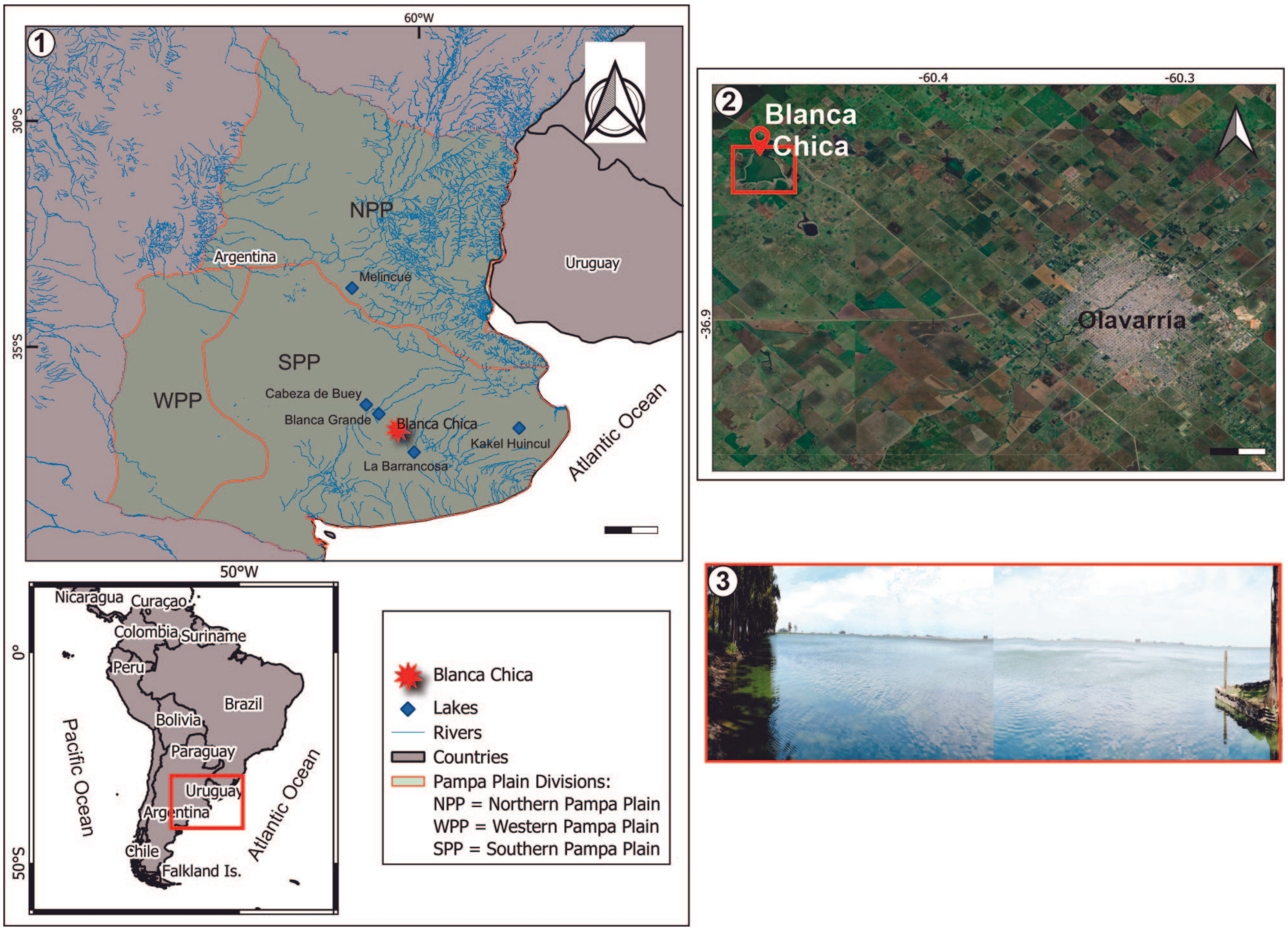

Figure 1.1, Map of study area of the Pampa plain showing the location of the Blanca Chica lake and other sites mentioned in the text. The map was designed following Iriondo (2010) and Zarate and Tripaldi (2012). Scale bar= 100 km. **2,** Location of the Blanca Chica lake and the Olavarría city (closest town). Scale bar= 2 km. (image from Landsat/Copernicus 2023, Google Earth, accessed May 8th, 2025). **3,** Image of the Blanca Chica lake during core extraction (2015).

depth: 0.2–0.3 m, chlorophyll concentration: 90–500 mg m^{-3}), warm temperature and polymictic lake of alkaline water (pH: 8–9.8), currently in a eutrophic state (Total Phosporous: 0.3–1.2 ppm) (Carrozzo *et al.*, 2020). The hydrological balance is highly controlled by precipitation and phreatic ground water input, therefore during dry periods the water body can desiccate. The significant interannual variability of precipitation can affect the hydrological balance of the lake system. Instrumental record of a low rainfall period and an extreme drought during 2011 CE (804.2 mm total annual precipitation) led to an almost complete drying up of the lake (Sanzano *et al.*, 2014).

According to Tonello (2006), Blanca Chica lake area vegetation is dominated by grasses such as *Stipa* Linnaeus 1753, *Piptochaetium napostaense* (Spegazzini) Hackel, *P. lejopodum* (Spegazzini) Henrard and *Poa ligularis Nees ex Steudel*. There are several accompanying herbs such as *Phyla* Loureiro, *Carex* Linnaeus 1753, *Adesmia* de Candolle, *Alternanthera* Forsskål, *Pamphalea* Lagasca, *Vicia* Linnaeus 1753, *Eryngium* Linnaeus 1753, *Sphaeralcea australis* Spegazzini and *Micropsis australis* Cabrera. In particular, the lake´s vegetation is composed by the reed (*Schoenoplectus californicus* (von Meyer) Soják, present only in a single area of the lake, and no other emerging or submerged macrophytes are observed in the lake (Sanzano *et al.*, 2014). At the study site, several *Eucalyptus* L'Héritier de Brutelle, *Casuarina* Linnaeus 1753 and Pinaceae trees grow on a dune next to the lake (Figs 1.2, 3). During the decade of 1990's, different recreational activities were carried out in the lake, which include sports and nautical fishing, and complementary uses such as shade and bonfires around the lake (Sanzano *et al.*, 2014).

The climate is temperate with an annual mean temperature of 14.5°C. Mean temperature varies from 19°C in January to 7.5°C in July. The annual temperature variation regime presents a pattern with a maximum of 29°C in January and a minimum of 2°C in July. Annual precipitation is 901 mm (1991–2020 period) with rainfall occurring mainly from spring (September) to autumn (March), with a maximum of 107.9 mm in January and a minimum of 34.8 mm in July (Estación Meteorológica Aeródromo de Olavarría, 36°53'20" S; 60°13'40" W, Servicio Meteorológico Nacional).

