



# Mid and late Holocene multiproxy analysis of environmental changes linked to sea-level fluctuation and climate variability of the Río de la Plata estuary

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## ARTICLE INFO

### Article history:

Received 26 March 2014

Received in revised form 15 December 2014

Accepted 6 January 2015

Available online 10 January 2015

### Keywords:

Pollen

Non-pollen palynomorphs (NPPs)

Diatoms

Holocene sea-level change

Uruguay

Argentina

## ABSTRACT

In the present study, we carried out pollen, diatom and other palynomorph analyses from a sedimentary sequence from the marshes of Arroyo Solís Grande, in the Río de la Plata northeastern coast (Uruguay), and compared the results with a regional model of surface pollen–vegetation relationship from the Atlantic coastal salt marshes (30°–37° S). Results indicated that salt marsh vegetation developed around the estuary between 8000 and 5100 cal yr BP, as the sea level rose and reached the Holocene sea-level highstand. Brackish marshes around the estuary between 5100 and 2900 cal yr BP reflect the late Holocene sea-level fall and associated increased input of freshwater. Brackish marshes and shallow salt pond environments between 2900 and 1000 cal yr BP are most probably linked to the Paraná delta formation and a further sea-level fall. Present-day marshes behind the sand bar characterize the last 1000 cal yr BP. The integration of our results with multiproxy records from the Río de la Plata southern coast (Argentina) and from the coastal plain of the southern Atlantic margin of South America (30°–37° S) revealed that marine influence during the maximum sea-level highstand resulted in the development of vegetation similar to that of the geographical region. However, after ca. 3000 cal yr BP, local differentiation related to different climate and geomorphology occurred at each area, thus resulting in the establishment of different modern plant communities at different times during the late Holocene.

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## 1. Introduction

Salt marsh sediments are one of the most reliable geological tide gauges (Barlow et al., 2013) and paleontological studies on these sediments add significant information to improve our understanding of the sea-level variability over the Holocene and provide insights into the debate about the relative importance of sea-level variation versus climate changes (Roe and van de Plassche, 2005; Woodroffe and Murray-Wallace, 2012).

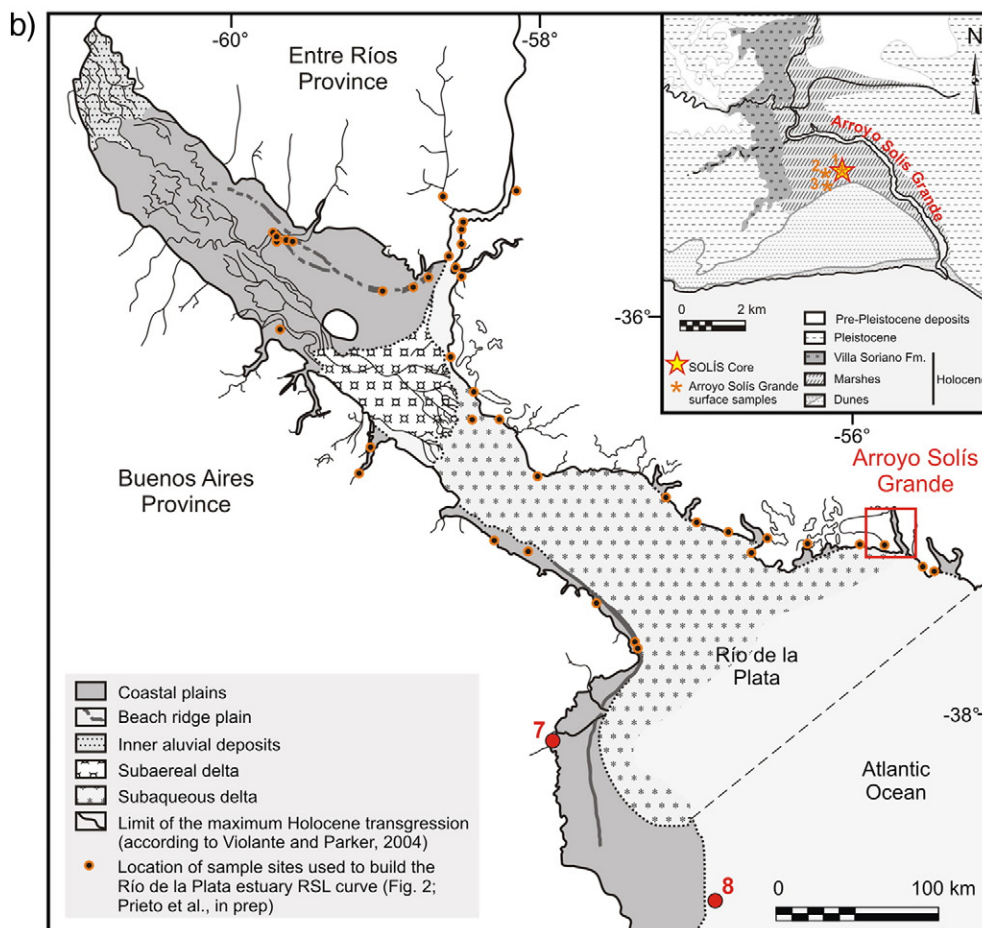
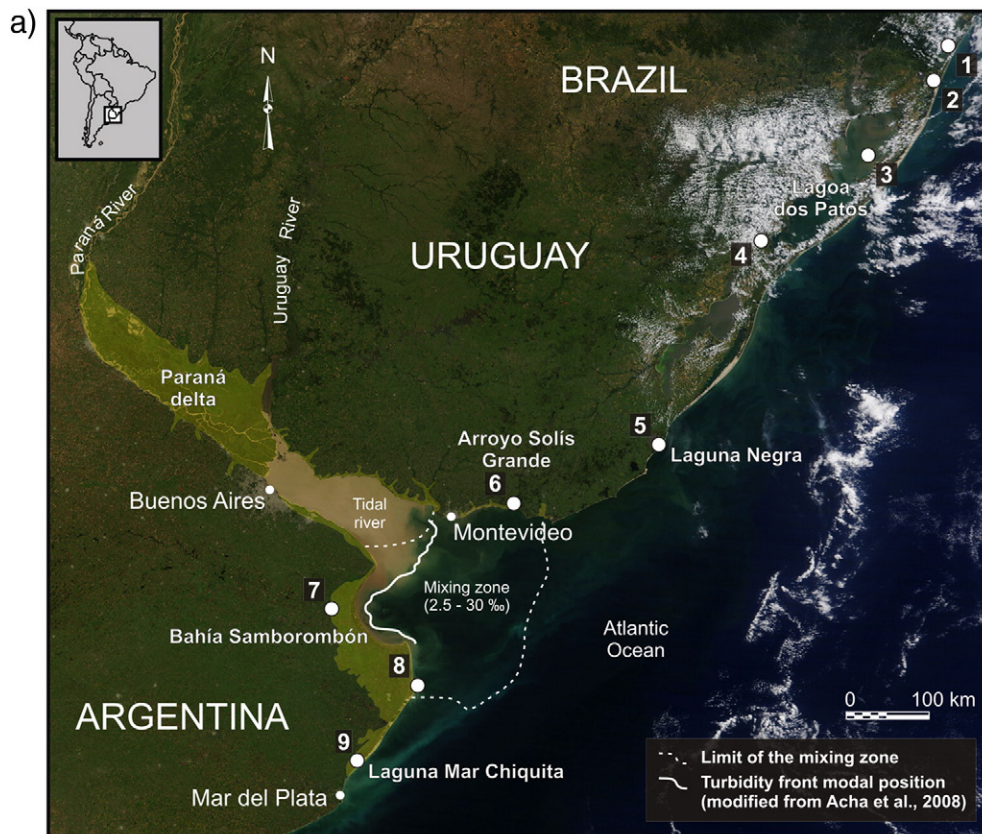
One of the most important estuarine environments in South America is the Río de la Plata estuary between Argentina and Uruguay at ~35° S (Fig. 1), whose river side is influenced by estuarine conditions that increase in salinity from the northwest to the southeast, resulting in extensive salt marshes at Bahía Samborombón (Fig. 1). This estuary has

been affected by sea-level fluctuations since the last glacial termination (LGT) (e.g., Parker et al., 1999; Fucks and de Francesco, 2003; Cavallotto et al., 2004; Violante and Parker, 2004; Cavallotto and Violante, 2005; Gyllencreutz et al., 2010) and rainfall regimes (Cavallotto et al., 2004; Gyllencreutz et al., 2010; Razik et al., 2013). The amount of annual rainfall and the sea-level fluctuations influenced the occurrence of seasonally inundated areas during the Holocene that affected the Río de la Plata estuary coastal ecosystems. The northeastern (Uruguay) and southwestern (Argentina) Río de la Plata coastal areas were differently affected by these sea-level fluctuations due to their different geomorphological characteristics (Cavallotto and Violante, 2005). The southwestern coastal plains were significantly affected because of their large expanse of gently sloping and low-relief environments resulting in major changes of the coastal marsh vegetation (Bahía Samborombón, Fig. 1) (Vilanova and Prieto, 2012). Instead, in the northeastern coast, which is formed by low hills where metamorphic basement rocks outcrop, fluvial–estuarine environments developed only in reduced coastal strips (Fig. 1) (Violante and Parker, 2004) and there is no information about the vegetation history of these coastal marshes.

Paleoenvironmental studies of the coastal water bodies on the Uruguayan Atlantic coast have been focused on reconstructing

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paleosalinity trends related to sea-level variations during the Holocene (García-Rodríguez et al., 2002, 2004a,b, 2010; Bracco et al., 2005; Inda et al., 2006) by analyzing silica remains (diatoms, chrysophyte cysts and opal phytoliths). On the other hand, palynological studies along the eastern coast of the Pampa region (Argentina) (Stutz et al., 2002, 2006; Borel et al., 2003; Stutz and Prieto, 2003; Vilanova et al., 2006a,b; Prieto et al., 2009) and the coastal plains of Rio Grande do Sul (Brazil) (e.g., Cordeiro and Lorscheitter, 1994; Neves and Lorscheitter, 1997; Lorscheitter and Dillenburg, 1998; Werneck and Lorscheitter, 2001) have provided indirect reconstruction of the sea-level and demonstrated that sea-level fluctuations and climate change were the main forcing factors affecting vegetation and coastal environmental changes during the Holocene.

