ON THE RELATIONSHIP BETWEEN HOLOCENE ENVIRONMENTAL VARIABILITY AND DIATOM COMPOSITION IN THE PEÑA LAGOON, SE URUGUAY

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Abstract

Uruguayan Southern lagoons exhibit high Holocene resolution paleoenvironmental - paleoclimatic records for inferring long-term regional changes. The multiproxy analysis of three sediment cores allowed to recognize Holocene climatic variability from the paleolimnological record of Peña lagoon over the last 2,458 yr BP. Four main stages were identified throughout the record. The first (2,458 – 1,500 cal yr BP) was characterized as a shallow meso – eutrophic system with high abundances of aerophilic benthic species (i.e., *Hantzschia amphioxys, Nitzschia brevissima, Frustulia* sp., *Luticola goeppertiana),* epiphytic taxa (i.e *Epithemia adnata, Eunotia* spp., *Rophalodia gibba*) and planktonic taxa (i.e. *Aulacoseira ambigua* and *A. granulata*). The second stage showed a noticeable change in the diatom assemblage dominated by fresh-brackish benthic species *Staurosira construens,* but also fluctuations in the abundance of *Aulacoseira ambigua* and *A. granulata,* which indicates the occurrence of temperate to cold and semiarid climatic conditions, including intervals of high rainfall. The core chronology allowed us to ascribe this stage to the Little Ice Age (LIA). The third stage, post 390 cal yr BP, showed the highest proportion of freshwater planktonic species throughout the entire core, thus indicating the development of a eutrophic system under relatively warm and wet conditions, which were assigned to the Current Warm Period. After *ca*. 1962 AD, a sharp increase in the abundance of epiphytic species (i.e., *Cocconeis placentula, Eunotia* spp, *Epithemia adnata* and *Encyonema minutum*) highlights the onset of the fourth stage, which was characterized by littoral expansion and consequently, the proliferation of associated macrophytes due to anthropogenic impacts.

Key words: Diatoms. Holocene. Southeastern Uruguay. Paleoecology

RELACIÓN ENTRE LA VARIABILIDAD AMBIENTAL HOLOCENA Y COMPOSICIÓN DIATOMOLÓGICA EN LA LAGUNA PEÑA, SE URUGUAY

Resumen

Las lagunas costeras del sudeste uruguayo son sistemas naturales que exhiben registros paleoclimaticos y paleoambientales de alta resolución temporal para analizar la variabilidad ambiental holocena. El análisis "*multiproxy*" de tres testigos sedimentarios permitió identificar la variabilidad climática Holocena en la laguna Peña durante los últimos 2458 años. Se identificaron cuatro estadios, el más antiguo (2458 a 1500 años cal AP), caracterizando un sistema somero meso – eutrófico, con abundancias relativas altas de especies bentónicas aerófílas (*Hantzschia amphioxys*, *Nitzschia brevissima*, *Frustulia sp.*, *Luticola goeppertiana*), especies epifíticas (*Epithemia adnata*, *Eunotia spp.*, *Rophalodia gibba*) y especies planctónicas (*Aulacoseira ambigua* y *A. granulata*). La segunda fase (1415 - 390 años cal. AP) se identifica por alto contenido de la especie bentónica dulce acuícola – salobre *Staurosira construens* y fluctuaciones de la abundancia de *Aulacoseira ambigua* y *A. granulata*, infiriendo condiciones climáticas templadas - frías y semiáridas con intervalos de precipitación. La cronología sedimentaria permite relacionar esta fase con la Pequeña Edad de Hielo. La tercera fase (posterior a 390 años cal AP) presenta la mayor proporción de especies dulceacuícolas planctónicas, indicando el desarrollo de un sistema eutrófico bajo condiciones cálidas y húmedas, asociadas al Periodo Cálido Actual (PCA). Posterior a los *ca.* 1962 AD, el aumento de especies epifíticas (*Cocconeis placentula*, Eunotia spp, *Epithemia adnata* y *Encyonema minutum*) infiere un sistema léntico con proliferación de macrófitas y una zona litoral ampliamente desarrollada, debido al impacto antrópico.

Palabras clave: Diatomeas. Holoceno Tardío. Sudeste Uruguayo. Paleoecología

URUGUAYAN coastal lagoon systems provide a multiple set of geomorphological elements as well as sedimentological, geochemical and biological indicators useful to reconstruct past environmental changes as well as the most recent anthropogenic impacts (Iriarte, 2006; del Puerto et al., 2011, Inda, 2016). Most of these lentic systems, developed after the Holocene marine transgression at around 5,500 cal. yr BP (García-Rodríguez et al., 2001; Bracco et al., 2005; Inda et al., 2006), offer valuable paleolimnological records for reconstructing climatic and environmental changes occurred in the region during the Holocene (Bracco et al., 2005; del Puerto et al., 2006, 2011, 2013; Garcia-Rodriguez et al., 2001, 2002a,2002b, 2004a, 2004b, 2004c; Garcia-Rodriguez & Witkowski, 2003; Inda et al., 2006, 2016). A general overview of the Holocene climate variability and associated geological processes along the Uruguayan coastal setting can be found in García-Rodriguez et al., (2011).

Previous paleolimnological reconstructions from the Peña Lagoon (Figure 1) based on the analysis of opal phytolith and isotopic records, highlighted the development of three climatic stages during the last 2,458 cal yr BP (del Puerto et al., 2013) The first, spanning from 2,458 cal years BP until 700 AD, was characterized by prevailing temperate and humid conditions. The second, lasted from 700 AD until 1,200 AD, was comparatively warmer and wetter and was assigned to the Medieval Warm Period. This stage was not uniform and included a colder and drier pulse. The third climatic stage extended from 1,200 AD until the present, and it showed high variability, with three dry/cold phases reaching their maximums at 1,300, 1,600 and 1,900 AD matching with the Little Ice Age (González-Rouco et al., 2003; Bracco et al., 2005; Piovano et al., 2009, Córdoba et al., 2014, Villalba, 1994).