Land-use change

The modern Pampa plain vegetation is the result of a series of processes, including two main distinguishable periods along the last 500 years which deeply modified the landscape (Ghersa & León, 2001). The first period spanning between 1550 and 1850 CE includes the onset of cattle rising, increasing the introduction and dispersal of both native and exotic weed seeds (Garavaglia, 1999). This expansion was not homogeneous neither in space nor time throughout the Pampa plain, due to geographical and ecological differences as well as social conflicts during the progress of the conquest by the European population over native territories (Banzato *et al.*, 2011; Sánchez, 2017). The second period of modifications takes place from ~1900–1920 until today, when an incipient but sustained expansion of agriculture took place at the same time as a greater technification of livestock practices along with an increment in urban population started. An important modification was the introduction in the area of tree species, either natural species from adjacent vegetation units, used in the construction of fences (*e.g.*, *Celtis tala* (Klotzsch) Liebmann and *Senegalia bonariensis* (Gillies Hooker & Arnott) Seigler & Ebinger); as well as species from the Northern Hemisphere and/or Australia (*e.g.*, *Populus* Linnaeus 1753 and *Eucalyptus* L'Héritier de Brutelle , *Pinus* Linnaeus 1753, *Cedrus* Trew 1755), and fruit trees (*Prunus* Linnaeus 1753 and *Malus* Miller). During the 20th century, a period of major agricultural development arose with the introduction of cereal crops throughout the Pampa plain, together with a succession of technological improvements. This period is locally known as *Pampa Agricola Cerealera* and took place before *ca.* 1950s, and began in the northern Pampa plain (31°–33° S; 60°–62° W) and spread out to the south-west, concentrating in the northeast of the Buenos Aires Province (Ghersa & León, 2001). After the mid-1970s, the introduction and subsequent widespread development of soybean crop produced other changes in land-use such as the decrease in livestock activity, the increase in the use of agrochemicals and the intensity of soil tillage as well as soil degradation due to the decrease in the organic matter (OM) content and the loss of nutrients (Viglizzo *et al.*, 2001; Pengue, 2009). In addition, in the mid-1970s a period with higher rainfall began and there was a change towards more humid conditions, known as the *Salto Climático* (Agosta & Compagnucci, 2008). This produced a shift of the isohyets to the west in the central and northeastern region of Argentina (Hoffman, 1989) with the expansion of the agricultural frontier of approximately 200 km toward the west, which greatly favored agricultural activity, especially in semi-arid regions. Finally, by *ca.* 1996 soybean crop was generally implemented by farmers due to availability of new transgenic varieties that caused more land degradation (Bilenca & Miñarro, 2004).

In particular, the demographic growth in the central-southern Pampa plain, where the Blanca Chica lake is located, occurred after 1880 CE with the establishment of Olavarría city in 1867 and the arrival of the railroad at 1883 CE. Before the demographic change by the end of the 19th century, the area was inhabited by native aborigines' tribes, with scarce impact in the landscape due to their hunter-gatherer activities. The immigrant population was made up of 900 inhabitants at that time. Nowadays, the main economic activities in the region are agriculture, livestock and to a lesser extent quarry mining. Currently, the Blanca Chica lake is a eutrophic shallow lake used for recreation and hosts fishing and water sports (Sanzano *et al.,* 2014).

MATERIALS AND METHODS

Chronology and Sediment description

A 50 cm long sediment core of the Blanca Chica lake (BCh; 36°50' S; 60°28' W), was recovered from the deepest part of the lake (2.15 m) in November 2015 with a *Vibracorer* equipped with a 5 cm inner diameter tube, operated from a platform.

An initial core description (BCh core) was made following the criteria proposed by the Limnological Research Center Core (http://lrc.geo.umn.edu/laccore/icd.html) and according to Schnurrenberger *et al.* (2003). Two primary types of observation were considered. First, the sedimentary structures, limits and colors were recognized and second, the identification of sedimentary textures (*e.g.,* clay, silt). Sediment colors were determined using the Munsell Color chart.

The age-depth model was constructed by combining radiocarbon ages, ^{210}Pb ages, ^{137}Cs activity and the use of stratigraphical chronomarkers (*i.e.*, *Eucalyptus* pollen) (Tab. 1). Excess ^{210}Pb and ^{137}Cs activity were measured on 12 samples between 0 and 12 cm depth at *Laboratoire de Radiochronologie-Centre d' études nordiques, Université Laval* (Quebec, Canadá). Cs-137 (^{137}Cs) is an anthropogenic radionuclide with global peaks in atmospheric fallout in 1959 and 1963 often used as chronostratigraphic markers, and with a third peak from the Chernobyl accident in 1986 recorded in some parts of the world (Mackenzie *et al.*, 2020). Radiocarbon dating was measured on bulk sediment by means of an Accelerator Mass Spectrometry (AMS) at DirectAMS (Radiocarbon Dating Service) and was calibrated with the Southern Hemisphere calibration curve (SHCal20, Hogg *et al.*, 2020).

The age model was built according to Aquino-López *et al.* (2018) by using the *Plum* model, in R version 3.6.0 (R Core Team, 2020). *Plum* takes a Bayesian approach to ^{210}Pb dating, like the BACON package (Blaauw & Christen, 2011), except that *Plum* uses the total ^{210}Pb instead of exclusively using the unsupported ^{210}Pb to determine the chronology. This allows the model to use the available data to decide on the supported levels of ^{210}Pb and implies that the uncertainty related to the chronology is not as strongly

TABLE 1 – Radiocarbon dates from the BCh core expressed in years before present (^{14}C years BP) and their correspondent calibrated years before present (cal. years BP).

Lab number	Core Depth (cm)	^{14}C years BP	Median probability (cal. years BP)	Upper 2 σ intercept (cal. years BP)
D-AMS 019990	BCh 23–24	460 ± 25	493	451–516
D-AMS 024149	BCh 32–33	986 ± 23	856	796–919
D-AMS 019991	BCh 49–50	1296 ± 23	1187	1087–1193

affected by user input. The resulting chronology provides more realistic uncertainties, as shown by simulations in Aquino-López *et al.* (2018), especially in the lower part of the ^{210}Pb activity profile where age model uncertainties are generally highest (Noble *et al.*, 2021).

The organic matter content was determined continuously every 1 cm by the Loss-On-Ignition (LOI) procedure (Heiri *et al.*, 2001). Samples were dried at 105 °C for 24 h, and then ignited at 550 °C for 4 h and finally at 900 °C for 2 h. Results are expressed as percentage of sediment weight loss related to the dry weight of the samples at 105 °C before combustion.

Pollen and NPPs analysis

The BCh core was subsampled at 1 cm intervals or at a lithological change. Pollen and non-pollen palynomorphs (NPPs) analysis was performed at 1 cm and 2 cm intervals from 0 to 50 cm depth. Samples for pollen and NPPs analysis were prepared following standard techniques, using warm KOH 10%, HCl 10%, heavy-liquid separation with $ZnCl_2$, HF and acetolysis (Bennett & Willis, 2001). Two *Lycopodium clavatum* Linnaeus 1753 tablets were added before treatment. Pollen sums varied between 500 and 1000 pollen grains. Abundance of each pollen type was calculated as a percentage of the total pollen sum (excluding exotic and long-distance tree pollen). NPPs, pollen of exotic trees as well as long distance tree pollen were calculated as a percentage of the pollen sum plus the sum of each group of taxa. Percentages of *Azolla filiculoides* Lamarck*, Ricciocarpos natans* (Linnaeus) Corda and Bryophyta spores were calculated as a percentage of the pollen sum plus spores' sum. Exotic trees include *Eucalyptus, Casuarina, Betula Linnaeus 1753*, *Cupressus Linnaeus 1753*, *Corylus Linnaeus 1753*, *Juglans* Linnaeus 1753 and genera of Pinaceae family (*Pinus*, *Cedrus*). Long distance trees include *Celtis tala* (Klotzsch) Liebmann, *Schinus Linnaeus 1753*, *Alnus* Miller, *Podocarpus L'Héritier ex Persoon* and *Nothofagus dombeyi* (de Mirbel) Oersted type. Other herbs include *Chrysanthemum Linnaeus 1753*, Rubiaceae, Lamiaceae, Papilionoideae, Solanaceae, Verbenaceae, Rutaceae, Euphorbiaceae, Caryophyllaceae, *Ephedra Linnaeus 1753*, Rosaceae, *Erodium* L'Héritier de Brutelle ex Aiton, Onagraceae, Malvaceae, Geraniaceae, Scrophulariaceae and Monocotyledoneae. The identification of pollen grains, spores and NPPs was made with reference to atlases, published keys and the reference collection of the Laboratory of Paleoecology and Palynology, Instituto de Investigaciones Marinas y Costeras- Consejo Nacional de Investigaciones Científicas y Técnicas- Universidad Nacional de Mar del Plata (IIMyC-CONICET-UNMdP).