In order to understand past environmental and climate changes in the Río de la Plata estuary coastal salt marsh ecosystems, in this study we present a multiproxy paleoenvironmental record from the marshes of Arroyo Solís Grande in the Río de la Plata northeastern coast (Uruguay), which includes pollen, non-pollen palynomorphs, diatoms and organic matter and carbonate content. This record was compared with a recent published multiproxy record from the Río de la Plata southern coast (Vilanova and Prieto, 2012) to give an overview of vegetation changes in relation to the relative sea-level (RSL) fluctuations and climate variability since 7160  $^{14}\text{C}$  yr BP (ca. 8000 cal yr BP). In addition, a modern pollen–vegetation relationship on the Atlantic coastal salt marshes between 30° and 37° S was compiled and compared with the fossil pollen record to interpret the vegetation changes. The integration of our results with those obtained from other palynological sequences from the coastal plain of the southern Atlantic margin of South America (30°–37° S) gives new insights into the Holocene evolution of the marshes associated with the RSL change, and provides an archive of both local and regional environmental dynamics, offering an overview of the evolution of salt marshes related to the impact of the Holocene sea-level changes.

## 2. Study area

### 2.1. Environmental setting

The Río de la Plata estuary constitutes the final outlet of La Plata Drainage Basin (LPDB), the second largest river system in South America, covering an area of about  $3.2 \times 10^6$  km<sup>2</sup> (Acha et al., 2008). The Río de la Plata is formed by the confluence of the Paraná and Uruguay rivers (Fig. 1) and is about 290 km long, widening from ~40 km at the upper reaches to 220 km at its outlet in the Atlantic Ocean (Pousa et al., 2013). The estuary is characterized by a salt-wedge regime, low seasonality in the river discharge, low tidal amplitude (<1 m), a broad and permanent connection to the sea, and high susceptibility to atmospheric forcing due to its shallowness and increasing width (Acha et al., 2008). Freshwater runoff is not an important contributing factor in estimating extreme levels in the region since floodings are mainly due to combination of tides and surge (D'Onofrio et al., 2008). The estuary is often swept by positive and negative storm surges due to strong southeasterly and northwesterly winds, respectively (D'Onofrio et al., 2008).

From the geomorphological point of view, the term “Río de la Plata” corresponds to a set of genetically interrelated landforms comprising both the subaerial and the subaquatic delta as well as the coastal plains of the northeastern Buenos Aires Province and southern Entre Ríos

Province of Argentina, and reduced estuarine areas of southwestern Uruguay (Fig. 1) (Cavallotto et al., 1999). In Uruguay, marshes partially sealed by dunes are formed at the lower reaches of major rivers that flow into the Río de la Plata. They receive the overflow water from Río de la Plata when the flow exceeds the drainage capacity of the narrow mouths during spring high tides, and are thus intermittently flooded (MTOP, 1980), producing a salinity gradient in the marshes within the riverine estuary. Toward the edges of the marshes, the areas are also flat, but with a gentle slope to the center, with permanent vegetation and drainage channels that drain the water during the sporadic floods. Because of the presence of shallow lakes and marshes, much of the solid materials carried by major streams do not reach the Río de la Plata. They act as sediment traps limiting the sediment supply to the coastal zone.

### 2.2. Climatic features

The atmospheric general circulation in the region is influenced by the South American Monsoon System (SAMS) and the South Atlantic semi-permanent high-pressure cell, both responsible for the transport of considerable moisture over the eastern LPDB and so for the seasonal peak precipitation in austral summer, when the Intertropical Convergence Zone (ITCZ) migrates southward (Vera et al., 2006; Garreaud et al., 2009; Razik et al., 2013). During austral winter, the Southern Westerly Wind Belt (SWWB) extends northward to ~30° S favored by the northerly position of ITCZ. As a consequence, the anticyclones pick up moisture from local air masses and generate precipitation along the eastern LPDB by creating tropospheric instabilities associated with persistent polar fronts (Garreaud et al., 2009; Razik et al., 2013). In addition, studies of ENSO-related rainfall anomalies at a global scale indicate that El Niño episodes are typically associated with anomalously wet conditions in the SE of South America (Garreaud et al., 2009). Another important characteristic of the Río de la Plata region is the development of strong south-easterly winds that during extreme events, locally known as “sudestada”, push its water upstream, causing severe flooding on the Argentine coast (D'Onofrio et al., 2008).

### 2.3. Holocene Río de la Plata estuary evolution background

According to Cavallotto and Violante (2005), the Holocene geomorphological evolution of the Río de la Plata estuary is related to sea-level fluctuations and climate changes after the LGT. The Río de la Plata paleovalley was flooded by the sea during the transgression leading to the formation of the estuarine environment. As sea-level rise progressed, a huge estuary occupied most of the Río de la Plata fluvial valley and most of the lower reaches of the streams that flow into the Río de la Plata. At the same time, in adjacent coastal areas, the shoreline retreated northwestwards. These processes continued until the sea-level reached a maximum stand at ca. 6500 cal yr BP (Cavallotto et al., 2004). During the sea-level fall, coastal progradation became the most important process and a regressive sequence originated. The Paraná delta formed by about 1700 cal yr BP, as a result of the increased fluvial discharge due to changing climatic conditions involving an increase in precipitation. The progradation of the coastal plains led to the current regional configuration and changed the previous estuarine environment to the current river conditions, characterized by the delta development overlying the estuarine system.

**Fig. 1.** a. Location map with core sites (white circles): 1. Werneck and Lorscheitter (2001); 2. Lorscheitter and Dillenburg (1998); 3. Cordeiro and Lorscheitter (1994); 4. Neves and Lorscheitter (1997); 5. García-Rodríguez et al. (2010); 6. This work; 7. Vilanova and Prieto (2012); 8. Vilanova et al. (2006a, 2008); 9. Borel et al. (2003); Stutz and Prieto (2003); Stutz et al. (2002, 2006, 2010). The yellow areas in Río de la Plata and the eastern Buenos Aires Province coast indicate potentially submerged areas during the Holocene RSL maximum. Map obtained from [http://eoimages.gsfc.nasa.gov/images/imagerecords/77000/77581/Uruguay\\_tmo\\_2012091\\_lrg.jpg](http://eoimages.gsfc.nasa.gov/images/imagerecords/77000/77581/Uruguay_tmo_2012091_lrg.jpg), date 23 October 2013. b. Regional geomorphological map (modified from Cavallotto et al., 2004). Inset map: Local geomorphological map of the study area of Arroyo Solís Grande (modified from Prost, 1982; Spoturno and Oyhanctabal, 2004).



Cavallotto et al. (2004) presented a RSL curve for the Holocene based on 14 uncalibrated  $^{14}\text{C}$  dates from 11 sites situated in the southwestern Río de la Plata re-plotted by Gyllencreutz et al. (2010) but using the calibrated ages (Fig. 2). This curve shows rising sea-levels following the LGT, reaching a highstand (+6.5 m) at ca. 6500 cal yr BP followed by a discontinuous regressive trend until the present (Fig. 2). On the other hand, Prieto et al. (in prep.) have proposed another Holocene RSL curve for Río de la Plata estuary from a compilation of 52 calibrated  $^{14}\text{C}$  data from 36 different sites situated along both coasts of the Río de la Plata estuary (Fig. 1). The RSL curve shows that the maximum highstand reached ca. 4 m above the present mean sea-level at 5800–5400 cal yr BP, followed by a gentle decrease toward the present position (Fig. 2). Both sea-level reconstructions show some discrepancies about timing and magnitude of the mid-Holocene highstand and the regressive trend. The latter curve is in close agreement with the Holocene RSL curve for Southern Brazil (Angulo et al., 2006) and the Uruguayan coast (Martínez and Rojas, 2013).

#### 2.4. Salt marsh coastal vegetation

Salt marshes along the coast of southern Brazil, Uruguay and the Pampa region of Argentina are formed in intertidal areas, lagoons and depressions that are seasonally inundated by seawater (Fig. 1). They are characterized by three main plant species which dominate the low- and mid-intertidal salt marshes: *Spartina alterniflora*, *Spartina densiflora* and *Sarcocornia perennis* (Isacch et al., 2006). The distribution of the vegetation is related to soil salinity and topographic position. In particular, the coastal salt marshes between Lagoa dos Patos (southern Brazil) and Laguna Mar Chiquita (southeastern Argentina) (Fig. 1) are characterized by the dominance of *S. densiflora* at the oceanic leading edge of the marshes and brackish marshes covering the inland border (Isacch et al., 2006). The upper vegetation communities spread far from the upper boundary of the tidal level because of the flat topography and salt soils, and there are no clear boundaries between salt and freshwater marsh habitats (Isacch et al., 2014). The dominant species of brackish marshes are mainly represented by *Scirpus maritimus*, *Scirpus americanus*, *Juncus acutus* and *Cortaderia selloana*. Other common associated taxa are in the families of Asteraceae, Polygonaceae and Fabaceae in Lagoa dos Patos; and Apiaceae and Chenopodiaceae in Laguna Mar Chiquita and middle and upper salt marsh of Bahía Samborombón (Isacch et al., 2006).

Particularly in the marshes situated at the lower reach of Arroyo Solís Grande, vegetation is quite heterogeneous. *S. alterniflora* and *S. densiflora* are the dominant species at the riverbank, while in the brackish marsh, *J. acutus*, *Sarcocornia fruticosa*, *Atriplex prostrata* and *Limonium brasiliense* are better represented (del Puerto, 1969; Chebataroff, 1973; Fagúndez and Lezama, 2005). Poorly drained sandy

soils are formed in depressions, where acid and nutrient-poor conditions allow the development of *Sphagnum* sp., *Lycopodiella alopecuroides*, *Drosera brevifolia*, *Utricularia* spp. and *Eryngium* cf. *pandanifolium* (del Puerto, 1969; Alonso-Paz and Bassagoda, 2002; Fagúndez and Lezama, 2005). In addition, there are isolated small patches of woody vegetation such as *Sapium glandulosum*, *Cephalanthus glabratus*, *Erythrina crista-galli*, *Scutia buxifolia* and *Sesbania virgata*.

### 3. Materials and methods

#### 3.1. Sampling and sediment analyses

A 736-cm-long core was retrieved from the marsh in the lower reach of Arroyo Solís Grande (34° 45' 35" S; 55° 25' 55" W; 2 m a.s.l.) using a piston corer, in January 2009, under dry-marsh conditions (Fig. 1). The 63-mm internal diameter core was opened in the laboratory, described in detail and sectioned at 1-cm intervals. Subsamples were analyzed for: (1) pollen and spores; (2) organic-walled dinoflagellate cysts (dinocysts), acritarchs and other non-pollen palynomorphs (all of them referred hereafter as NPPs in the text); (3) diatoms; and (4) organic matter and carbonate content. Organic matter content was measured every 2 cm, while carbonate content was measured on the same levels of the pollen samples studied. Organic matter and carbonate contents were estimated by loss on ignition (LOI), and results are expressed as percentages of weight loss of the sediment related to the dry weight of the samples before combustion (Heiri et al., 2001).