In this paper, we explored biological and physical indicators of Holocene climatic variability from the paleolimnological record of Peña lagoon. Since, multiproxy studies provide the means to identify sensitivities, strengths, and weaknesses of different proxies related to the environmental forcing (Birks & Birks, 2006), the analysis of both diatom assemblages and facies analysis are included to strengthen previous environmental reconstructions mostly based on isotopes and the opal phytolith record (del Puerto et al., 2013). Diatoms are microscopic algae, abundant in almost all aquatic habitats. They are sensitive organisms, that respond to environmental factors, influencing some water variables (i.e., pH, salinity, water level fluctuations, and trophic status), representing one of the biological indicator that have been widely used to paleoenvironmental reconstructions (Battarbee, 2000; Battarbee et al., 2002; Lamper & Sommer, 2007; Smol, 2008). Similarly, sedimentological features, such as grain size and magnetic susceptibility, may help to delineate depositional dynamics, clastic, biological, and/or authigenic sediment sources (Sandgren & Snowball 2002; Ver Straeten et al., 2011). Moreover, the study of phytoliths assemblages allow to infer the paleovegetation in the local area reflecting climatic and environmental characteristics (Fredlund & Tieszen, 1994; Lu & Liu, 2003a, b). Although this proxy present taphonomic problems it does not always reflect the original plant communities precisely (Lu et al., 2006).

Our results showed that the combined analyses of biological indicators with data derived from stable isotopic composition of organic matter, geochemistry, and physical proxies (i.e., magnetic susceptibility, sedimentary facies, among others) allow to infer past lake-catchment changes related to climate change during the 2,458 yr BP. Finally, this paper provides new results to be included in the general framework of the MATES Program (Multiproxy Approach for Tracking Environmental changes in Southern South America) which aims to integrate paleoclimate research across Argentina and Uruguay.

METHODS

Study site and climate setting

Peña lagoon is a freshwater lagoon (34°00´13´´ S - 53° 33´10´´ W), located in a narrow sedimentary fringe called "La Angostura", situated between the Atlantic Ocean and the Negra Lagoon (Fig. 1). The catchment and lagoon area are 0.5 Km^2 and *ca*. 0.05 Km^2 respectively. The maximum water depth is 1.8 m (del Puerto et al., 2013). The lagoon is located in Santa Teresa National Park, which has been drastically modified during the 20th Century. More information about the site setting and vegetation can be found in del Puerto et al., (2013).

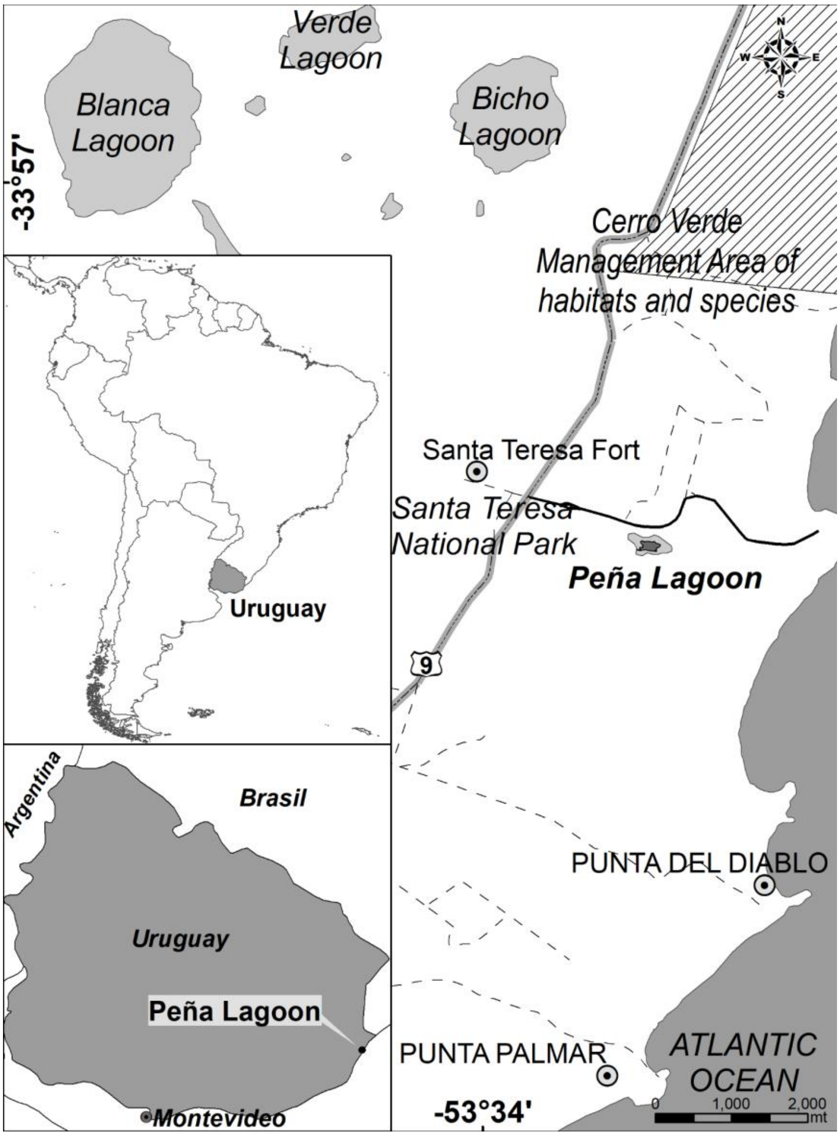


Figure 1. Geographical location of Peña Lagoon. Gray point represents coring stations.

Peña Lagoon is part of a group of small marginal water bodies located on the 10 – 20 m a.s.l. contour lines of the Uruguayan coast (Kruk et al., 2006). The topography indicates that, in contrast to the major coastal lagoons, this aquatic system was originated as the result of fluvial damming by movement of the sand dunes (Bracco et al., 2011).