Stratigraphic diagrams were plotted with Tilia 2.0.41 (Grimm, 2015). The samples were classified using a restricted cluster using the distance of Edwards and Cavalli-Sforza as a measure of dissimilarity. Cluster analysis was performed with the CONISS software included in the Tilia-Graph package (Grimm, 2015). Pollen and NPPs were considered for the zonation. CONISS cluster dendrograms are displayed on the right side of the diagrams, showing the zones.

Vascular plant nomenclature follows the database Flora del Conosur, Catálogo de las Plantas Vasculares published online by the Instituto de Botánica Darwinion (http://www.darwin.edu.ar/Proyectos/FloraArgentina/fa.htm).

RESULTS

Chronology and Sediment description

In order to successfully perform consistent reconstructions based on lake sediments to interpret Late Quaternary environmental changes, highly constrained chronologies are essential. In particular, ^{210}Pb radiochronology is a widely used technique for dating lake sediments spanning the past 100–150 years (Appleby, 2001). Nevertheless, in some cases, radiometric profiles exhibit significant deviations from the simple exponential decline of unsupported ^{210}Pb concentrations. For instance, episodic events (*e.g.*, historical floods, windstorms, earthquakes, or volcanic ash deposition) can introduce biases, resulting in non-exponential and non-monotonic unsupported $^{210}Pb_{(uns)}$ depth profiles (Córdoba *et al.*, 2017). Thus, a chronological framework developed through the combination of ^{210}Pb and ^{137}Cs dates and stratigraphic chronomarkers of known age, such as tephra layers, high total organic carbon (TOC) values or pollen markers, allows researchers to cross-check the age model, which often presents slight deviations from the monotonic decay pattern (Córdoba *et al.*, 2017; Sánchez Vuichard *et al.*, 2023).

In the Pampa plain, an important chronomarker in lacustrine sequences is the presence of exotic tree pollen, reflecting the historical absence of such species prior to their introduction into the region for agricultural use (*e.g.*, windbreaks, cattle shade). *Eucalyptus* spp. pollen is a particularly ubiquitous chronomarker, corresponding to trees introduced into the area around 1858 CE (Sánchez Vuichard, 2019). As mentioned previously (see Land-use change), these exotic species typically begin to appear in sediment records around 1880 CE, accounting for the lag due to tree growth, flowering and pollen dispersal, as well as the establishment and demographic expansion of towns in the region. This inference is supported by historical chronicles, the autoecology of the genus, and the recurring presence of *Eucalyptus* pollen in numerous lacustrine records of the Pampas (Veervorst, 1967; Sánchez Vuichard, 2019). Therefore, the first occurrence of *Eucalyptus* spp. pollen at 12 cm depth in the BCh core was assigned to 1880 CE, following the criteria established by Sánchez Vuichard *et al.* (2021). Additionally, the ^{137}Cs activity profile was used to validate the ^{210}Pb-derived chronology, with the peak in ^{137}Cs at 6.5 cm corresponding to the global fallout maximum of 1963 CE. According to the age-depth model, the uppermost 50 cm of the BCh core spans from approximately 2015 CE to 263 CE, encompassing the last ~1700 years.

In addition to these independent time markers, three radiocarbon (^{14}C) dates were obtained from bulk organic matter at 23–24, 32–33 and 49–50 cm depth (Tab. 1). These yielded ages of 460 ± 25, 986 ± 23, and 1296 ± 23 ^{14}C years BP, respectively. After calibration with the SHCal20 curve, the median calibrated ages were 493, 856, and 1187 cal. years BP, with no stratigraphic inversions. These dates anchored the bottommost portion of the age-depth model and extended chronological control beyond the range of ^{210}Pb and ^{137}Cs. Radiocarbon dating thus played a critical role in establishing the long-term temporal context of the core, particularly for interpreting late Holocene environmental dynamics.

The age-depth model was developed using the R package rplum and exhibited a high degree of stratigraphic memory (posterior mode ~0.8), consistent with stable and undisturbed sedimentation. Sediment accumulation was non-linear along the core (Fig. 2). The uppermost 30 cm, corresponding to the last ~420 cal. years BP, shows relatively high sedimentation rates (~14 years/cm). Below 30 cm, the slope of the age-depth curve steepens, reflecting a shift to slower accumulation: from 30 to 40 cm, the rate decreased to ~78 years/cm, and from 40 to 50 cm it stabilized at ~50 years/cm. These changes likely reflect

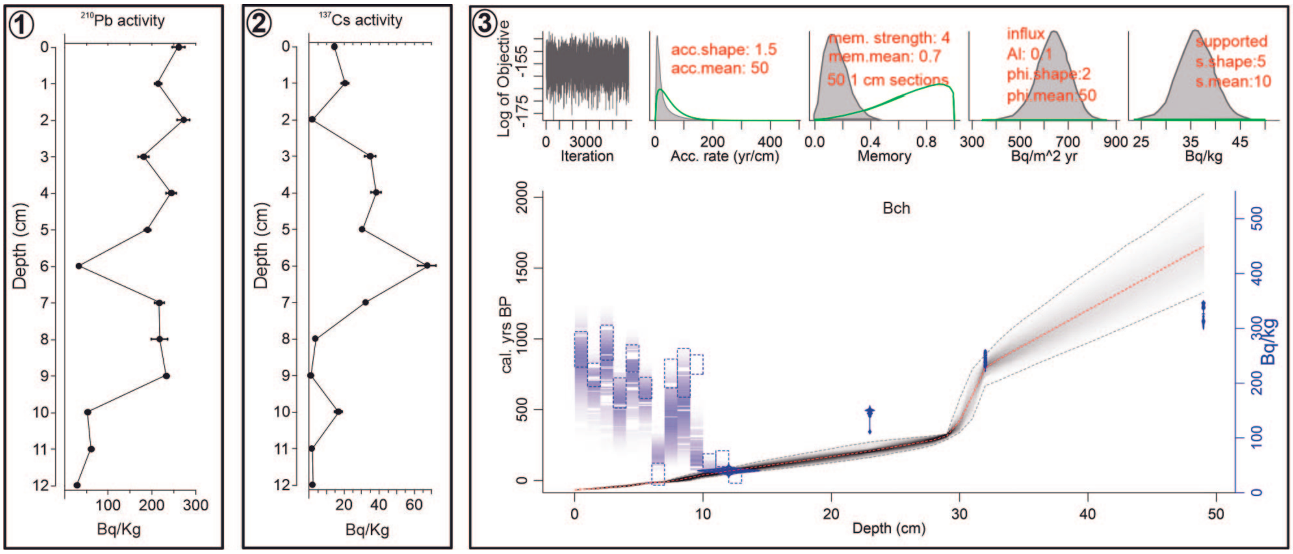

Figure 2. 1, Down-core radioisotope activity of ^{210}Pb (total) and associated errors (Bq/ Kg) for the BCh core. **2,** Down-core radioisotope activity of ^{137}Cs and associated errors (Bq/Kg) for the BCh core. **3,** Age-depth model for the Blanca Chica lake obtained using Plum (Aquino-López *et al.*, 2018). The resulting age-depth model is shown with a red dashed line and its 95% confidence intervals (in black dashed lines). Blue plots show the calibrated ^{14}C dates while blue squares show the ^{210}Pb ages. **Acc. Rate:** Acumulation rate; **Influx:** Influx ^{210}Pb (Bq/ m^2 yr).

variations in sediment supply, land use, or hydrological conditions over the last two millennia. The integration of multiple dating techniques—^{210}Pb, ^{137}Cs, ^{14}C and biostratigraphic markers—provided a robust chronological framework that supports the high-resolution environmental and paleoecological reconstructions discussed in subsequent sections (Fig. 2).