#### 3.2. Palynological analysis

Volumetric subsamples of 2–3 cm<sup>3</sup> were taken with a syringe of 1-cm diameter at predetermined intervals for pollen and NPP analyses. Standard palynological techniques were performed for pollen extraction using KOH, HCl, ZnCl<sub>2</sub> for heavy liquid separation, HF and acetolysis (Fægri and Iversen, 1989). Three *Lycopodium clavatum* spore tablets were added before treatment to calculate pollen concentration (Stockmarr, 1971). Identification of NPPs was based on van Geel (2001), Borel et al. (2003) and Borel (2007), and includes *Botryococcus*, *Pediastrum*, *Zygnemataceae* and *Pseudoschizaea* (algae and cyanobacteria); *Peridinoideae*, *Operculodinium* and *Spiniferites* (dinocysts); and *Mychistridium* and *Cymatiosphaera* (acritarchs). Pollen and spores were identified using atlases and published keys (Markgraf and D'Antoni, 1978; Prieto and Quattrocchio, 1993), and the reference collections at the Laboratorio de Paleocología y Palinología, Universidad Nacional de Mar del Plata, Argentina.

At least 300 pollen grains were counted for most samples, except samples from 28, 67 and 88 cm depth where pollen content was too low. Each pollen type was calculated as the percentage of the total pollen sum. NPPs were calculated as the percentage of the pollen sum plus NPP sum. Bryophytes, Lycophytes and Monilophytes were calculated as percentages of the pollen sum plus spores sum. Vascular plant nomenclature follows the nomenclature system of the Institute of Botany Darwin of Argentina (<http://www.darwin.edu.ar>) and of the Missouri Botanical Garden (<http://www.tropicos.org/>).

Additionally, surface pollen samples from salt marshes along the coast of southern Brazil, Uruguay and the Pampa region of Argentina (30°–37° S) were compiled for this study (Fig. 3), and provided useful information about the relation between modern pollen assemblages and salt marsh vegetation that were used to interpret the fossil pollen assemblages from Arroyo Solís Grande sequence.

#### 3.3. Diatom analysis

Diatom samples were treated with Na<sub>2</sub>P<sub>2</sub>O<sub>7</sub>, 35% HCl and 30% H<sub>2</sub>O<sub>2</sub> (Metzeltin and García-Rodríguez, 2003). A minimum of 300 valves was counted in each sample. Diatom species were identified according to Hasle and Syvertsen (1996), Metzeltin and García-Rodríguez

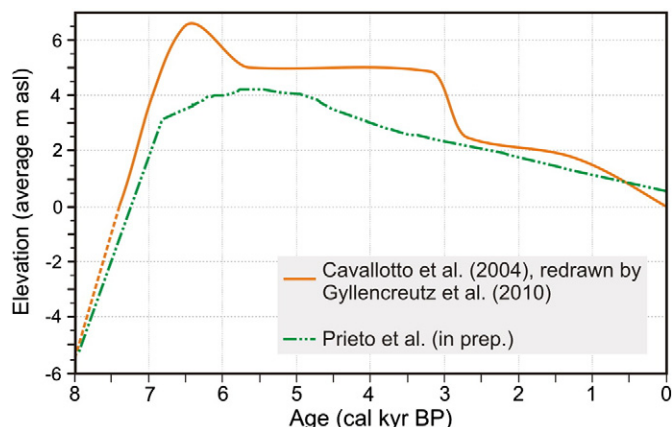
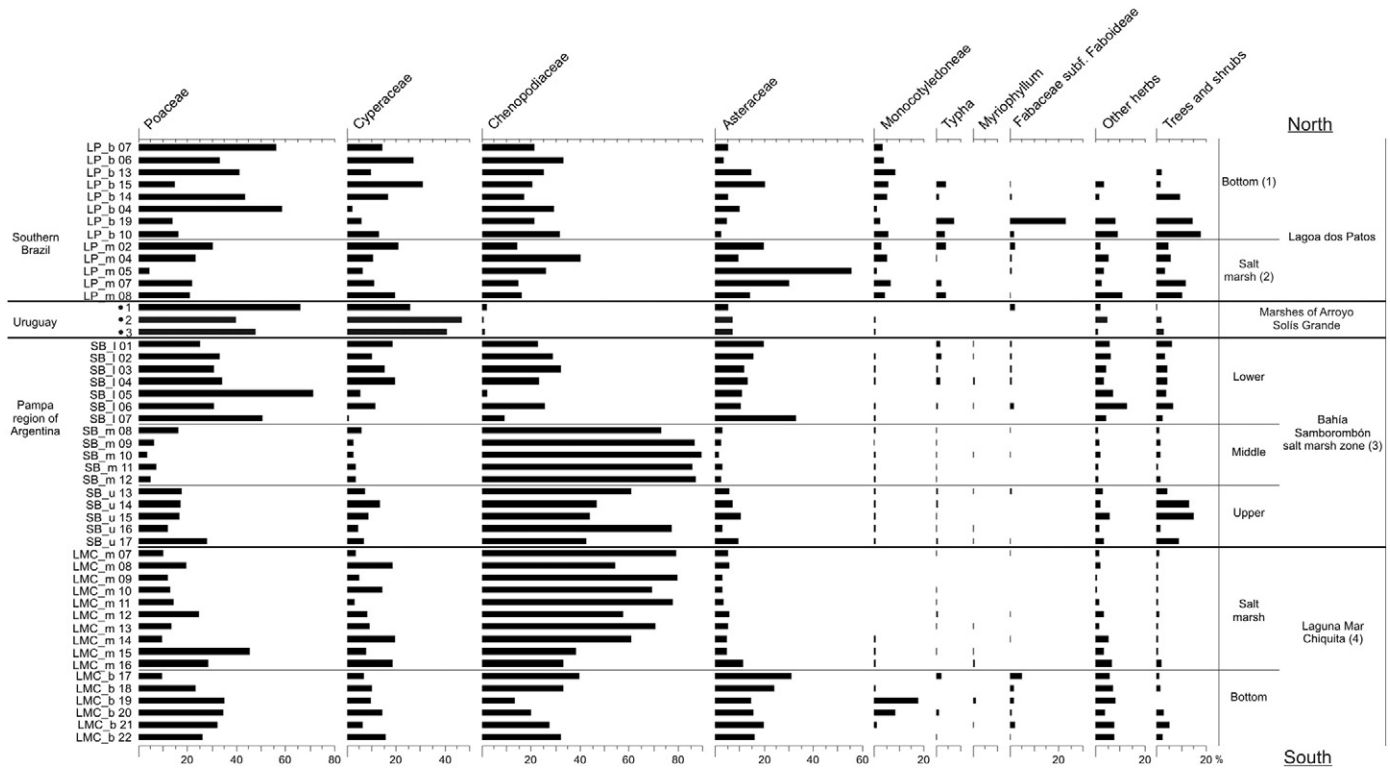


Fig. 2. Curves of RSL variation for the last ca. 8000 cal yr BP for Río de la Plata estuary.



**Fig. 3.** Regional surface pollen percentage diagram according to sample's location (ordinated from north to south) from coastal salt marshes between Lagoa dos Patos (southern Brazil) and Laguna Mar Chiquita (southeastern Argentina). Lagoa dos Patos pollen data are from percentage tables (1: Medeanic et al., 2007; 2: Medeanic, 2006); Bahía Samborombón (3: Vilanova and Prieto, 2012) and Laguna Mar Chiquita (4: Stutz and Prieto, 2003) data are from raw pollen database. Sample numbers are presented as in the original published works. Unpublished samples from Uruguay are showed with black circles.

(2003) and Metzeltin et al. (2005). A total of 30 diatom species was identified.

### 3.4. Numerical analyses

Percentage pollen data were square root transformed prior to numerical analyses in order to stabilize their variances. Palynological and diatom zones (PZ and DZ, respectively) were determined by CONISS stratigraphical constrained cluster analysis (Grimm, 2004), performed on the total pollen sum plus NPP sum, and on the total diatom species, respectively. Diagrams were drawn using TGVView 2.0.4 program (Grimm, 2004).

Pollen Salinity Index (PSI) (modified from Vilanova et al., 2006a) was estimated. PSI represents halophytic pollen types (Chenopodiaceae, *L. brasiliense* and *Ruppia*) as a percentage of halophytic plus hydrophytic pollen types (Amaranthaceae, Cyperaceae, *Myriophyllum* and *Typha*) and freshwater algae. Poaceae was not considered as it does not correspond exclusively to halophytic taxa. Principal Component Analysis (PCA) was performed on modern surface samples and on fossil pollen samples for the variables detailed in Fig. 3, performed with CANOCO version 4.5 program (ter Braak and Šmilauer, 2003).

### 3.5. Chronology

The chronology of Arroyo Solís Grande core is based on five radiocarbon dates, determined on bulk organic matter and shell samples (Table 1). Due to the probability that bulk organic carbon samples may include older, reworked organic matter and the age of the sediment may be overestimates (Nakamura et al., 2012) the combustion of the bulk organic matter samples was done at low temperature (400 °C) in order to omit any clay that could made the sample look older (R. Cruz, written communication, 2013). These bulk organic carbon dates are

considered to represent maximum ages (Compton, 2001). On the other hand, the conventional radiocarbon age is viewed as mean age for the sediment interval sampled required for organic radiocarbon analyses.

Results were calibrated against the Southern Hemisphere curve, SHCal13 (Hogg et al., 2013) using the program Calib Rev. 7.0.2 (Stuiver et al., 2005). Age–depth model was constructed by linear interpolation using Tilia 2.0.4 software (Grimm, 2004). Ages are reported as calendar years before present (cal yr BP) where “present” is defined as 1950 AD. Dates obtained from the age–depth model are rounded to the nearest 100 years without indicating errors.