The study region is located along the boundary between subtropical and temperate regions of Southeastern South America (Cerveny, 1998). South America regional climate distribution is defined by continental north-to-south variations, east-west asymmetries (given by the presence of the Andes), land mass shape and the boundary conditions imposed by a cold southeastern Pacific and a warm southwestern Atlantic (Garreaud et al., 2009). Extending Eastward the Andes and covering a vast lowland area from Colombia and Venezuela up to the Argentinean Pampas in the south, it is the most outstanding geographical feature that provides a unique environment for the development of a Monsoon-like circulation (Zhou and Lau, 1998; Vera et al., 2006). Summertime climate in Southeastern South America is linked to the South Atlantic Convergence Zone (SACZ) in the form of a rainfall seesaw: increased rains in the SACZ are correlated with decreased rainfall in SESA (Doyle and Barros 2002). The SACZ, in turn, may be forced by South Atlantic SST anomalies (Barreiro et al. 2002, 2005). The wind and water mass regime are controlled by the interaction between the tropical anticyclone of the South Atlantic and the migratory polar anticyclone (Fonzar, 1994).

In the study area, the Atlantic influence causes moderate daily and annual thermal amplitude with high levels of relative humidity. Mean temperature is 17 °C and mean historical total annual precipitation is 1200 mm (PROBIDES, 1999; IBERSIS, 2001). Interannual climate variability is influenced by El Niño Southern Oscillation (ENSO). El Niño episodes are mostly associated with anomalously wet conditions while drought anomalies are observed during La Niña events. However, ENSO at a regional scale exhibits significant seasonal fluctuations, such as impacts on rainfall, which show considerable variability during the 20th Century. Decadal and interdecadal variability are possibly forced by the Pacific Decadal Oscillation (PDO) and the Antarctic Oscillation (AAO) over South America (Barreiro and Tippman, 2008; Garreaud et al., 2009).

Core collection, sampling and previous analysis

Cores LP1 and LP2 (95 and 156 cm long respectively) were taken in 2010 using a piston corer. Both cores were retrieved very closely, thus, a composite core LP1-LP2 can be considered. A third core LP3 (106 cm long) was collected in 2014 with the same methodology used in 2010. The sampling sites, of the cores are shown in Fig 1. The opening procedure, dating, geochemistry, organic matter and isotopes analysis for the core LP1 - LP2 are described in detail by del Puerto et al. (2013). Samples for diatoms and grain size analysis were taken every 2 cm in the LP1 core (0 -95 cm) and in the basal part of the LP2 core (95 – 156 cm), both cores represent the entire record of Peña Lagoon of 156 cm long. The sedimentological description was performed on core LP3. Core correlation between LP3 and both LP1 - LP2 was established through the inspection of sedimentological features such as sedimentary structures, magnetic susceptibility core profiles, grain size values and content of sedimentary organic matter.

Sedimentological analysis: grain size, magnetic susceptibility measurement

The sediment grain-size was measured in samples from the LP1 and the LP2 cores using a laser diffraction grain size analyzer (HORIBA LA-950; Centro de Investigaciones en Ciencias de la Tierra (CICTERRA). Samples were pretreated with 20 mL of 30% H_2O_2 to eliminate the organic matter, and with 20 mL HCl (10%) to remove carbonates. Finally, samples were rinsed with deionized water and dispersed in 10 mL of $(NaPO_3)_6$ solution to prevent particles from aggregating. Grain size data were analyzed using the statistical program GRADISTAT 8.0. Sediment description was performed according to

Schnurrenberger et al. (2003). The Munsell chart was utilized to characterize sediment color. The volume specific magnetic susceptibility (κ) of sediments was measured on the surface of the split half core at 1 cm intervals with a Bartington F-sensor. Values are given in 10^{-6} SI (dimensionless). Sedimentary core LP3 was inspected through XR radiograph in the Department of Image at the Universidad Nacional de Cordoba Argentina (UNC) to further identify sedimentary structures.

Diatom analysis

Samples for diatom analyses (n = 39) were pre-treated with H_2O_2 for organic matter removal and with HCl for carbonate removal as indicated in Metzeltin and Garcia-Rodriguez (2003). Permanent microscope slides were mounted using Entellan resin (Refractive Index: 1.54).

Slides were inspected at 1000x magnification with oil immersion using an Olympus BX53 light microscope. A minimum of 400 diatom valves was counted in each slide along randomly selected transects according to Battarbee *et al*. (2002). The relative abundances of individual species were calculated by dividing the number of valves from each species by the total number of valves counted on each slide. Diatoms were identified to species level using the appropriate keys (Metzeltin et al., 2005, Metzeltin and García-Rodríguez 2003, Krammer and Lange-Bertalot 1986, 1988, 1991a, 1991b; Frenguelli, 1941, 1945; Round, 1990; ANSP Algae Image Database). Ecological information of diatom taxa preferences (i.e trophic status, moisture and salinity) was extracted from Round et al. (1990), Denys (1991), Van Dam et al. (1994), Rühland et al. (2003), Hassan (2010) and Solak et al. (2012).

The vertical distribution of the most abundant diatoms (*i.e.* those species with relative abundance higher than 3% in at least three intervals) was plotted against core depth using C2 software (Juggins, 2005). Diatom zones were determined using constrained cluster analysis (CONISS) using the software Tilia v. 2.0.38.

Geochemistry

Isotopic composition of organic matter ($\delta^{13}C$) as well as C/N ratios were used to infer the sedimentary organic matter source/composition in Peña Lagoon. Data were taken from del Puerto et al. (2013). The stable carbon isotope composition ($\delta^{13}C$) and the ratio Carbon-Nitrogen (C/N) can be employed to assess the origin and composition of sedimentary organic matter (Lamb et al., 2006).

RESULTS

Sedimentology and geochemistry

With the aim of establishing a stratigraphic correlation between cores LP3 and the composite core LP1 - LP2, we compared magnetic susceptibility values throughout core LP3 to grain size variations of core LP1 - LP2. Since high MS values observed in core LP3 match with coarser sediments in LP1 and LP2 (Fig.2) both variables were simultaneously used as stratigraphic markers for core correlation. Core LP3 showed a uniform pattern of magnetic susceptibility (average 4.7 SI) that was interrupted by distinct shifts to higher peak values (maximum 38.7 SI) at 19, 62 and 104 cm depth.