Five sedimentary facies (F1 to F5) were identified according to changes in color, texture and macroscopic structures (Fig. 3; Tab. 2). The BCh sedimentary core is mainly composed of massive sediments alternating with laminated dark greenish gray and greenish black sediments with variable organic matter content. The sedimentary facies where further associated into three sedimentary units (Unit 1–3). Sedimentary structures, facies contacts, organic matter content and sedimentation rate values were considered to define the sedimentary units.

Unit 1 (U1; *ca*. 260 to *ca*. 1660 CE): This unit is composed of alternating F1 and F2 facies. Facies 1 was characterized by diffuse and millimeter lamination, alternating clear and dark laminations with low and high organic matter content (between 8 to 12% OM), respectively. Facies 2 is composed of alternating very dark greenish gray and greenish black massive and banded sediments, up to *ca*. 650 CE. Organic matter content and sedimentation rate show constant values along the unit (~10% and < 0.05cm/yr, respectively), being the lowest of the entire record.

Unit 2 (U2; *ca*. 1660 to *ca*. 1830 CE): This unit is formed by facies F2 and F3. Facies 3 is composed of massive very dark greenish gray mottled sediments with OM contents ranging from 8% to 12%. The organic matter content showed a decreasing trend along F3 towards the top. A transitional contact is present during from F3 to F2. Facies 2 presented an increase in the organic matter content (12%) in Unit 2. The sedimentation rate values show an increasing trend towards the top, reaching 0.01 cm/year.

Unit 3 (U3; *ca*. 1830 to *ca*. 2015 CE): This unit is composed of facies F2, F4 and F5. Facies 4 correspond to massive greenish black highly bioturbated sediments and present sharp and irregular contact both in top and bottom. Facies 5 is composed of very dark greenish gray clay-silt intraclasts, suspended in a muddy matrix rich in organic matter. Organic matter content exhibited in this unit the highest values (16%) of the record. The sedimentation rate presented the highest values in the entire record, with values that reached up to 0.35 cm/years.

Pollen and NPPs analysis

According to the cluster analysis, four pollen and NPPs assemblage zones called Blanca Chica Pollen (BCP 1–4) were established (Fig. 4).

BCP1 (*ca*. 260 to *ca*. 800 CE): This zone was characterized by Cyperaceae (≤ 47%) and Poaceae (≤ 36.8%) and accompanied by Chenopodioideae, Asteroideae (≤ 36.9%, ≤ 15%, respectively), *Ambrosia* and *Plantago* (≤ 5%, both).

TABLE 2 – Facies name, description and organic matter content.

Facies Name	Description	Organic Matter (%)
F1: Laminated mud	Alternating light and dark laminate with high organic matter content. The colors vary between very dark greenish gray (Gley 1 3/10y) and greenish black (Gley 1 2.5/10y)	5–13.5
F2: Massive dark mud	Massive, homogeneous sediments. The colors vary between very dark greenish gray (Gley 1/3/10Y) and greenish-black (Gley 1 2.5/10Y).	4.5–15
F3: Mottled mud	Massive sediments with Greenish black (Gley 1 2.5/10Y) mottled overprinted in a very dark greenish gray (Gley 1 3/10Y)	10–13
F4: Massive organic mud	Massive organic sediments with greenish black color (Gley 1 2.5/10Y). Organic Matter values are never below 8%.	8–12
F5: Organic mud with intraclasts	Silty clay intraclasts in a mud matrix. The color is very dark greenish gray (Gley 1 3/10Y).	14–15

Cyperaceae had the highest values at the base and decreased towards the top of the zone. The other emergent macrophytes (*Polyonum*, *Phyla nodiflora*, *Triglochin*, *Typha*, Apiaceae) were present in low values (≤ 5%). Among the NPPs, *Pediastrum* dominated the zone increasing towards the top (≤ 48.5%), accompanied by Zygnemataceae