## 4. Results

### 4.1. Regional modern pollen salt marsh coastal vegetation (30°–37° S)

Surface samples for salt marshes along the coast of southern Brazil, Uruguay and the Pampa region of Argentina (30°–37° S) reveal that Chenopodiaceae, Poaceae, Cyperaceae and Asteraceae are the dominant pollen taxa (Fig. 3). Chenopodiaceae pollen is dominant in the middle and upper salt marsh of Bahía Samborombón and salt marsh of Laguna Mar Chiquita. Brackish marsh vegetation is represented by Fabaceae subf. Faboideae and other herbs (e.g., *Rumex paraguayensis*, *Polygonum neglectum*, *Apium leptophyllum*, *Apium sellowianum*). Trees and shrubs pollen are mainly represented by Palmae, *Alchornea*, Apocymaceae and Anacardiaceae in Lagoa dos Patos (Medeanic, 2006; Medeanic et al., 2007), *Lithraea/Schinus*, *Myrsine*, *Ephedra* and *Dodonaea viscosa* in Uruguay (D. Mourelle, unpublished data) and mainly *Celtis* in the Pampa region (Stutz and Prieto, 2003; Vilanova and Prieto, 2012). Pollen samples from bottom of Laguna Mar Chiquita and Lagoa dos Patos, as well as those from lower salt marsh of Bahía Samborombón, emphasize the role of these sites as a pollen catchment area. Lagoons

**Table 1**  
Radiocarbon dates from Arroyo Solís Grande core.

Sample depth (cm)	Uncalibrated age ( $^{14}\text{C}$ yr BP)	Calibrated age weighted average/cal yr BP (2 $\sigma$ range)	Laboratory no.	Material
111–113	1232 $\pm$ 37	1105 (978–1257)	AA87090 <sup>a</sup>	bulk organic matter
136–137	1294 $\pm$ 39	1177 (1072–1270)	AA99173 <sup>a</sup>	bulk organic matter
166–173	3590 $\pm$ 85	3837 (3614–4084)	URU0530 <sup>b</sup>	bulk organic matter
439–440	5065 $\pm$ 41	5776 (5657–5896)	AA92541 <sup>a</sup>	bulk organic matter
727–728	7160 $\pm$ 30	7950 (7860–8011)	UGAMS 11502 <sup>c</sup>	<i>Heleobia australis</i>

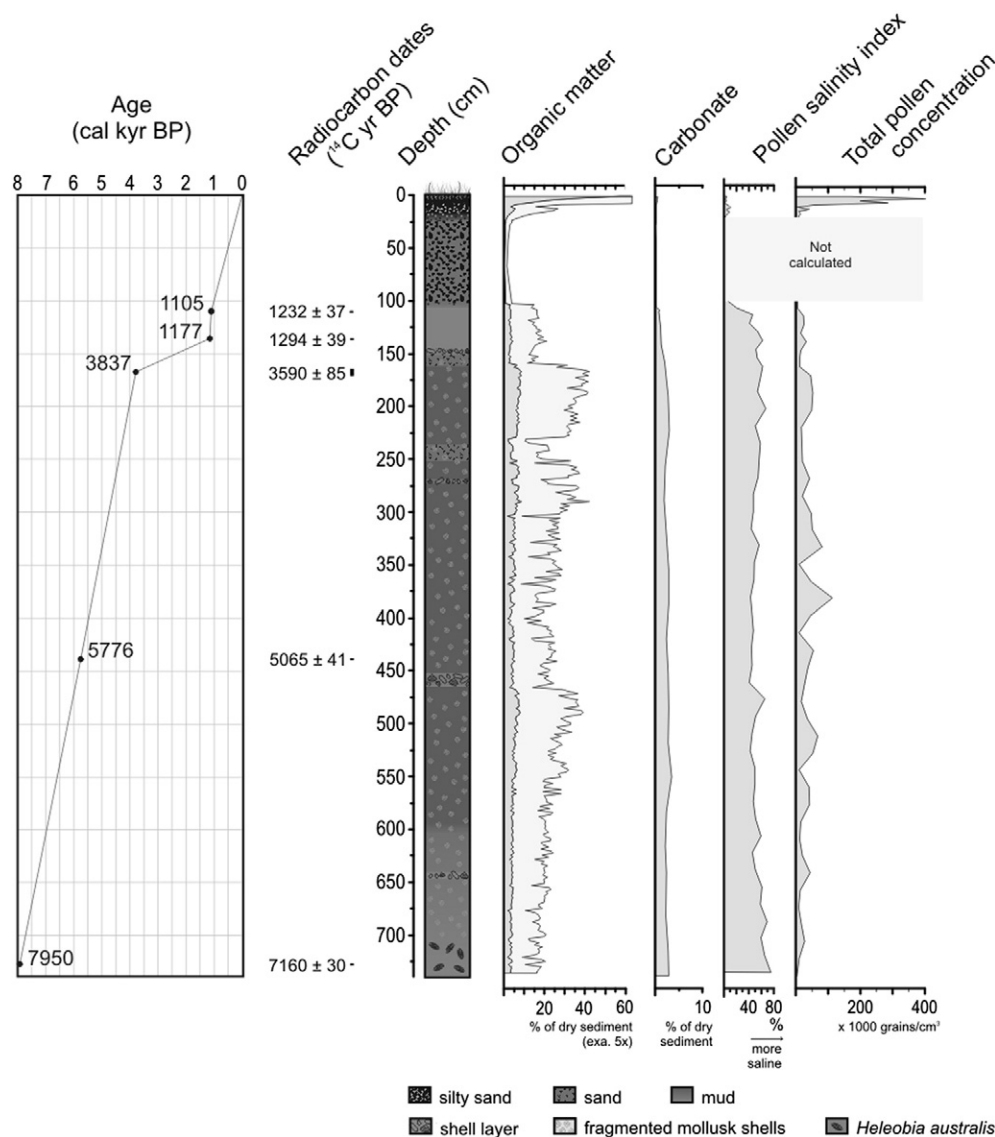
<sup>a</sup> NSF Arizona AMS Facility.  
<sup>b</sup> Conventional date Laboratorio Datación  $^{14}\text{C}$ , Cátedra de Radioquímica, Facultad de Química (UdelaR).  
<sup>c</sup> AMS Center for Applied Isotope Studies (CASI).

and lower salt marshes not only provide pollen from the local vegetation, but also pollen from all the surrounding vegetation transported by wind, in suspension by streams and rivers or redeposited by tides (Stutz and Prieto, 2003; Medeanic et al., 2007; Vilanova and Prieto, 2012). Differences in the bottom pollen assemblages of Lagoa dos Patos have been related to different location of samples within the lagoon (Medeanic et al., 2007).

**4.2. Arroyo Solís Grande sequence**

**4.2.1. Chronology and stratigraphy**

The age–depth model indicates a basal age of ca. 8000 cal yr BP for the sequence, which was divided into five lithologic units, according to changes in sediment composition (Fig. 4; Table 2). Between 736 and 142 cm sediments are greenish gray silty clay with interbedded



**Fig. 4.** Age–depth model curve, sediment description, organic matter and carbonate content on sediments, pollen salinity index, total pollen concentration and radiocarbon dates from Arroyo Solís Grande sequence, plotted against depth.



**Table 2**  
Sedimentary description of the Arroyo Solís Grande core.

Depth (cm)	Sediment characteristics
106–0	Gray silty sand; lowest organic matter and carbonate content overall the core (<1%). Incipient soil develops. Sharp increase in organic matter content (up to 57.5%)
142–106	Gray mud, organic matter ~2.5% and carbonate content ~1%
588–142	Gray silty clay with fragmented mollusk shells; three shell layer at 448–459 cm (fragments of <i>Macra isabelleana</i> , <i>Ostrea</i> sp. and other indeterminable mollusks), 260–268 cm ( <i>Tagelus plebeius</i> and other indeterminable mollusks), and 142–150 cm (fragments of <i>Erodona mactroides</i> and other indeterminable mollusks); two sand layers at 236–246 and 151–159 cm; organic matter content trend to gradually increase toward the top (from 3 to 9%) and the carbonate content is the highest overall the core (<3.5%)
695–588	Dark gray silty clay with fragmented mollusk shells and a layer at 638–642 cm with fragments of <i>Ostrea cf. equestris</i> and other indeterminable mollusks; organic matter ~3% and carbonate content <3%
736–695	Gray compact silty clay with <i>Heleobia australis</i> entire shells without reworking evidence; organic matter ~3% and carbonate content <3%

layers of fine sand, scattered or concentrated shells and relatively high organic matter; these characteristics suggest the sediment to belong to the Villa Soriano Formation (Goso, 1972) (Fig. 4; Table 2). This sedimentary sequence corresponds to: (1) estuarine depositional system of the transgressive system track and (2) the inner estuary depositional systems of the highstand system track (Cavallotto and Violante, 2005). The first sequence was deposited during the transgressive event (between ca. 18,000 and 6000  $^{14}\text{C}$  yr BP). The second corresponds to estuarine environments developed in the lower reaches of major rivers that flow into the Río de la Plata during the regressive event (Cavallotto and Violante, 2005). The top 142 cm correspond to gray mud and gray silty sand (Fig. 4; Table 2). The latter correspond to sandy dunes and marshes where an incipient soil is developed. The deposition of these sediments could be related to the delta formation by

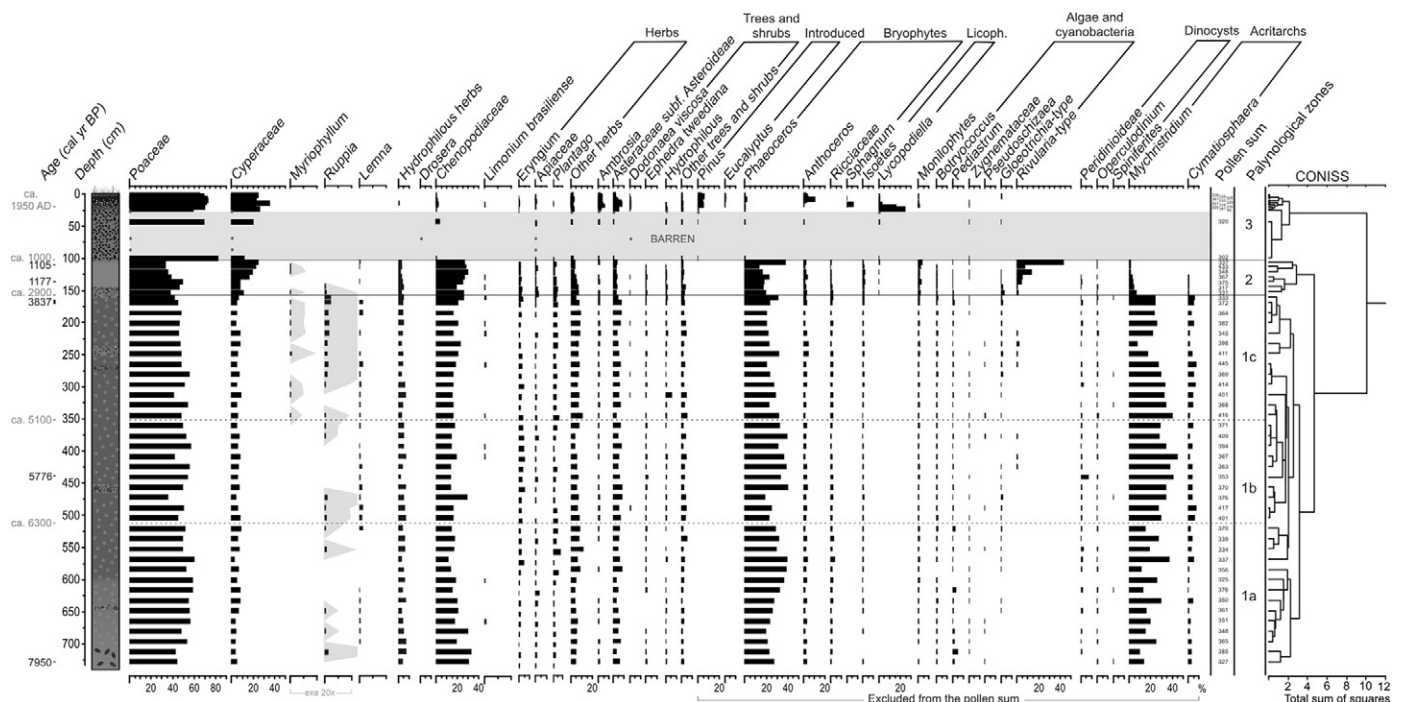
about 1700 cal yr BP, as result of increasing fluvial discharge (Cavallotto et al., 2004; Violante and Parker, 2004).