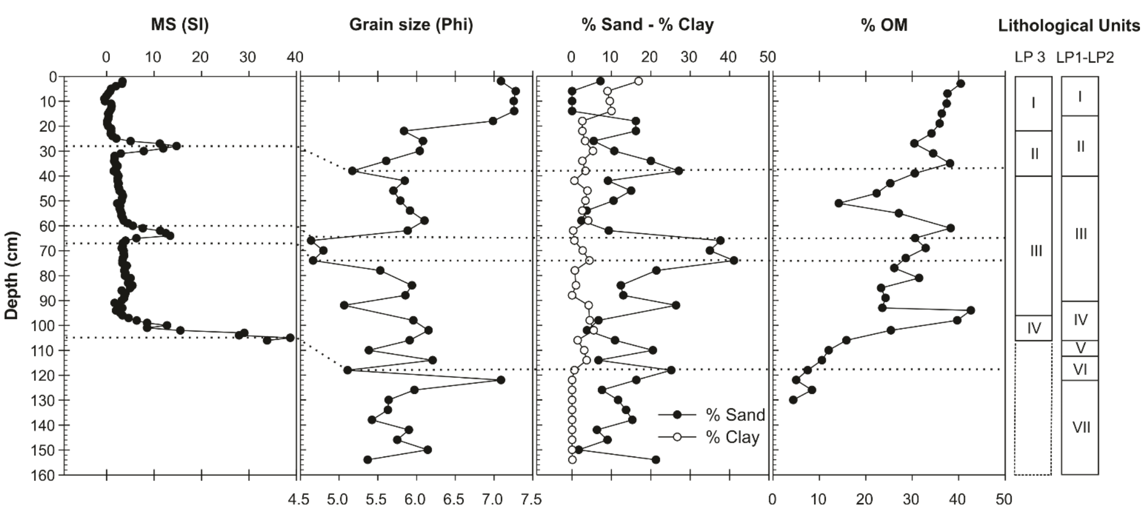


Figure 2. Correlation of the core LP3 with the LP1 - LP2 composite core. Dotted lines indicates the stratigraphic correlation between magnetic susceptibility (MS) of the LP3 core with grain size, percentage of sand - clay and percentage of sedimentary organic matter measured in the LP1 - LP2 composite core (Published data by del Puerto et al., 2013 and provided by the authors). The right side plot shows the correspondence of lithological units of the LP3 core with those identified by del Puerto et al (2013). Based on physical data, LU V, VI and VII from core LP1 - LP2 were considered within LU IV identified in LP3.

The core LP3 consisted of massive to banded and laminated, dark-gray – black, sandy-silty muds, with abundant fibrous plant remains. Based on the sedimentological features, magnetic susceptibility, grain size, OM content and sediment color (Fig. 2 and 3), the sedimentary record was subdivided into four lithological units (LU): LU IV (106 –93 cm): Massive Sandy Muds; LU III (93 – 41 cm): Banded organic-rich Sandy Muds; LU II (41 – 20 cm): Massive Sandy Muds and LU I (20 – 0 cm): Banded Medium Silt Muds. A summary of lithological units characteristics, photographs and XR radiographs is presented in Figure 3.

Photographs, XR radiographs (negative) and LU of LP3	Lithological Unit Description
	**LU_I Banded Medium Silt Muds** Dark grey medium silt mud (10YR 4/1) Organic matter 35.9 - 40% Magnetic susceptibility (SI) -0.5 - 3.3 Grain size (Phi) 7.0 - 7.3
	LU_II Massive sandy Muds Dark grey sandy mud (10YR 4/1) Organic matter 25.3 - 38% Magnetic susceptibility (SI) 0.9 - 14.7 Grain size (Phi) 5.2 - 6.1
	LU_III Banded organic rich Sandy Muds Dark grey sandy mud (10YR 4/1) fining upward with plant remains Organic matter 14 - 38% Magnetic susceptibility (SI) 1.7 - 13.4 Grain size (Phi) 4.7 - 6.1
	LU_IV Massive Sandy Muds Black coarse to fine sandy medium silt (10YR 2/1) Organic matter 15.8 - 42% Magnetic susceptibility (SI) 1.9 - 38.7 Grain size (Phi) 5.1 - 7.1

Figure 3. Description of LP3 lithological units: (1) Photograph of the sedimentary record LP3 (106 cm) and (2) corresponding X ray image, (3) banded zone of LU I (10 – 15 cm), (4) massive sandy mud of LU II (26 – 31 cm), (5) fibrous plants remains zone of LU III (48 – 57 cm), (6) sandy sediments present in LU III (84 – 90 cm) and (g) black sandy mud zone of LU IV (93 – 100 cm).

The relationship between $\delta^{13}C$ and C/N ratio values for each lithological unit is shown in Fig. 4. In the LU IV, $\delta^{13}C$ values ranged between – 26.7‰ and – 23.0‰, while C/N values ranged between 8.5 and 14.9. The LU III, exhibited $\delta^{13}C$ values between – 27.0‰ and – 24.5‰ and C/N values between 10.0 and 13.7. In the LU II, $\delta^{13}C$ ranged between – 24.7‰ and – 23.9‰ and C/N values ranged between 12.7 and 13.7. The LU I showed $\delta^{13}C$ values ranging between – 25.8‰ and – 23.9‰, and C/N ratios ranging between 10.6 and 12.7.