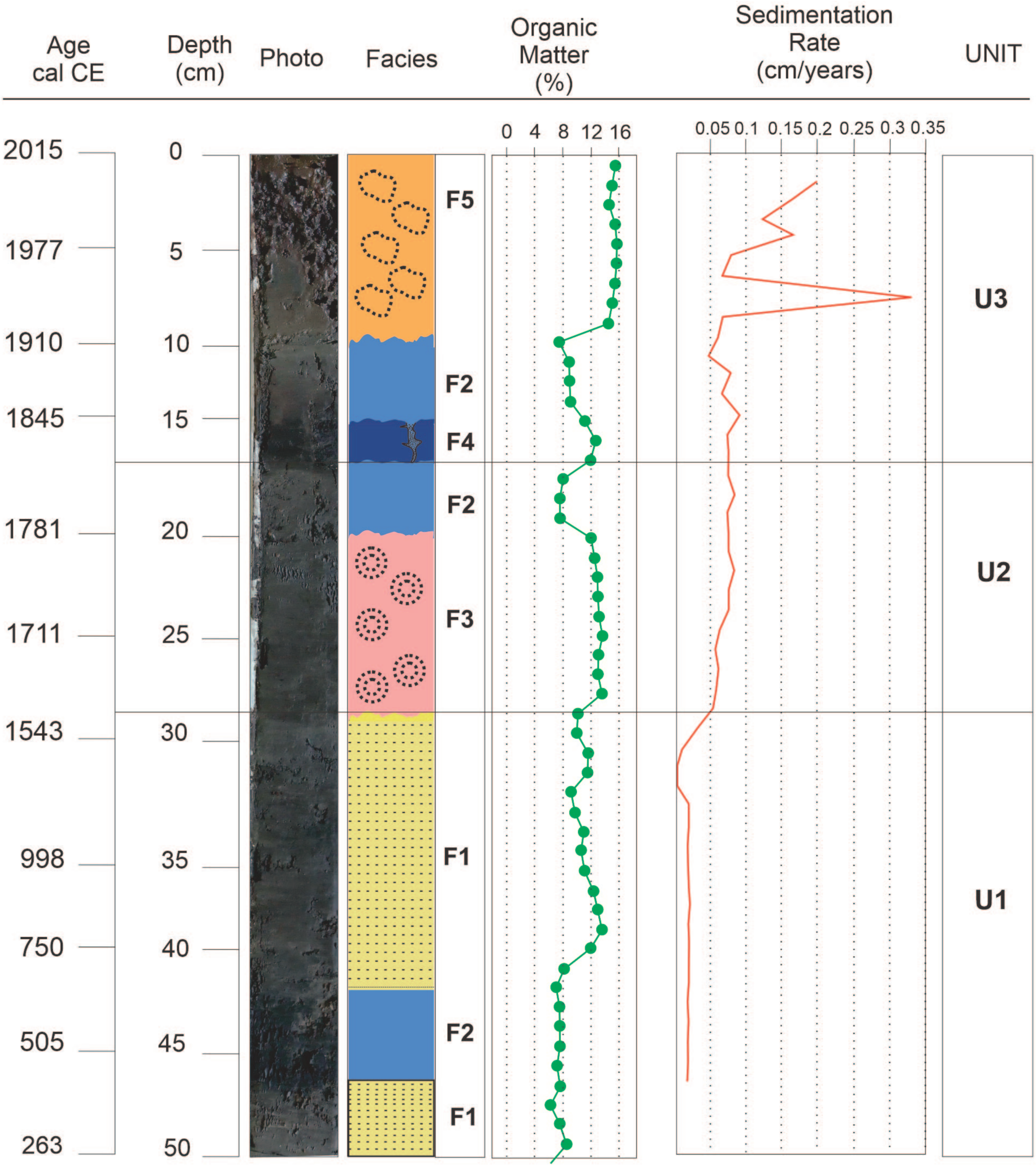

Figure 3. Core depth, photograph and sedimentological facies (F1–5) and units (U1–3) description for the BCh core. Percent organic matter profiles and sedimentation rates are also shown.

(including *Spirogyra*, *Zygnema* and *Mougeotia*) (≤ 6.5%) and *Botryococcus braunii* (2.7%). Bryophyta presented its highest value (13.4%).

BCP2 (*ca*. 800 to *ca*. 1600 CE): This zone was characterized by dominance of Chenopodioideae (88%). Cyperaceae and Poaceae (≤ 31.4% and ≤ 27.5%, respectively) were also present. Towards the top of the zone *Myriophyllum* began to increase values. The other emergent macrophytes were present in low values, but *Phyla nodiflora* and *Typha* disappeared in this zone. Among the NPPs *Pediastrum* dominated the zone (≤ 33%), accompanied by a diverse algae community (Desmidiaceae, *Scenedesmus,* Zygnemataceae, *Botryococcus braunii)* and *Cobricosphaeridium* acritarchs.

BCP3 (*ca*. 1600 to *ca*. 1835 CE): This zone was dominated by Poaceae (≤ 67%) and Cyperaceae (33.6 %), accompanied by Chenopodioideae (≤ 15%), Asteroideae and *Ambrosia* (≤ 10%, both). *Potamogeton* increased and exhibited the highest values (23%) and *Myriophyllum* kept stable values. Other pollen types that include exotic species (Asteraceae subf. Cichorioideae, *Rumex* and *Plantago*) were present. The emergent macrophytes maintained the same values as in the previous zone. Among the NPPs, *Pediastrum* (≤ 45%) dominated the zone accompanied by *Cobricosphaeridium*, Zygnemataceae and Desmidiaceae (≤ 7%, 4% and 2%, respectively).

BCP4 a (*ca*. 1835 to *ca*. 1922 CE): This zone was characterized by Poaceae (≤ 42%) and Cyperaceae (≤ 29%). *Myriophyllum* exhibited the highest values (≤ 33%) and later started to decrease towards the top of the zone. The presence of exotic tree taxa, *Eucalyptus*, *Casuarina* and Pinaceae, was observed. Among the NPPs, *Pediastrum* dominated the zone (≤ 39%), accompanied by *Scenedesmus* (≤ 31%).

BCP4 b (*ca*. 1922 to 2015 CE): This zone was characterized by Poaceae (≤ 48%), accompanied by *Ambrosia* (≤ 22%) and Cyperaceae (≤ 14%). From the base to the top of this zone, exotic tree taxa such as *Eucalyptus*, Pinaceae and *Casuarina* increased and exhibited the highest values. In addition, the other pollen types with exotic species (*Carduus*, *Centaurea*, Asteraceae subf. Cichorioideae, *Plantago*, *Rumex* and Brassicaceae) increased its values. Among the NPPs, a trend towards the dominance of planktonic algae was recognized during this zone. *Pediastrum* dominated the zone (42%), accompanied by *Scenedesmus*, *Tetraedron* and *Tetrastrum* (31%, 7% and 2%, respectively). *Filinia* and other rotifers exhibited its maximum values from this moment towards the top of the zone.

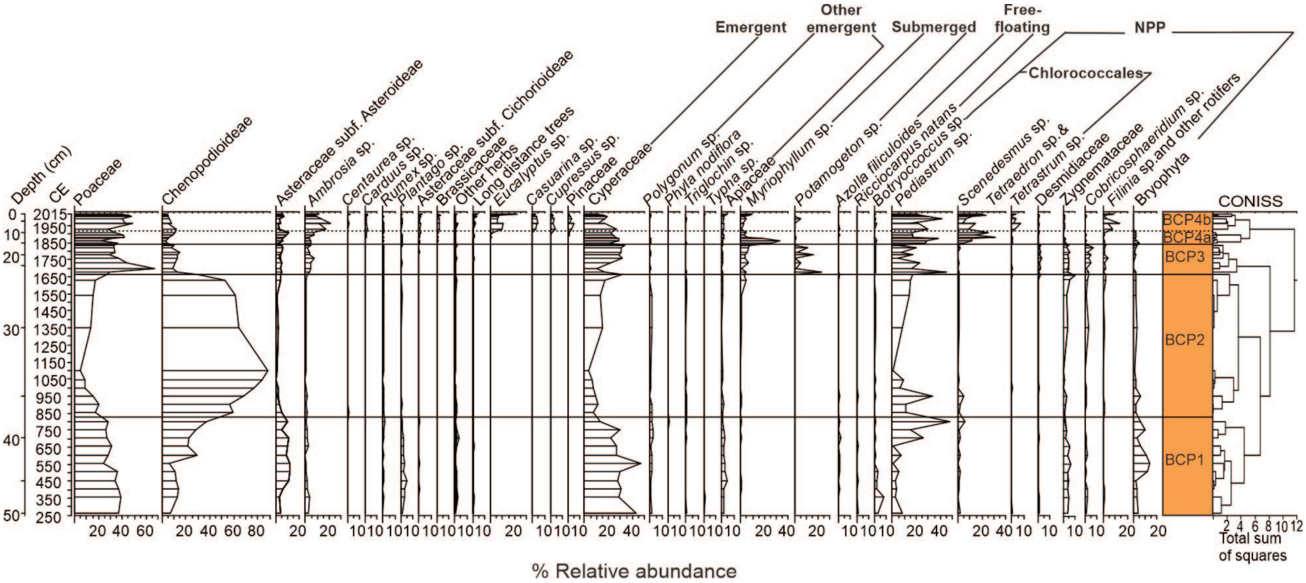

Figure 4. Pollen and non-pollen palinomorphs (NPPs) diagram for the BCh core. Black horizontal lines correspond to the pollen zone divisions defined using CONISS (Grimm, 2015) (right side).

The two oldest pollen and NPPs assemblage zones, BCP 1–2, corresponded to the first sedimentological unit called Blanca Chica Sedimentological Unit (BCSU) 1. And the last two pollen and NPPs zones BCP 3–4 corresponded to the last two sedimentological units BCSU 2–3.