#### 4.2.2. Palynological zones

Three palynological zones (PZ) are defined based on the CONISS cluster analysis. Subzones were visually established to accommodate distinctive changes in the representation of minor pollen and NPP taxa (Fig. 5; Table 3). PZ 1 (736–156 cm) is characterized by the dominance of Poaceae and Chenopodiaceae, accompanied by Cyperaceae, Asteraceae subf. Asteroideae and hydrophilous herbs. Woody taxa are present. *Phaeoceros* dominates among spores. Algae, cyanobacteria and dinocysts are frequent. In PZ 1a *Mychristridium* shows fluctuating values that increase and stabilize in PZ 1b, where *Ruppia* is frequent. PZ 1c is characterized by the appearance of *Myriophyllum*, high *Ruppia* values and low *Mychristridium*. PZ 2 (156–103 cm) is represented by a similar palynological assemblage that PZ 1, Cyperaceae are high and increase toward the upper part of the zone. *Mychristridium* decreases and *Rivularia*-type increases. PZ 3 (103–0 cm) is characterized by a sharp increase of Poaceae and an abrupt reduction of Chenopodiaceae. *Sphagnum* spores appeared and *Lycopodiella* registered a notable increase. Algae and cyanobacteria decreases.

#### 4.2.3. Diatom zones

Fig. 6 shows the changes in relative abundance of the diatom species, with their salinity requirements. Three diatom zones are defined based on the CONISS cluster analysis. DZ 1 (736–160 cm) is represented almost entirely by the polyhaline tycho planktonic *Paralia sulcata* (mean abundance of 90%). DZ 2 (159–106 cm) is characterized by a striking decrease in the relative abundances of *P. sulcata* and the dominance of the benthic polyhaline *Pseudopodosira echinus*. There is also a significant abundance of mesohaline species. In DZ 3 (105–0 cm), poly and mesohaline diatom species are replaced with oligohaline taxa (both benthic and planktonic). The most abundant diatoms are *Aulacoseira cf. distans*, *Pinularia* spp., *Gomphonema parvulum*, *Anomeoneis seriatis*, *Stauroneis* sp. and *Frustulia rhomboides*. No diatoms were recovered at 1, 6, 10, 24, 28 and 43 cm depth.



**Fig. 5.** Pollen and NPPs percentage diagram and palynological zones. The gray rectangle represents barren samples (the presence of pollen types on those samples are represented by black circles).

**Table 3**  
Description of pollen and NPPs assemblage zones from Arroyo Solís Grande core and paleoenvironmental interpretation.

PZ	Depth (cm)/age (cal yr BP)	Pollen, spores and NPPs characteristics	Interpretation
3	103–0/1000–Present	Sharp increase of Poaceae to its present abundance (~75%) accompanied by Cyperaceae (~25%), abrupt reduction of Chenopodiaceae (~2%), Asteraceae subf. Asteroideae (<8%) and <i>Ambrosia</i> (<6%) increases. Woody taxa also occur (<2%). <i>Limonium brasiliense</i> and <i>Dodonaea viscosa</i> are present in some samples. <i>Pinus</i> (~6%) and <i>Eucalyptus</i> (<1.5%) are present in the upper part of the zone. <i>Phaeoceros</i> reduces notably (<2%); <i>Lycopodiella</i> increases (<32%); <i>Sphagnum</i> appeared (<7%). Algae and cyanobacteria decreases (<0.5%).	About 1950 AD, human modification. Onset of the actual marshes behind the sandy barrier. Dune stabilization.
2	156–103/2900–1000	Dominance of Poaceae (that diminish toward the top of the zone, ~35%) accompanied by Chenopodiaceae (<30%) and Cyperaceae (<25%); Asteraceae subf. Asteroideae and hydrophilous herbs (<4%). Woody taxa also occur (<4%). <i>Limonium brasiliense</i> and <i>Dodonaea viscosa</i> are present. <i>Phaeoceros</i> dominates (<25%); <i>Lycopodiella</i> appeared (<0.5%). Frequent algae and cyanobacteria (<4.5%); dinocysts (<1%); <i>Cymatiosphaera</i> (<1%) and <i>Mychristridium</i> decreases (<7%). <i>Rivularia</i> -type increases notably (<44%).	Brackish marshes on shallow salt pond environments.
1c	350–156/5100–2900	Dominance of Poaceae (up to 60%) and Chenopodiaceae (up to 25%); accompanied by Cyperaceae, Asteraceae subf. Asteroideae (<10%) and hydrophilous herbs (<5%). Woody taxa also occur (<8%). Frequent occurrence of <i>Ruppia</i> (<2%) and <i>Myriophyllum</i> appeared (<1%), <i>Limonium brasiliense</i> and <i>Dodonaea viscosa</i> are present. <i>Phaeoceros</i> dominates (<30%). Frequent algae and cyanobacteria (<4.5%), <i>Rivularia</i> -type is present in some samples; dinocysts (~1.5%); <i>Cymatiosphaera</i> (<8%) and <i>Mychristridium</i> decreases to ~20%.	Brackish marshes around an estuary. Restricted tidal and limited marine influence upstream. Increase of freshwater influence.
1b	512–350/6300–5100	Dominance of Poaceae (up to 60%) and Chenopodiaceae (<20%); accompanied by Cyperaceae, Asteraceae subf. Asteroideae (<10%) and hydrophilous herbs (<5.5%). Woody taxa also occur (<8%). Occurrence of <i>Ruppia</i> (<1%). <i>Phaeoceros</i> dominates (<40%). Frequent algae and cyanobacteria (<4.5%), <i>Rivularia</i> -type is present in some samples; dinocysts (~1.5%); <i>Cymatiosphaera</i> (<8%) and <i>Mychristridium</i> values increase up to 45%.	Salt marsh (dominated by <i>Spartina</i> sp.) around an estuary. Stabilization of tidal regime. Higher marine influence.
1a	736–512/8000–6300	Dominance of Poaceae (up to 60%) and Chenopodiaceae (10–35%); accompanied by Cyperaceae, Asteraceae subf. Asteroideae (<10%) and hydrophilous herbs (<6%). Woody taxa also occur (<5%). <i>Phaeoceros</i> dominates (20–40%). Frequent algae and cyanobacteria (<6%); dinocysts (~1.5%); <i>Cymatiosphaera</i> (<6%) and <i>Mychristridium</i> with fluctuating values (10–35%).	Salt marsh (dominated by <i>Spartina</i> sp. and Chenopodiaceae) around an estuary. Influence of the tides in the outer estuary zone.

#### 4.3. Relationship between fossil and modern pollen assemblages

The first two PCA-axes account together for 45.3% of the total variance (Fig. 7). The first axis ( $\lambda_1 = 25.3\%$ ), splits the samples according to their proportion of Chenopodiaceae, Cyperaceae and Poaceae versus the other variables. On the second axis ( $\lambda_2 = 20\%$ ) samples are grouped according to their proportion of Chenopodiaceae versus Poaceae and Cyperaceae. As a result, fossil samples are separated into two clusters: one that contains samples from PZ 1, PZ 2 and the lower salt marsh zone of Bahía Samborombón and the bottom of the Laguna Mar Chiquita; and the other one which consists of samples from PZ 3 and modern marsh of the Arroyo Solís Grande lower reach.

### 5. Discussion

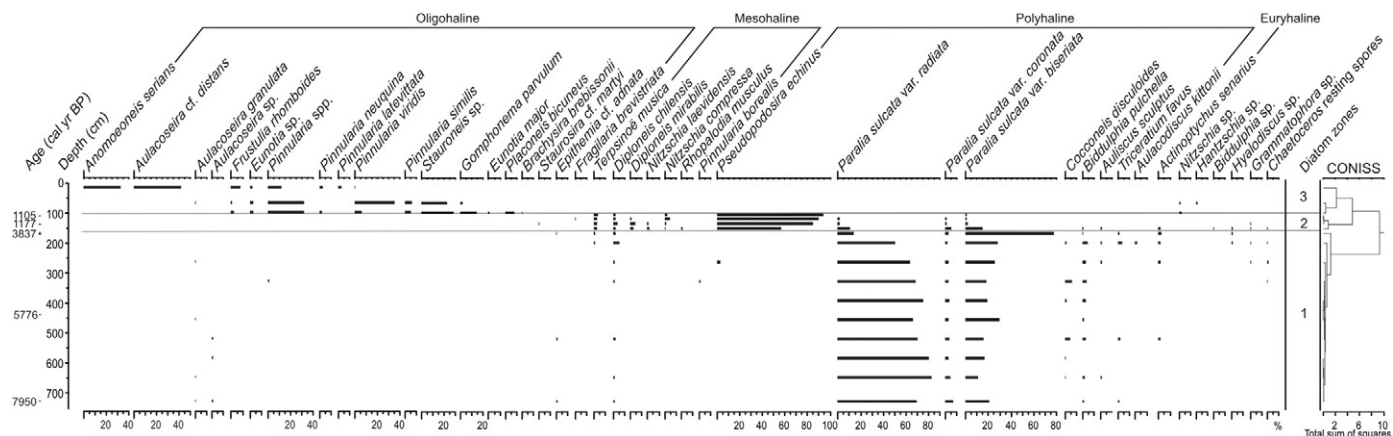
#### 5.1. Paleoenvironmental reconstruction

Fossil pollen assemblages from ca. 8000 to 1000 cal yr BP are comparable with both surface samples from the Bahía Samborombón lower

salt marsh zone and samples from the bottom of Laguna Mar Chiquita (Fig. 7), suggesting the development of salt marsh vegetation. Both organic matter content and total pollen concentration fluctuate (Fig. 4), probably due to different rates of sediment deposition. On the other hand, PSI values indicate relatively high salinity conditions during this period (Fig. 4). The pollen assemblages from the last ca. 1000 cal yr BP are similar to those of the surface samples from the modern marsh of the Arroyo Solís Grande lower reach (Fig. 7). This is also supported by the abrupt decreases of PSI values that indicate low salinity related to the complete onset of the sand bar that isolated the marsh area. The increase in organic matter and the total pollen concentration to the top support the soil development (Fig. 4).