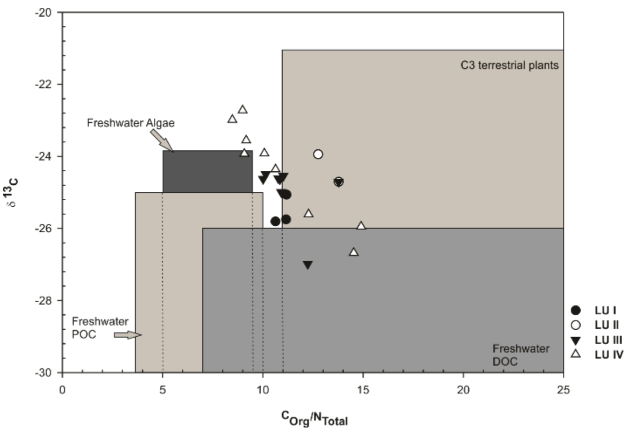


Figure 4. The relationship between $\delta^{13}C$ values and C/N ratios sediment cores (LP1 – LP2) (Published data by del Puerto et al., 2013 and provided by the authors), including typical ranges of sources according to data presented by Meyers (1994) and Lamb et al. (2006).

Diatoms

A total of 109 species were identified in 39 samples selected from cores LP1 (0 – 95 cm) and LP2 (95 – 156 cm). The vertical distribution of the most abundant diatom species, the percentage of diatom groups (i.e., Planktonic, Benthic and Epiphytic) and the Diatom Association Zones (DAZ), inferred from the stratigraphic constrained cluster analysis are presented in Figure 5.

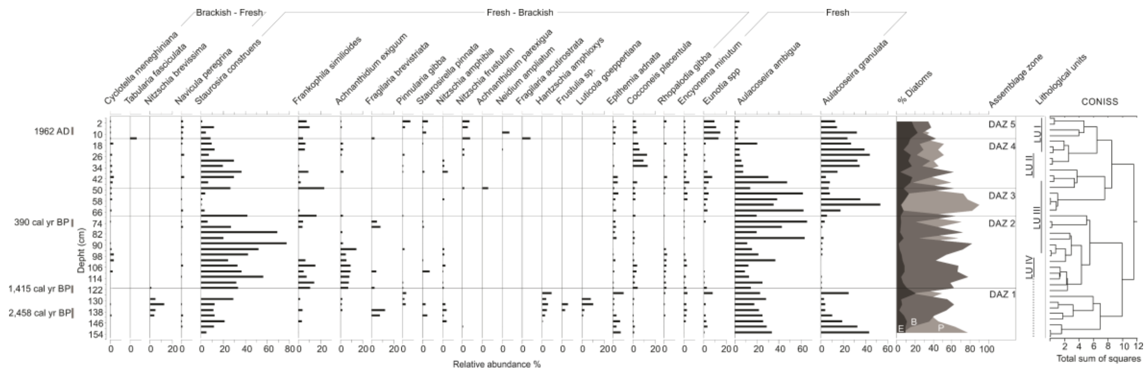


Figure 5. Relative abundance of diatom species of cores LP1 (0 – 95 cm) and LP2 (95 – 106 cm). Percentage of groups of diatoms; planktonic (P), benthic (B) and epiphytic (E). Clustering groups, lithological units (LU) and Diatom Assemblage Zones (DAZ) are shown to the right of the plot.

Those species with a relative abundance lower than 3% were excluded from the statistical analysis as they are considered as rare species (Whiting and Mc Intire 1985, in Hassan et al., 2006). Therefore, a set of 26 representative co-dominant species with a relative abundance ≥ 3% in at least two intervals are presented in Figure 5.

Cluster analysis allowed us to identify five diatom zones (DAZ) (Fig. 5). DAZ 1, encompassed the basal section of the sedimentary record (156 – 122 cm), and was dominated by *Staurosira construens* Ehrenberg, *Aulacoseira ambigua* (Grunow) Simonsen, *Aulacoseira granulata* (Ehrenberg) Simonsen, *Fragilaria brevistriata* (Grunow) Van Heurck, *Enc*yonema *minutum* (Hilse) D.G.Mann in Round, *Nitzschia* *amphibia* Grunow, *Hantzschia amphioxys* (Ehrenberg) Grunow, *Eunotia* spp, *Epithemia adnata* (Kützing) Brébisson, *Nitzschia brevissima* Grunow, *Frustulia* sp., *Luticola goeppertiana* (Bleisch ex Rabenhorst) D.G.Mann in Round and *Rophalodia gibba* (Ehrenberg) O. Müller. The most abundant diatom species in this zone consisted of freshwater planktonic species *Aulacoseira ambigua* (26%), *Aulacoseira granulata* (18%) from 156 cm to 148 cm, and 148 to 122 cm the benthic – brackish/freshwater species of *Staurosira construens* (13%). DAZ 1 exhibited a mean value of 55.5% of benthic aerophilic taxa (i.e., *Hantzschia amphioxys*, *Nitzschia brevissima*, *Frustulia* sp., *Luticola goeppertiana*) from which 19.5% were epiphytic (i.e., *Epithemia adnata*, *Eunotia* spp., *Rophalodia gibba*) and 25% planktonic. In the interval 134 - 122 cm there was an increase in epiphytic species (Fig. 5).

In DAZ 2 (122 – 70 cm) the benthic brackish/freshwater species *Staurosira construens* showed a relative abundance of 40%, while *Aulacoseira ambigua* exhibited a relative abundance of 27%. In addition, lower frequencies of *Cyclotella meneghiniana* Kützing, *Frankophila similioides* Lange-Bertalot and U. Rumrich, *Achnanthidium exiguum* (Grunow) Czarnecki, *Fragilaria brevistriata*, *Epithemia adnata*, *Cocconeis placentula* Ehrenberg and *Rhopalodia gibba*, were observed. The relative abundance of benthic taxa increased to a mean value of 66.5%, while the planktonic species *Aulacoseira granulata* decreased sharply (Fig. 5).

In DAZ 3 (70 – 50 cm) the relative abundance of planktonic taxa increased, reaching here the highest value (62%) of the entire core, dominated by *Aulacoseira ambigua* (43%) and *Aulacoseira granulata* (25%). The benthic taxa decreased to 26%, and low proportions of *Staurosira construens*; *Epithemia adnata*, *Rhopalodia gibba*, *Eunotia* spp. and *Encyonema minutum* were observed throughout this zone (Fig. 5).