DISCUSSION

Lake evolution

The multi-proxy analysis of the sedimentary record of Blanca Chica lake indicated the presence of a permanent water body since 260 CE to 2015 CE (last 1700 years). Simultaneous changes in the biological and physical indicators (plant remains, algae and sediments) allowed the lake history reconstruction and the identification of four stages: an initial mesotrophic, turbid and high-level lake; followed by a long-lasting mesotrophic, brackish to subsaline lake with fluctuating low water levels; and finally, a perennial, turbid, eutrophic, alkaline lake.

Stage 1: 260–800 CE: *Mesotrophic, turbid, fresh water and high to intermediate water level lake conditions*. Between *ca.* 260–800 CE the development of a mesotrophic, turbid, freshwater, medium size water body occurred. The lamination represented in facies F1 (unit BCSU1) indicated the deposition of sediments in a pelagic environment, in a context of high lake levels (*e.g.*, Guerra *et al.*, 2015). Moreover, this period was dominated by phytoplankton taxa such as *Pediastrum*, *Botryococcus braunii*, *Scenedesmus*, and *Tetraedron*, which are consistent with high water-lake level conditions currently found in turbid shallow Pampean lakes (Allende *et al.*, 2009; Izaguirre *et al.*, 2012; Sanzano *et al.*, 2014). *Pediastrum* dominance indicated a freshwater environment and a medium to large size water body, enriched in nutrients (Medeanic, 2006; Reynolds, 2006; Sánchez Vuichard *et al.,* 2021). High nutrient content at Hinojales lake (southeastern Pampa plain, 37° 34′ S; 57° 27′ W) were inferred based on the dominance of *Pediastrum* and *Scenedesmus* (Borel *et al.*, 2003). Furthermore, during this period the increase in the organic matter content along with the laminated and massive sediments (F2) supported the inference of a lake with medium to high nutrient content and high water-level. Thus, the record of Blanca Chica lake allows to infer a period of increased precipitation, that in turn increased the runoff of nutrients into the lake. According to Guerra *et al.* (2015), massive organic matter-rich levels (like the ones present in F2 in Blanca Chica lake) were associated with higher lake productivity and wet phases in the Melincué lake (central Pampa plain, 33° 42′ S; 61° 29′ W). In agreement with this interpretation, a study carried out in La Brava lake (37° 52′ S; 57° 59′ W) indicated an increase in the content of organic matter and in primary production associated with an increase in the water level at *ca*. 2000 cal. years BP with an increasing fluvial contribution by *ca*. 1600 cal. years BP (Laprida *et al.*, 2014).

Stage 2: 800–1660 CE**:** *Brackish, mesotrophic lake.* Between *ca*. 800–1660 CE a saline mesotrophic and low water level lake can be inferred. The laminated sediments (F1) indicate sediments deposition under high water-lake levels, in similar conditions to stage 1. However, the notorious increase and dominance of Chenopodioideae during the entire period and the decrease of the green algae *Pediastrum* and *Scenedesmus* suggested a reduction of the lake size, probably associated to lower precipitation as also mentioned by Tonello and Prieto (2008) for this period. Furthermore, decreasing sedimentation rates, estimated for the end of this period, pointed towards diminished sediment inputs into the lake as a consequence of comparatively drier conditions regarding stage 1. This discrepancy between sedimentation and biological proxies can be resolved by looking closely at the sedimentation rate at the end of this period, which decreased to the lowest values for this record, suggesting a low sediment input to the lake and a period of dry conditions. In this context, the preservation of the lamination may be due to a good preservation of organic matter (as a result of anoxia condition) and high inorganic carbon content product to the salinity concentration, similar to that mentioned for Mar Chiquita lake (Piovano *et al.*, 2002). A common feature of Pampean shallow lakes during lake-shrinking stages is the presence of halophytic plants that quickly colonized the saline mudflats fringing the water-body (Sánchez Vuichard *et al.*, 2021). Furthermore, the presence of *Cobricosphaeridium* indicated a saline environment associated with lower precipitations that led to salinization and low water levels (Stutz *et al.*, 2012). Thus, a change to drier conditions regarding stage 1, including a pulse of precipitation, can be inferred for the area. Sánchez Vuichard *et al.* (2021) mentioned a shallow and ephemeral lake environment for a central Pampa plain lake (Cabeza de Buey lake, 36° 17′ S; 61° 10′ W) for the period 1320–1630 CE. Congruently, the paleohydrological reconstruction revealed very shallow and dry conditions between 806–1880 CE for a northern Pampa plain lake (Melincué lake), registered by massive deposits with low organic matter (Guerra *et al.*, 2015). In accordance, progressive drier conditions *ca.* 1530–1900 CE were suggested for Blanca Grande lake (López-Blanco *et al.*, 2021).

Stage 3: 1660–1830 CE: *Highly fluctuating, saline, mesotrophic lake*. During this period, a permanent, alkaline, saline, turbid, mesotrophic lake subjected to desiccation periods is denoted. The sedimentary U2 suggested the sedimentation in a littoral environment exposed to recurrent lake expansions and also under the effect of phreatic groundwater fluctuations, as remarked by the presence of mottled structures. The gradual transition from F3 to F2 along with the decrease in the organic matter content, suggested low water lake level conditions. The increase of the sedimentation rate values towards the top, may suggest that during low lake levels the reworking or cannibalization of the exposed littoral enhanced the occurrence of sediment fluxes into the inner lake (pelagic zone). The increase in *Pediastrum* and the decrease in Chenopodioideae suggested an increase in the input of water into the system and the development of a permanent lake. Nonetheless, the increase in the submerged macrophytes (*Myriophyllum* and *Potamogeton*) and the filamentous chlorophytes of the Zygnemataceae family (mainly *Spirogyra*) additionally supported the development of low water lake level.

The presence of *Spirogyr*a, along with *Cobricosphaeridium*, indicated a shallow, saline-water lake, since this genus of freshwater macroalgae produces zygospores in water depths generally shallower than 50 cm, and some species tolerate slightly saline conditions (Sánchez Vuichard *et al.*, 2021). Thus, the development of submerged macrophytes and Zygnemataceae algae might have been favored by a low lake level, related to comparatively drier periods of less precipitation. Similar lake fluctuations were reconstructed in the area. For instance, Cabeza de Buey lake experienced a wet phase since 1630 CE, but *ca.* 1800 CE a dry period with reduction of the lake size was inferred (Sánchez Vuichard *et al.*, 2021). López-Blanco *et al.* (2021) mentioned lake level fluctuations with a progressive reduction of level from between 1472–1930 CE and ascribed it to drier conditions for Blanca Grande lake. In agreement, La Barrancosa lake was a small temporary wetland where frequent desiccation occurred during 1800–1860 CE (Plastani *et al.*, 2019). Congruently, an abrupt shift to drier conditions was mentioned for Melincué lake during the transition between the end of the Medieval Climatic Anomaly and the beginning of the Little Ice Age (Guerra *et al.*, 2015).

Stage 4: 1830–2015 CE: *Permanent, turbid, eutrophic, alkaline lake.* Throughout this period, a permanent, turbid, eutrophic, alkaline, high water level lake is inferred. According to the sedimentary record, this period was represented by silt sediments with different characteristics indicated by the succession in the F4, F2 and F5 facies. The initial deposition (F4) under low lake levels can be inferred by the presence of bioturbated sediments and decreased organic matter content.