Pollen, NPP and diatom analyses allowed us to determine three major periods of paleoenvironmental changes (Figs. 5 and 6):

1. From ca. 8000 to ca. 2900 cal yr BP (PZ 1; DZ 1), estuarine conditions were inferred by: (1) the dominance of the marine brackish diatom *P. sulcata*, which tolerates salinity ranges between 15 and 22 (Hassan et al., 2009); (2) the high values of the acritarchs *Mychristridium* and *Cymatiosphaera*, frequent in modern inter- to



**Fig. 6.** Diatom percentage diagram, and diatom zones.



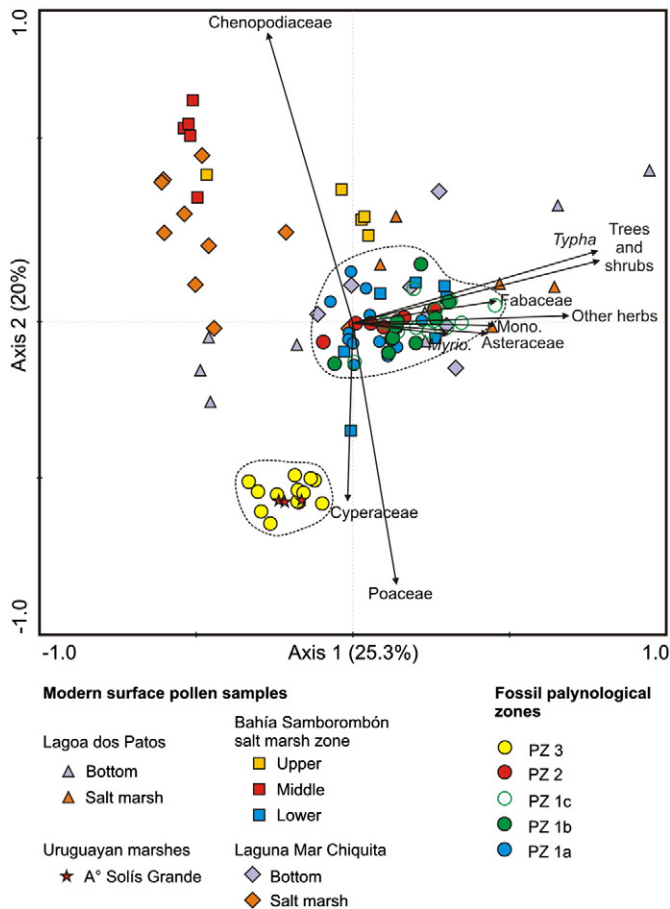


Fig. 7. PCA distance biplot of the taxa and combined regional modern surface (see Fig. 3) and fossil pollen percentage data. Mono.: Monocotyledoneae; Myrio.: Myriophyllum.

sub-tidal estuary zones (Grill and Guerin, 1995); and (3) the euryhaline dinocysts *Operculodinium* and *Spiniferites*, distributed within a very wide range of environmental variables (temperature, salinity and nutrients) in recent marine sediments (Rochon et al., 1999; Marret and Zonneveld, 2003). High acritarch values (up to 45%) may indicate that the sampling site was probably situated in the outer estuary zone, taking into account that acritarchs never reach more than 8% in the lower salt marsh zone of Bahía Samborombón (Vilanova and Prieto, 2012) or in the salt marsh and bottom of Lagoa dos Patos (Medeanic, 2006; Medeanic et al., 2007). In addition, dinocysts represented by a few eurytopic cosmopolitan forms are able to tolerate stressful conditions characteristic of estuarine environments. Percentages of *Chenopodiaceae* pollen are lower than those of both the middle and upper salt marshes of Bahía Samborombón and the salt marsh of Laguna Mar Chiquita modern samples. Such a difference may be related to the longer distance of the sampling site from the estuary edge. *Chenopodiaceae* are well represented if locally present; however, pollen values decline rapidly with distance from the source (Stutz and Prieto, 2003). *Poaceae* dominate the pollen assemblage and are better represented in places where *Spartina* sp. grows in the salt marsh (Fig. 5). The freshwater influence is indicated by algae and cyanobacteria. Peridinioid cysts suggest the presence of a low-energy brackish or brackish/freshwater body neighboring the marsh, away from the tidal influence (Borel et al., 2003; Borel, 2007). *Phaeoceros*, *Anthoceros*, *Ricciaceae* and *Isöetes* spores, as well as woody taxa and herbs, suggest the occurrence of runoff transported from the hinterland source area to the estuary. These spores might not be local as they are not recorded on surface samples from coastal vegetation (Mourelle and Prieto, 2012). Moreover,

taking into account that hydrophilous woody taxa (*Cephalanthus*, *Salix*, *Sapium* and *Sebastiania*) and other trees and shrubs (*Ephedra tweediana*, *Celtis*, *Lithraea*/Schinus and *Myrsine*), mostly entomophilous, show higher percentages than those of the surface grassland samples of the campos region in Uruguay (Mourelle and Prieto, 2012), it may be expected that such pollen taxa entered the estuary via fluvial processes. This interpretation involves the development of riparian forest patches near the salt marsh since ca. 8000 cal yr BP, close to the Río de la Plata northern coast.

A series of relatively long-term environmental changes are recorded during this period:

- 1.1. Between ca. 8000 and 6300 cal yr BP (PZ 1a), the high and fluctuating percentages of acritarchs (Fig. 8) might be related to the influence of the tides in the outer estuary during the transgression. The record of *Heleobia australis* at ca. 8000 cal yr BP indicates that marine influence reached a longer distance into the upper reaches of Arroyo Solís Grande than it does at present (Fig. 9). This species inhabits low energy environments such as estuarine and coastal lagoons (Carcedo and Fiori, 2012), or marine-influenced salt marshes with reduced freshwater inputs (Canepuccia et al., 2007). These proxies suggest enhanced input of marine water related to an increase in RSL (Fig. 8). At the southern margin of the Río de la Plata, middle marsh prevailed between 8500 and 7800 cal yr BP with progressive tidal influence after 7800 cal yr BP with the development of a low marsh with longer tidal submergence, higher inundation frequency and higher energy in intertidal-subtidal estuarine environment (Vilanova and Prieto, 2012). This halophytic vegetation developed ca. 30 km away from the present Bahía Samborombón coastline (site 7, Fig. 1; Vilanova and Prieto, 2012) in an open coastal environment (Violante et al., 2001).
- 1.2. From ca. 6300 to 5100 cal yr BP (PZ 1b), acritarch values slightly higher and more stable than those of the previous period (Fig. 8) could be related to a stabilization of tidal regime and a higher marine input. This interpretation is in agreement with a sea-level highstand (+4 m) at ca. 5800–5400 cal yr BP instead of a sea-level fall (Fig. 8). Landward migration of the littoral environments occurred during this period; the shoreline of the coastal areas reached the maximum retreat (Cavallotto et al., 2004) and the brackish water interface of the Río de la Plata was displaced about 300 km westwards (Martínez et al., 2006). Northwestwards, littoral drift dominated, originating the development of beach ridge systems and the transformation of the protected areas behind them into tidal plains and marshes (Cavallotto and Violante, 2005). At the southern margin of the Río de la Plata (site 7, Fig. 1), low marsh brackish grasses related to sea-level highstand developed in an estuary which extended more than 25 km inland from the present coast and developed during ca. 1000 yr (Vilanova and Prieto, 2012). Proxy records suggest highest marine input and mixohaline conditions at ca. 6200–5500 cal yr BP in the area (Vilanova and Prieto, 2012), thus indicating changes of regional nature.
- 1.3. After ca. 5100 cal yr BP (PZ 1c), the appearance of the low salinity-tolerant *Myriophyllum*, the increase in *Ruppia* values and the declining trend of *Myristidinium* (Fig. 5) reflect increased freshwater input and decreased salinity derived from the transition from brackish to freshwater conditions. These conditions are in agreement with the direction of environmental change indicated by the increase in mesohaline diatoms (Figs. 6 and 8). *Ruppia* represents *Ruppia maritima*, a submerged macrophyte that currently occurs in temporarily to permanently flooded mesohaline–hyperhaline estuarine wetlands, and that is best adapted to stable water levels (Kantrud, 1991). This suggests less turbid waters that allow more light penetration for *Ruppia* proliferation (Bermejo and de Zayas, 2009). During this time, the RSL curves show both a