In DAZ 4 (50 – 14 cm) planktonic and benthic taxa reached the 43% and 33% respectively. DAZ 4 was dominated by *Staurosira construens*, and *Aulacoseira granulata*, with lower proportions of *Aulacoseira ambigua* and *Cocconeis placentula*, showing higher abundances towards the upper section of the zone. Conversely, lower percentages of *Frankophila similioides*, *Encyonema minutum*, *Nitzschia amphibia*, *Epithemia adnata*, *Eunotia* spp and *Cyclotella meneghiniana*, were registered in DAZ 4. The percentage of *Aulacoseira ambigua* was higher than that of the upper section of the zone, while *Aulacoseira granulata* displayed lower values in the basal section of the zone (Fig. 5).

In DAZ 5 (14 – 2 cm), diatom assemblages were dominated by *Eunotia* spp and *Aulacoseira granulata*, but *Staurosira construens,* displayed a decreasing upward trend. *Aulacoseira ambigua* showed the lowest abundances of the core. In the subsurface sediments of this zone, the occurrence of *Nitzschia frustulum*, *Nitzschia ampliatum*, *Pinnularia gibba*, *Staurosirella pinnata* and *Tabularia fasciculata* was observed (Fig. 5).

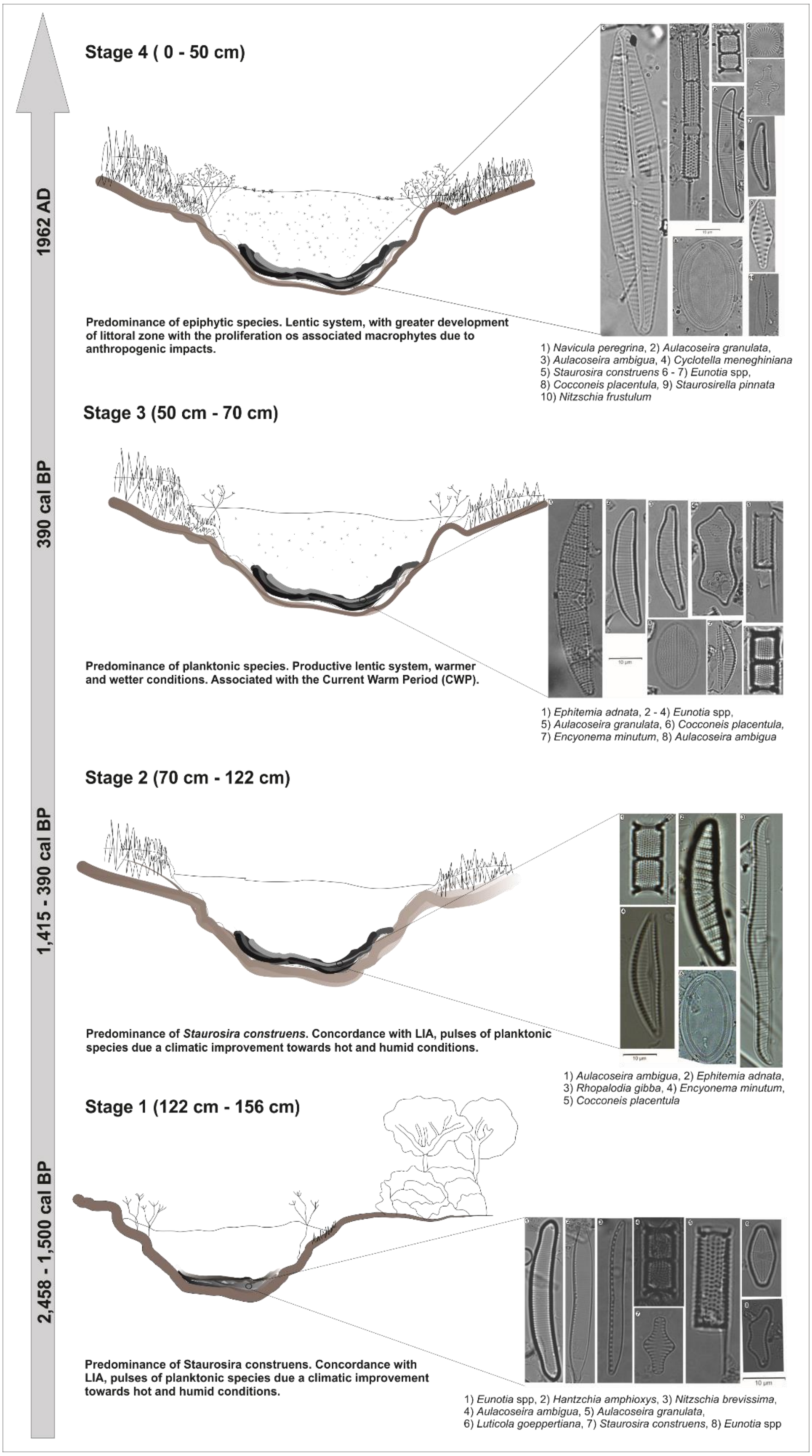
DISCUSSION

The combined analysis of geochemical, sedimentological proxy-data (Fig. 2 and 4) and diatom assemblages (Fig. 5) allowed to infer distinct changes in the environmental conditions of Peña Lagoon throughout the past 2,458 yr BP.

Four lithological units (LU) were defined according to changes in grain size composition as well as in the magnetic susceptibility ratio, which are considered as indicators of different sediment sources. Coarser sediments in lithological unit II - III with high MS ratios are attributed to an increased input of sandy sediments from the lake watershed.

According to Meyers (1994) the $\delta^{13}C$ and C/N ratio values allowed us to infer a mixed source of sedimentary organic matter with signals of freshwater microalgae and C3 terrestrial plants in lithological unit IV (Fig. 4), where an environment with important proliferation of grasses and phytoplankton/microphytobenthos was inferred by del Puerto et al., (2013). Similar environmental conditions in the source of sedimentary organic matter were observed in LU III and LU I, based on $\delta^{13}C$ and C/N ratio values (Fig. 4). However, in LU II, both isotopic and C/N values indicate that the organic matter completely derived from the C3 terrestrial plants (Fig. 4). Therefore, the changes in the isotopic composition of OM and C/N ratios allowed us to reliably infer past changes in organic matter composition where signals of freshwater microalgae and continental C3 plants were the most important sources.