During this interval, F2 represents a transitional phase within the lacustrine system, marking a shift from low-stand to high-stand lake-level conditions. The subsequent deposition of F5 reflects the establishment of a high-stand system, characterized by an abrupt and energetically dynamic shift, as evidenced by the sharp and irregular contact between F2 and F5. This hydrodynamic shift facilitated the reworking and mobilization of previously subaerially exposed bottom sediments or from supralittoral areas, leading to the formation of intraclasts through transport, and redeposition processes Then, the transport of intraclasts, (formed in supralittoral areas) into the lake by surficial current and their presence in muddy organic matter-rich sediments, in the pelagic zone, indicated an increase in the lake water level and thus an expansion of the lake. According to Sánchez Vuichard *et al.* (2021), the massive organic rich muds and the increased organic matter suggested the development of a lake of intermediate to high water level and a high primary productivity. The denudation of soils as a consequence of agriculture and cattle rising provides more clastic material that is contributed to the system, shown by the increase in the sedimentation rate. As aforementioned, the Pampa plain has been subjected to the increase and intensification of these activities during the last 75 years (see land-use change).

At the same time, the pollen and NPPs remains allowed reconstructing that the aquatic community changed over the last 150 years towards species associated with eutrophic conditions and higher water levels, probably related to the pasture-arable conversion that started around 1880 CE and the increase in precipitation after 1975 CE. Along the 20th century, pampean lakes became more eutrophic as a consequence of increased nutrient loading connected mainly with the intensification of agriculture that occurred during the last 50 years (Quirós *et al.*, 2006; Plastani *et al.*, 2019; Sánchez Vuichard *et al.*, 2021). The process of eutrophication in Blanca Chica lake was evidenced by the increase of the chlorococcales algae, the decline in abundance of angiosperms (*Myriophyllum* and *Potamogeton*), the increase in the rotifers and the organic matter content. The decline of the submerged macrophytes could be caused by the increase of nutrients that entered into the system due to the increase of agriculture and precipitation. *Myriophyllum* is known to decline over the mesotrophic-eutrophic transition (Sayer *et al.*, 2010). The eutrophication process and deeper water column due to higher lake level, were also supported by the great abundance of *Pediastrum*, *Scenedesmus*, *Tetraedron* and *Tetrastrum*. Cony *et al.* (2014) reported species of *Pediastrum* and *Scenedesmus* as indicators of high nutrient concentrations, while evaluating the trophic state and the characteristics of the phytoplankton community during one-year-cycle of a shallow lake in the southwestern Pampa plain. Furthermore, eutrophic conditions promote the development of characteristic rotifer species of pampean lakes such as *Filinia longiseta*, among others (Claps *et al.*, 2011; Ardohain *et al.*, 2014). Then, an increase in precipitation in Blanca Chica lake area with the consequent increase of the lake level was inferred, which contributed to increase the runoff of nutrients and sediments into the lake, which in turn favored phytoplankton growth and turbidity and reduced light availability for macrophyte growth. In accordance, an important water level rise associated with the increase in precipitation was inferred for Cabeza de Buey lake from 1880 CE to the present (Sánchez Vuichard *et al.*, 2021). Similar interpretations mentioned wetter conditions, higher lake levels and the establishment of a perennial shallow lake *ca*. 1940 CE for La Barrancosa lake (Plastani *et al.*, 2019). In agreement, López-Blanco *et al.* (2021) mentioned higher and relatively steady values of lake level with episodes of high energy from *ca*. 1940 CE. Since 1970 CE, changes in the rainfall spatial distribution due to an increase in the precipitation values, known as *Salto Climático* (Agosta & Compagnucci, 2008), promoted a significant increase in the levels and extension of the lakes and littoral areas, which reached the maximum values reconstructed since the Little Ice Age (Córdoba *et al.*, 2014; Guerra *et al.*, 2015; Plastani *et al.*, 2019).

Regional Vegetation

Since the Pleistocene–Holocene transition, the regional vegetation of Pampa plain has been grassland and did not show great changes (Prieto, 1996, 2000; Tonello & Prieto, 2009). The same regional vegetation characterized by grassland and accompanied by herbs was reported during the Holocene (De Francesco *et al.*, 2022; Stutz *et al.*, 2024). In agreement, during the last 1700 years the regional vegetation in the Blanca Chica lake area was represented by grasses (Poaceae) accompanied by herbs such as *Plantago*, *Ambrosia*, *Rumex* and taxa belonging to Asteraceae subf. Asteroideae and Asteraceae subf. Cichorioideae.

As aforesaid, the current landscape of the Pampa plain was influenced by human activities since the European settlement in the 1600s, but cattle became intensive at 1810 CE and agriculture started *ca*. 1900 CE. Particularly, colonists from Russia and Germany established in Olavarría, the closest town to the lake, from 1878 CE on within a national strategy of inhabiting the Pampa plain. Intensification of the farming activities to obtain wheat, potatoes, corn and vegetables transformed the original landscape of the Blanca Chica lake area (López-Blanco *et al.*, 2021). The presence of *Plantago*, *Rumex* and Asteraceae subf. Cichorioideae has been regular since *ca*. 250 CE, with the increase of percentages of the three pollen types as well as Brassicaceae values but since 1850 CE. These four pollen types represent exotic and native species. Therefore, their presence in the record between *ca*. 250 and *ca*. 1830 CE could be interpreted as representative of native vegetation, while after 1830 CE the increase of Brassicaceae and Asteraceae subf. Cichorioideae could be associated with both native and exotic species introduced with agriculture intensification throughout the Pampa plain. According to Vervoorst (1967), the species *Brassica nigra* Linnaeus 1753, *Rumex crispus* Linnaeus 1753 and *Plantago lanceolata* Linnaeus 1753 are introduced weeds associated to crops. Asteraceae subf. Cichorioideae increase was related to agriculture since it is an indicator of soils that have been tiled over several years (Prieto *et al.*, 2004). *Carduus* and *Centaurea* (Asteraceae subf. Asteroideae) presence in the pollen record after 1830 CE suggests cattle impact (Sánchez Vuichard, 2019). According to Ghersa and León (2001), extensive thistles (*Cynara cardunculus* Linnaeus 1753, *Silybum marianum* (Linnaeus) Gaertner, *Carduus acanthoides* Linnaeus 1753 and *C. tenuiflorus* Curtis) replaced the grassland following the large domestic herbivore's introduction at 1700s. *Ambrosia*'s percentages increase (Asteraceae subf. Asteroideae) after 1830 could be associated both with cattle impact and intensive agriculture, since it quickly colonizes overgrazed grasslands and is an important crop weed (Vervoorst, 1967; Poggio *et al.*, 2015). Different human impacts in the landscape transformation based on *Ambrosia*'s percentages increase were identified in Cabeza de Buey and Kakel Huincul lakes (Sánchez Vuichard *et al.*, 2021, 2023). Finally, other human activities as the use of trees in farmlands (see Land-use change) and the foundation of Olavarría city were identified by the increase of *Eucalyptus*, *Pinus* and other exotic trees pollen after 1880 CE. Furthermore, agriculture intensification in central Pampa plain was detected based on the increase in Brassicaceae, Asteraceae subf. Cichorioideae and *Ambrosia* values after 1900. The exotic species of these taxa are related to crops and agriculture (Vervoorst 1967; Prieto *et al.*, 2004; Poggio *et al.*, 2015). As aforementioned, the agriculture was implemented at *ca.* 1880 in the Blanca Chica lake area and the intensification started by the end of 1980's as denoted by the increase in diagnostic pollen taxa. Moreover, the acceleration in the eutrophication process related to the adoption of soy crops was observed by *ca.* 1995 as represented by the increase in algae and the presence of submerged macrophytes.