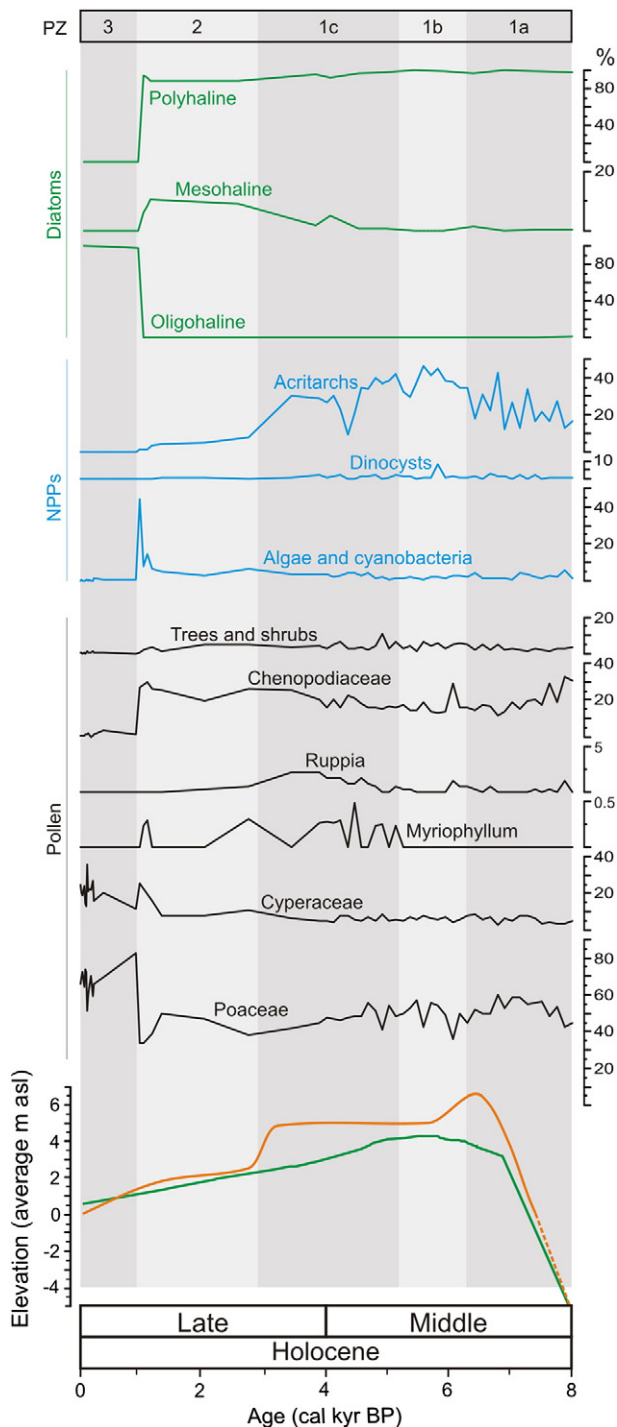


Fig. 8. Summary pollen, NPPs and diatom percentage diagram, plotted against calibrated age scale (cal yr BP), and Río de la Plata RSL curves (see Fig. 2). PZ: palynological zones.

gentle decrease and a period of stabilization (Fig. 8), and coastal progradation became the most important process in the Río de la Plata and adjacent inner shelf (Cavallotto et al., 2004). Our data agree with a slow sea-level decrease instead of a period of stabilization, but also with the RSL curve for Southern Brazil (Angulo et al., 2006) and the Uruguayan coast (Martínez and Rojas, 2013). The progradation of local-scale sand bars partially encloses the Arroyo Solís Grande mouth, thus restricting the marine influence upstream, which led to a decrease in the brackish water input and stimulated the development of marshes (Fig. 9). Due to the regressive event, floodplains were

gradually exposed thus favoring the development and gradual expansion of brackish marsh vegetation, represented by the occurrence of *L. brasiliense* and an increase of Chenopodiaceae (Fig. 5). *D. viscosa* appears in many samples, reflecting the development of psammophilous coastal vegetation on the sand bars. However, we cannot dismiss increased freshwater input related to the increased precipitation over the LPDB, which has become more evident since ca. 4000 cal yr BP, due to SAMS intensification and the increased ENSO variability (Razik et al., 2013). At the southern margin of the Río de la Plata (site 7, Fig. 1), a transition from low marsh brackish grasses to high marsh halophytic community occurred between ca. 5500 and 4800 cal yr BP, followed by a transition to brackish marsh vegetation at ca. 4800 cal yr BP with weaker estuarine conditions (Vilanova and Prieto, 2012) related to the regressive event and littoral ridge progradation (Violante et al., 2001; Fucks et al., 2010). This reflects similar vegetation evolution on both Río de la Plata estuary coasts.

2. Around ca. 2900 cal yr BP (PZ 2, DZ 2), a reduction in the estuary area is suggested by the sharp decrease of *Mychistridium*, *Cymatiosphaera* and *P. sulcata*, the latter being replaced by *P. echinus* accompanied by a mesohaline diatom assemblage (Figs. 5, 6 and 8). *P. echinus* is currently found in salt pond environments with a salinity optimum of 20 (Tanimura and Sato, 1997; Hermany et al., 2013). Additionally, the gradual water-level fall is reflected by the progressive increase in *Rivularia*-type, a periphyton alga closely related to emergent vegetation and a reliable indicator of shallow water levels (<30 cm) (Rayó, 2011) which is rarely observed in estuarine environments (Medeanic et al., 2008). The disappearance of *Ruppia* suggests restrictive conditions such as turbid water or less brackish water. At about 3000–2000 cal yr BP, the ENSO-amplitude was further enhanced, causing higher precipitation over LPDB during El Niño years and thus increasing the Paraná River discharge, which favored sediment transport to the western South Atlantic (Gyllencreutz et al., 2010; Razik et al., 2013). This is concomitant with the mud deposition indicating a low sediment deposition rate (Fig. 4) related to the displacement of the fresh–salt water interface (turbidity front) of the Río de la Plata near the present position (Fig. 1), related to intense deposition of the Paraná River and the Paraná delta formation by ca. 1700 cal yr BP (Cavallotto and Violante, 2005). This mud input originated the outer submersed bar of the Río de la Plata, referred to as *Barra del Indio* shoal and the muddy tidal flat of Bahía Samborombón (Cavallotto and Violante, 2005). The water-level reduction related to the sea-level fall and the sand bar formation generated protected areas behind barriers with stagnant shallow waters that favored the development of halophytic communities represented by Chenopodiaceae and Poaceae (Figs. 8 and 9). The increase of Cyperaceae and the appearance of *Lycopodiella* suggest the formation of marshes similar to the present ones. At the southern margin of the Río de la Plata, the proxy record located far away from the Bahía Samborombón shoreline (site 7, Fig. 1) suggests the absence of marine influence and freshwater to brackish conditions (Vilanova and Prieto, 2012). This is related to a wide paleo-Bahía Samborombón in which new beach ridges began to spread in decreasing levels toward the coast (Violante et al., 2001).
3. After ca. 1000 cal yr BP (PZ 3, DZ 3), the development of salt marshes and brackish marshes was interrupted by the complete establishment of the sand bar that almost isolated the area behind it with only narrow inlets to Río de la Plata waters (Fig. 9). The significant change in both pollen and diatom assemblages (Figs. 5 and 6), the organic matter content and the lithology (Fig. 4) suggest a high sediment deposition rate rather than a hiatus in the sequence. The low total pollen concentration in some samples could be related to such a high sand sedimentation rate. Thereafter, the pollen assemblage reveals the dune stabilization by Poaceae, Asteraceae subf. Asteroideae, *Ambrosia* and *D. viscosa*. The dune stabilization allowed

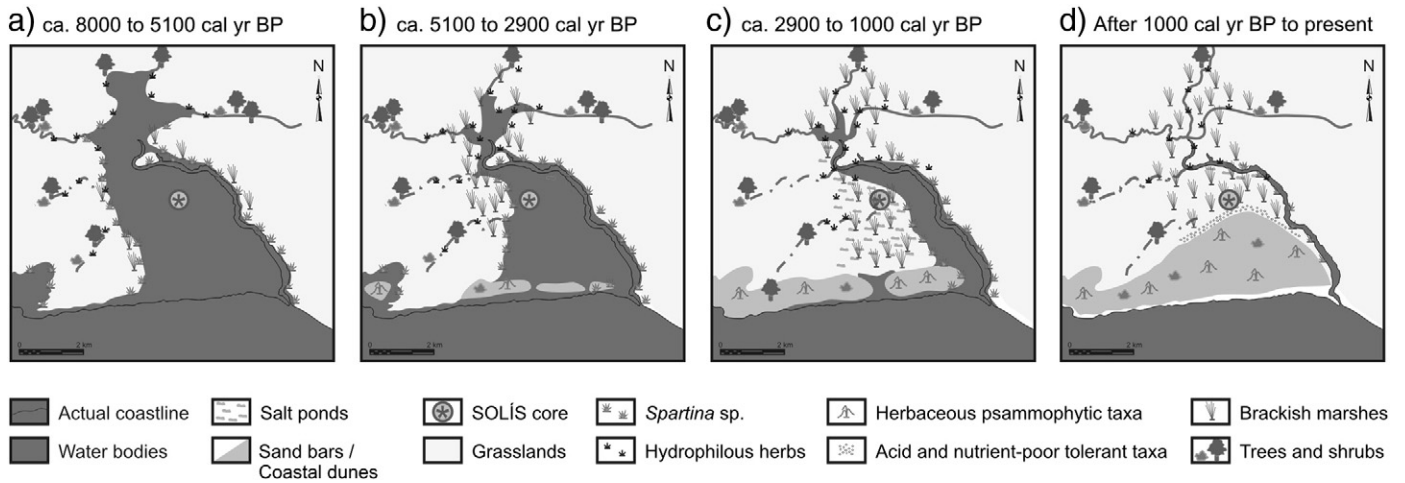


Fig. 9. Schematic representation of the Arroyo Solís Grande marsh vegetation evolution according to the sea-level variation during the last ca. 8000 cal yr BP.

the onset of the modern marshes of Arroyo Solís Grande (Fig. 9). The formation of the sand bar could be related to the formation of the Paraná delta as a result of increasing fluvial discharge (Cavallotto and Violante, 2005). In addition, in some samples of DZ 3, diatoms were absent, which indicates that the area might have become dried up and re-filled respectively. Simultaneously, in a location far from the present Bahía Samborombón shoreline (site 7, Fig. 1), marine influence is absent and grassland vegetation develops (Vilanova and Prieto, 2012).

The human modification of the Arroyo Solís Grande area is indicated by *Pinus* sp. and *Eucalyptus* sp. alien species, concurrently with the decrease of *Sphagnum* and *Lycopodiella* spores since ca. 1950 AD.

## 5.2. Comparison with other records between 30° and 37° S

In order to highlight the regional character of the Río de la Plata estuary and the environmental evolution associated with eustatic and climatic forcing factors, we compared our results with those obtained from other palynological sequences from the coastal plain of the southern Atlantic margin of South America between 30° and 37° S (Fig. 10).