The variability in diatom assemblages (DAZ 1-5) combined with physical and chemical proxies indicate four main stages during the past 2,458 yr BP in Peña Lagoon, as depicted in Fig. 6.



Stage 4 (0 - 50 cm)
1962 AD
Predominance of epiphytic species. Lentic system, with greater development of littoral zone with the proliferation os associated macrophytes due to anthropogenic impacts.
1) Navicula peregrina, 2) Aulacoseira granulata, 3) Aulacoseira ambigua, 4) Cyclotella meneghiniana 5) Staurosira construens 6 - 7) Eunotia spp, 8) Cocconeis placentula, 9) Staurosirella pinnata 10) Nitzschia frustulum
Stage 3 (50 cm - 70 cm)
390 cal BP
Predominance of planktonic species. Productive lentic system, warmer and wetter conditions. Associated with the Current Warm Period (CWP).
1) Ephitemia adnata, 2 - 4) Eunotia spp, 5) Aulacoseira granulata, 6) Cocconeis placentula, 7) Encyonema minutum, 8) Aulacoseira ambigua
Stage 2 (70 cm - 122 cm)
1,415 - 390 cal BP
Predominance of Staurosira construens. Concordance with LIA, pulses of planktonic species due a climatic improvement towards hot and humid conditions.
1) Aulacoseira ambigua, 2) Ephitemia adnata, 3) Rhopalodia gibba, 4) Encyonema minutum, 5) Cocconeis placentula
Stage 1 (122 cm - 156 cm)
2,458 - 1,500 cal BP
Predominance of Staurosira construens. Concordance with LIA, pulses of planktonic species due a climatic improvement towards hot and humid conditions.
1) Eunotia spp, 2) Hantzchia amphioxys, 3) Nitzschia brevissima, 4) Aulacoseira ambigua, 5) Aulacoseira granulata, 6) Luticola goeppertiana, 7) Staurosira construens, 8) Eunotia spp

Figure 6. Holocene main climatic variability stages in Peña Lagoon over the last 2,458 cal yr BP.

Stage 1

This stage is recorded from 122 to 156 cm (i.e., DAZ 1). The age of basal sediments is unknown, but the interval of 127.5 cm was dated at 2,458 cal yr BP and the top at 1,415 cal yr BP. Sediments are dominantly sandy-muds (Fig. 2 - 3) with a coarsening trend at the basal part of the core (ca. ø 5.3) thus suggesting sandy sediment inputs from the surrounding lagoon area. Allochthonous inputs of organic matter derived from the watershed can be considered according to $\delta^{13}C$ values (-23.6‰), which indicate a terrestrial plant inputs (Meyers, 1994; Wei et al., 2010) (Fig. 4). Previous results also inferred such external inputs using the OP/OBP index (opal phytolith:other biosiliceous particles ratio) as a proxy, which showed both the highest values of the record and dominance of C4 phytoliths (del Puerto et al., 2013). The uppermost section of stage 1 (dated at 1,415 yr BP) could be ascribed to warm temperate and humid conditions, corresponding to the Medieval Warm Period (MWP; *ca*. 1500 years BP), inferred for the Pampean region by Piovano et al. (2009) and in Uruguay by Perez et al. (2016) as warmer and more humid pulses with variations in rainfall and wind patterns for 1,200 cal yr BP.

Benthic taxa characteristic of moist or temporarily dry sediments (Denys, 1991; Van Dam et al., 1994) accounted for 55% of the diatom abundance from which 19.5% consisted of epiphytic taxa, thus indicating the presence of aquatic plants associated to a shallow system with a well-developed littoral zone. Li et al. (2015) inferred similar conditions based on high abundances of epiphytic taxa (*i.e*, *Epithemia adnata, Cocconeis placentula*) in south-western China. In addition, a meso eutrophic brackish system (e.g., Denys, 1991; Van Dam et al., 1994), with significant water turbulence and associated turbidity can be inferred from the occurrence of the planktonic species *Aulacoseira* *granulata* and *Aulacoseira ambigua* in the basal section of the core (150 - 156 cm). Moreover, *A. granulata* is considered a thermophilic diatom linked to water temperatures higher than 15°C (Rioual et al., 2007), this taxa have been reported in modern Pampean lakes sediments from Argentina in temperatures ranging from 7 up to 25 °C (Hassan, 2015) The decreasing upward trend in the abundance of both planktonic species, together with the occurrence of *Hantzschia amphioxys*, *Nitzschia brevissima*, *Frustulia* sp. and *Luticola goeppertiana* in DAZ 1, suggest a reduction in the water column productivity of the system, higher salinity (~ 0.9 – 1.8‰, Denys, 1991; Van Dam et al., 1994), cooler conditions, and a decrease in water turbidity, possibly as a result of a reduction in windy conditions. The fine grain size fraction of sediments above 140 cm depth, indicate lower runoff from the catchment.

Results are consistent with previous reconstructions which analyzed the phytolith record of Negra lagoon, where a warm/wet period was also identified between 1,980 ± 40 yr BP and 930 ± 45 yr BP, although an intermediate drier/colder episode has been proposed (Bracco et al., 2005a; 2005b; 2010; del Puerto, 2009) Furthermore, paleolimnological studies in the southern Pampa plains of Argentina suggested that it is fairly acceptable to assume that during the middle–late Holocene, the ratio of evaporation to precipitation was higher, thus leading to salinization, low water levels and possible desiccation of lakes (Stutz et al., 2012). In the northern region of the Pampa plain, a paleolimnological record indicates brackish to saline conditions with pulses of short-periodic freshwater conditions for 4,840 – 1,200 cal. yr BP (Stutz et al., 2012), as well as dry conditions during most of the Holocene (Piovano et al., 2009).