Paleoclimatic evolution

The multi-indicator analyses of Blanca Chica shallow lake revealed the potential of this archive from the central-southern Pampa plain for inferring climatic conditions during the last two millennia. A general context of humid climatic conditions associated with higher precipitation values was observed for the period 260–800 CE. During this period, water availability in the central-southern Pampa plain was high with higher water levels in the Blanca Chica shallow lake. In agreement, greater water availability since ~-50 CE was denoted by the establishment of permanent water bodies in other central-southern pampean shallow lakes (Stutz *et al.*, 2014; De Francesco *et al.*, 2022). On the contrary, the development of low stand phases was mentioned for the Mar Chiquita shallow lake (northern Pampa plain) until *ca.* 650 CE (Cuña-Rodriguez *et al.*, 2020). After drier conditions in the western Pampa plain, more positive balances and the commencement of water bodies and following increasing lake levels were reported for the Primera Laguna and Nassau lakes *ca.* 575 and 1045 CE, respectively (Vilanova *et al.*, 2022).This humid period was followed by a drier climatic scenario with less precipitation values for the period 800–1830 CE, when water availability was lower in central-southern Pampa plain evidenced by low lake water levels. This period contemplates the MCA, the LIA and the transition period. Positive and negative hydrological balances were mentioned during MCA (950–1350 CE) and LIA (1500–1850 CE), respectively (Bird *et al.*, 2011; Thompson *et al.*, 2013). Nonetheless, the Blanca Chica shallow lake did not show the positive trend, and suggests a drier climatic scenario for central-southern Pampa plain during MCA and LIA periods. Between 1350 and 1550 CE, water availability was low in a general context of dry climatic conditions in central and southeastern Pampa plain, indicated by low water levels in the Cabeza de Buey and Kakel Huincul shallow lakes (see location in Fig. 1), respectively. Subsequently, there was a change towards more humid conditions that were detected first in the southeastern and then in the central Pampa plain which lasted until 1670 CE in the Kakel Huincul lake and 1750 CE in the Cabeza de Buey lake. A shift to dry conditions took place both in the southeast and in the center of the Pampa plain *ca.* 1700 until 1900 CE (Sánchez Vuichard *et al.*, 2021, 2023). Meanwhile, hydroclimatic conditions in the Laguna Blanca Grande (central Pampa plain) indicated a humid phase around *ca.* 1450 CE and progressive drier conditions *ca*. 1530–1900 CE, in agreement with LIA conditions (López-Blanco *et al.*, 2021). In the northern Pampa plain, humid conditions were mentioned from ~650 CE up to 1150 CE denoted by a marked increment in the lake water level, coinciding partially with MCA period and conditions. Afterwards, drier conditions that continued until 1700 CE were inferred in the Mar Chiquita lake, which matched partially with LIA period and conditions (Cuña-Rodriguez *et al.*, 2020). The Melincué lake experienced general dry conditions from 800 to 1880 CE, with wetter phases disrupting the general dry context. A humid phase was registered in 1204 CE, which was contemporaneous with the MCA period and conditions, and the most remarkable humid pulse was at 1454 CE after the end of MCA. Subsequently, intensive droughts between 1492–1880 CE were suggested, being coeval with LIA period and conditions (Guerra *et al.*, 2015). In the western Pampa plain, humid conditions were suggested for the periods 575–1212 and 1045–1180 CE for the Primera Laguna (PL) and Nassau lakes respectively, which are partially consistent with MCA period and conditions. Later, both lakes exposed variable-low lake levels and more frequent desiccation processes between 1212–1757 and 1180–1655 CE, matching LIA conditions (Vilanova *et al.*, 2022).

While the interpretation of lakes variations in globally established climatic periods such as the MCA and the LIA is necessary, this is not always strictly possible. Since the Pampa plain is a heterogeneous climatic area with climatic subregions that have marked temperature and precipitation gradients and differences in oceanic influence and topography (Aliaga *et al.*, 2017), it is desirable to understand the regional expression of global events such as the MCA and LIA among regions of the Pampa plain. For example, when considering the southeastern lakes (Stutz *et al.*, 2014), a negative water balance for almost the entire record of the MCA and its transition to the LIA is indicated. However, these lakes registered a climatic pattern like that of the southwestern lakes during the LIA (Seitz *et al.*, 2020), where the climatic conditions are more humid. This scenario contrasts with that evidenced in the Blanca Chica lake record, where the LIA is recorded as a dry period. Nevertheless, the dry pattern agrees with that recorded for the western lakes (Nassau and Primera Laguna; Vilanova *et al.*, 2022) and with the Cabeza de Buey lake in the center of the Pampa plain (Sánchez Vuichard *et al.*, 2021). There is a generalized and demonstrated consensus that all the Pampa plain lakes studied up to now showed positive water balances from *ca*. 1850 with increases in lake water levels, despite all the different conditions. This moment coincides with the end of the LIA and the end of a dry period, recorded for most of the lakes systems. These wet conditions increased around 1970 and continued to the present and are well registered in the response of lake systems and instrumental precipitation records (Plastani *et al.*, 2019; Sánchez Vuichard *et al.*, 2023, 2024). This increase in precipitation over the Pampa plain has been associated with an intensification of the South American Monsoon System and a weakening of the South Atlantic Convergence Zone during the austral summer (Córdoba *et al.*, 2014). Considering the latter, we suggest that the lack of consistency among lake records may be due to the differences in resolution as well as to the high fluctuation and low sedimentation rate of these lake systems. Furthermore, differences in paleoenvironmental reconstructions could be caused by the scarce records analyzed so far in comparison to the large number of shallow lakes present in the Pampa plain, and that the available data is not in widely distributed locations. On the other hand, the climatic and topographical heterogeneity, as well as the differences in the history of land use (Aliaga *et al.*, 2017; Sánchez Vuichard, 2019) make it difficult to interpret a regional character. In order to respond to the complexity that arises from spatial variability, it is necessary to obtain consistent data in specific areas of the region.

CONCLUSIONS

The data provided in this study is an example of how, through the integration of several indicators, environmental change in lake ecosystems can be tracked. Combining sedimentological and biological information enabled to reconstruct Blanca Chica lake evolution history for the last 1700 years. This shallow lake presented a low and high energy sedimentation environment and exhibited sensitivity to precipitation changes in the region. In agreement with other pampean shallow lakes, the changes observed in the lake communities before 1880 CE were a result of climatic perturbations (increase/decrease rainfall) while after 1880

CE, they were a combination of climatic (increases and decreases of precipitation values) and anthropic forcings (cattle, intensive agriculture and urbanization), that generated the eutrophication process. It is important to highlight that during the last period, the important peak in lake sedimentation evidenced that anthropogenic impacts affected the lake basin through the agriculture and cattle implemented in the region. Agriculture represented the main activity and later the subsequent cattle farming incorporation, which along with increased precipitation generated an accelerated eutrophication during the last 30 years. Moreover, the paleoenvironmental reconstruction of the Blanca Chica lake and its comparison with the evolution of other lakes in the region contributed to the understanding of the climatic and anthropogenic evolution of the central Pampa plain for the last 1700 years. The recovery of a suitable archive from the Blanca Chica lake presented an exceptional opportunity to fill the scarcity of paleoenvironmental data for this sub-region and enabled us to disentangle the relative significance of different forces, like climate fluctuations and changes in land use.

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