During the mid-Holocene, paleoclimatic conditions in the region were controlled by a more northward average position of the ITCZ (Haug et al., 2001). As a result, ENSO intensity was weaker, and so there was less discharge through the Paraná River system (Gyllencreutz et al., 2010). During this period, due to sea-level highstand (Fig. 2) and stabilization of the Río de la Plata, LPDB sediments would have been

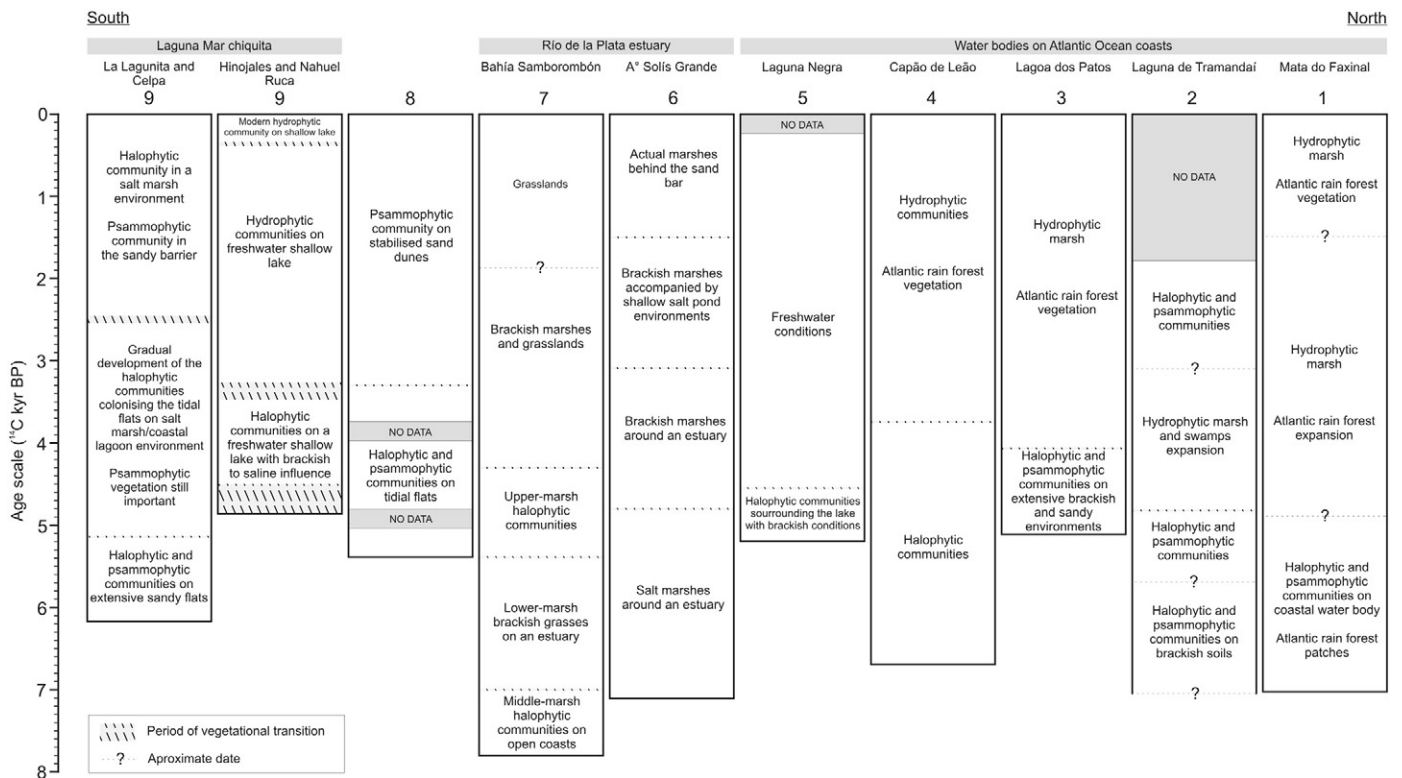


Fig. 10. Summarized vegetational changes between 30° and 37° S: 1. Werneck and Lorscheitter (2001); 2. Lorscheitter and Dillenburg (1998); 3. Cordeiro and Lorscheitter (1994); 4. Neves and Lorscheitter (1997); 5. García-Rodríguez et al. (2010); 6. This work; 7. Vilanova and Prieto (2012); 8. Vilanova et al. (2006a, 2008); 9. Borel et al. (2003); Stutz and Prieto (2003); and Stutz et al. (2002, 2006, 2010).



trapped in the estuary (Violante and Parker, 2004) and halophytic communities developed on their coasts. Psammophytic and halophytic communities develop on extensive tidal sand flats in the Laguna Mar Chiquita coastal area (site 9, Figs. 1 and 10), as well as around Río Grande do Sul (RGS) coastal water bodies (sites 1 and 2, Figs. 1 and 10). Consequently, despite some temporal offset, the similar vegetation communities across the region during this period reflect higher brackish influence as a consistent regional response to marine influence.

At about 5000 cal yr BP, the ITCZ shifted southwards (Haug et al., 2001; Wanner et al., 2008). As a consequence, SAMS intensified over SE South America and the onset of modern type of ENSO variability was established at ca. 4000 cal yr BP, when the increase in precipitation in LPDB became more evident (Gyllencreutz et al., 2010; Razik et al., 2013). This fact could be responsible for the increased freshwater input in the area, which, together with the gradual RSL decrease, would have favored the development of brackish marshes on the Río de la Plata coasts. At this time, psammophytic and halophytic communities still develop on Laguna Mar Chiquita coastal area (site 9, Figs. 1 and 10), southern Bahía Samborombón (site 8, Figs. 1 and 10), the Atlantic coast of Uruguay (site 5, Figs. 1 and 10) and southern RGS (sites 3 and 4, Figs. 1 and 10). The effects of increasing precipitation on LPDB are also reflected by the development of hydrophytic marsh communities and the development of Atlantic forest on the northern RGS coast (sites 1 and 2, Figs. 1 and 10).

At about 3000 cal yr BP, the ENSO amplitude was further enhanced, causing increased precipitations over LPDB and Paraná River discharge during El Niño years (Gyllencreutz et al., 2010). The RSL continues to decrease (Fig. 2), while the Paraná delta started to form at ca. 1700 cal yr BP, as a result of the increasing fluvial discharge and sediment transport (Cavallotto et al., 2004; Violante and Parker, 2004). This agrees with our data at the Arroyo Solís Grande lower reach, where the present marshes behind the sand bar were developing. However, overall, differences related to the location of each sequence with respect to the coastline position during the Holocene are observed in the region. The continuous sea-level fall to its present position affected each sub-region differently, related to the geomorphology, and the establishment of the modern plant communities occurred at different times during the late Holocene. At the Laguna Mar Chiquita coastal area, halophytic communities develop in a salt marsh environment and psammophytic communities in sand bars (site 9, Figs. 1 and 10), while in water bodies farther from the coastline hydrophytic communities develop (site 9, Figs. 1 and 10). Southwards at Bahía Samborombón, psammophytic communities develop on established sand dunes (site 8, Figs. 1 and 10). Nevertheless, on the Uruguayan and RGS coasts, hydrophytic marshes and freshwater conditions on coastal water bodies, as well as the establishment of Atlantic forest in RGS, are inferred during this period (sites 1, 3, 4 and 5, Fig. 1). Particularly, Lorscheitter and Dillenburg (1998) (site 2, Fig. 1) observed the development of psammophytic and halophytic communities similar to those described for the Argentine coast. However, according to the authors, such communities would correspond to a new transgression over RGS coastal plains which would have taken place at ca. 1800 yr BP (−1.5 m a.s.l.).

## 6. Conclusions

This study enhances our understanding of the paleoenvironmental framework of the Río de la Plata estuary area by yielding new information on vegetational and environmental changes. The comparison of fossil pollen records with a regional modern pollen–vegetation model from Atlantic coastal salt marshes between 30° and 37° S improves the reconstruction of marsh vegetation evolution in the northeastern Río de la Plata coast since ca. 8000 cal yr BP. The main events characterizing the paleoenvironmental changes include: (i) the development of salt marsh vegetation around the estuary as the sea-level rose between 8000 and 6300 cal yr BP; (ii) the stabilization of the tidal regime and an increasing input of marine water related to the Holocene sea-level

maximum between 6300 and 5100 cal yr BP; (iii) the development of brackish marshes around the estuary related to the Holocene sea-level fall coupled with increasing input of freshwater associated with an increase in precipitation over the LPDB between 5100 and 2900 cal yr BP; (iv) the development of brackish marsh and shallow salt pond environments between 2900 and 1000 cal yr BP linked to the displacement of the turbidity front of the Río de la Plata near the present position in relation to the intense deposition of the Paraná River and the Paraná delta formation by ca. 1700 cal yr BP; and (v) the development of the present-day marshes after ca. 1000 cal yr BP, due to the complete establishment of the sand bar that almost isolated the Arroyo Solís Grande lower reach area. Pollen assemblages indicate the development of riparian forest patches near the salt marsh since ca. 8000 cal yr BP, close to the Río de la Plata northern coast.

Analysis of NPP curves in conjunction with those of salt marsh vegetation (e.g., Poaceae, Chenopodiaceae, Cyperaceae) provided a good indication of sea-level changes and environmental processes that occurred in the Río de la Plata coastal area. Such reconstruction shows that palynomorphs and diatoms from salt marsh records can be used as biological tide gauges. NPPs appear to be a reliable proxy for the study of coastal sediments, and were a great complement for the pollen analysis.

The regional modern pollen–vegetation model demonstrates that the salt marsh vegetation of southeastern South America is reflected in the pollen assemblages by the co-dominance of Poaceae and Chenopodiaceae, accompanied by Cyperaceae and Asteraceae and different trees and shrubs according to the latitude location. These represent the main local plant communities and show that they might be a good proxy for RSL changes, not only for temperate coasts but also for mangrove ecosystems (Urrego et al., 2013).

Comparison of the palynological records from the Río de la Plata estuary with those from the coastal plain of the southern Atlantic margin of South America (30°–37° S) reveals that marine influence during the period of maximum sea-level highstand strongly influenced the development of similar vegetation in the region. However, local differentiation after ca. 3000 cal yr BP related to the climate and geomorphology occurs at each area, and so the establishment of the different modern plant communities occurred at different times during the late Holocene.

## Acknowledgments

This research was supported by grants of CONICET (PIP 1265/09) and Universidad Nacional de Mar del Plata (Exa 15/E550) to A.R.P., PEDECIBA and SNI-ANIL. We thank I. Vilanova and S. Stutz for providing modern pollen data from Bahía de Samborombón and Laguna Mar Chiquita, respectively; C.G. de Francesco for the gastropod identification; and D. Panario and R. Bracco for their support during the field work. V. Markgraf provided valuable comments on an early version of the manuscript. We thank R. Bracco for dating sample URU0530, the (NSF)-Arizona AMS Facility and T. Jull for financial support for dating, and to the anonymous reviewers for suggested improvements of the manuscript.

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