Stage 2

This stage is recorded by sandy mud sediments entirely matching DAZ 2 (122 cm – 70 cm), which was dominated by the benthic species *Staurosira construens* with pulses of increased abundance of *Aulacoseira ambigua* (Fig. 5). The age of the section is ca. 1,415 cal. yr BP (117 cm) while the top corresponds to 390 cal yr BP (73 cm).

High abundances of the fragilarioid species *Staurosira construens* (Stoermer, 1993 in Fey et al., 2009), which are also in agreement with the disappearance of a thermophilic species *A. granulata* allowed us to infer cold conditions during this stage. Likewise, del Puerto et al. (2013) reported an increase of pooid and chloridoid phytolith morphotypes as well as an increase in the temperature:humidity (T:H) index, thus suggesting lower average temperature values, and either more arid or highly seasonal conditions. Above 90 cm depth, an allochthonous input from runoff processes due to increased rainfall was inferred based on changes in the relative abundance of *S. construens,* and *A. ambigua*. In addition, changes in the relative abundance of *S. construens,* and the increase in *A. ambigua* indicate a reduction in salinity to < 0.9 (Van Dam et al., 1994; Alcántara et al., 2002). At the same level, the coarser sediments, high content of sedimentary OM, high values of C/N ratio and a $\delta^{13}C$ can be attributed to higher external inputs. In agreement with this, high terrestrial inputs and lower mean annual temperatures were inferred by del Puerto et al. (2013) based on an increase in phytoliths of winter grasses. Considering the age of the uppermost section of this stage, it can be assigned to the Little Ice Age (LIA). Moreover, other paleolimnological records from Southern Uruguay (Bracco et al., 2011a, 2011b) indicate a climatic deterioration linked to the Little Ice Age (LIA) with estimated chronologies between 800 - 200 yr BP, thus suggesting semiarid climatic conditions with intervals of rainfall increase. In the central plain of Argentina, high salinities and low lake levels for the LIA were identified. Such conditions persisted until the early 1970s, after which extreme pulses of positive water balances were inferred (Villalba, 1994; Piovano et al., 2004; 2009; Córdoba et al., 2014)

Stage 3 (after 390 cal yr BP)

This stage matches entirely with DAZ 3 (50 cm – 70 cm) where a clear increase in the abundance of planktonic freshwater species *Aulacoseira granulata* and *A. ambigua*, together with higher C/N ratios, suggest an autochthonous contribution to the bulk organic matter (Fig. 4) with a diminished external input which is also supported by the finer grain sediment size. Both planktonic species are considered eutrophic freshwater taxa. High abundances of these taxa were observed during conditions of increasing eutrophic conditions in the Baltic Sea (Andrén, 1999) and in the Bothnian sea (Andrén et al., 2016). In the Southern argentinean pampas, *A. granulata* was the dominant species under high nutrient loading and turbid conditions in the lake Lonkoy, associated with higher water levels and low salinities (Hassan, 2013). Comparatively higher abundances of planktonic diatoms in the Peña Lagoon can be attributed to the onset of warmer conditions, as previously reported by del Puerto et al. (2013) based on the increase in small grass cells. The presence of *A. ambigua* and *A. granulata* species suggest higher water column trophic state conditions (Bicudo et al., 2016) during stage 3 compared to stage 2.

The presence of sandy muds (part of LU II) and C3 terrestrial plant sources of sedimentary organic matter (Fig. 4), in addition to the presence of genus *Aulacoseira*, indicate fairly windy conditions during this stage. *Aulacoseira* has been used in many geographical regions as a proxy for strong wind stress, turbulent water, and nutrient upwelling conditions (Wang et al., 2008). Furthermore, del Puerto et al. (2013) observed variability in phytolith composition and inferred colder and drier conditions by 300 yr BP, which is in agreement with the aeolian sand input into the water body.

Stage 4

The uppermost 50 cm of the sedimentary record that include DAZ 4 and DAZ 5, consisted of finer grain size and higher content of OM, thus reflecting higher primary productivity since 1962 AD to the present. High proportions of epiphytic species such as *Cocconeis placentula*, *Eunotia* spp, *Epithemia adnata* and *Encyonema minutum* suggest a eutrophic lenthic system with a well-developed littoral zone associated with macrophyte proliferation. Based on the increase in phytoliths of the morphotype Oryzoide a similar paleoenvironment was reported by del Puerto et al. (2013), where an increase in hydrophilic vegetation might have been triggered by warm and humid conditions. The higher trophic state can be inferred from the increasing upward trend in sedimentary OM and acidic waters, as suggested by the increase of *Eunotia* spp, which are characteristic of humic waters, where macrophyte degradation is commonly observed (Eloranta y Soininen, 2002). Similar changes were reported in the top 10 cm of the paleolimnological record (attributed to the last century) of Lake Lonkoy in Argentina, which were ascribed to the agricultural impact (Hassan, 2013). Even though, in the surrounding area of Peña Lagoon there are no significant agricultural practices, there is a water treatment plant which throws the residuary sediment waste into the Peña lagoon thus leading the proliferation of macrophytes.

FINAL REMARKS

The diatom assemblages, organic matter composition and sedimentological proxies allowed to recognize four main environmental stages for the last 2,458 cal yr BP: (i) a shallow meso – eutrophic system with high abundances of aerophilic benthic species, with high inputs from the watershed, and organic matter signals of C3 plants. This stage could be ascribed to the Medieval Warm Period (ii) a system dominated by brackish/freshwater species, with high terrestrial inputs and low temperatures synchronous with the Little Ice Age, (iii) a system dominated by planktonic freshwater species, high proportion of autochthonous sedimentary organic matter during the Current Warm Period, and (iv) a eutrophic system with high proportions of epiphytic taxa, and the proliferation of macrophytes in the littoral zone due to recent human impacts.

The results remarks, the importance of developing paleolimnological research at a regional scale in South East of South America in order to evaluate the timing and magnitude of climatic changes during the Holocene as well the most recent response of aquatic systems to human activities.

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