Salt marsh palynological assemblages as modern analogue tools for interpreting past vegetation zones and environmental conditions in the NE coastal plain of Argentina

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A B S T R A C T

In this study we examine the distribution patterns of modern palynological assemblages from different salt marsh zones and microenvironments in order to generate reference data for the north-central sector of Bahía Samborombón, to be used as analogues for interpreting fossil palynological assemblages. For the modern palynological analysis, 23 surface sediment samples were taken from different tidal environments in the coastal zone, including intertidal, low, middle and high salt marsh. The results allowed to differentiate and characterize the tidal environments from the palynological point of view. Small changes in the microrelief such as tidal channels, cheniers, and depressions areas, modify the local vegetation and therefore determine the final palynological assemblage. Fossil data from the central zone of Bahía Samborombón (PM 1 stratigraphic sequence) was compared with the modern pollen data to interpret vegetation and paleoenvironmental changes; which demonstrated that salinity, mainly related to the tidal influence, drove the paleoenvironmental changes. This study provides new modern palynological data for Bahía Samborombón and may constitute an important tool to interpret Holocene fossil sediment sequences. This data could be used in future paleoenvironmental reconstructions in coastal plain deposits whose evolution are linked to relative sea-level fluctuations.

1. Introduction

The study of palynological assemblages in modern sedimentary environments is important for the understanding of the modern pollen-vegetation relationship. The analysis of the modern assemblages can also include non pollen palynomorphs (NNP) as indicators for different environmental conditions, particularly in salt marshes (e.g. spores, acritarchs, dynocists, among others). The pollen-vegetation model shows how the vegetation and the corresponding environmental conditions are reflected by the palynological spectra and the spatial distribution. Therefore, it can be a useful analogue to be compared with fossil pollen assemblages to reconstruct past vegetation and environmental conditions (e.g. Birks and Birks, 1980; Prieto, 1992; Stutz et al., 2002; Medeanic et al., 2016).

In the development of the modern analogue the complex interaction of factors that condition the representation of vegetation in the pollen assemblages should be taken into account, as well as the representation of non-vascular plants, fungi, and algae. Among these factors are: (1) pollen productivity related to the type of pollination; (2) dispersion and transport processes (aerial, aquatic fluvial-marine); (3) depositional and post-depositional processes such as re-suspension and/or re-sedimentation (biostratinomical processes), and re-work (diagenetic process) by eolian and/or aquatic agents. All these factors cause the absence, under-representation, and/or over-representation of the pollen types.

The palynological analysis contributes to interpret the paleoenvironmental conditions with high precision, mainly if those specific NPPs indicators of ecological conditions are recorded, such as dinoflagellate cysts and colonial algae; whose changes in abundance are related to the dynamic of the sedimentary systems and the sea-level change in littoral environments (Grindrod, 1988; García-Moreiras et al., 2015).

For the Argentinian, Uruguayan and Brazilian coastal plains, several

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models concerning the relationships of modern pollen-vegetation have been developed. These models allow the recognition of the vegetation changes and the paleoenvironmental conditions related to the sea-level fluctuations and the climatic variability during the Holocene (e.g. Grill and Guerstein, 1995; Stutz and Prieto, 2003; Fontana, 2005; Medeanic, 2006; Vilanova and Prieto, 2012; Masciardi et al., 2013; Mourelle et al., 2015; Medeanic et al., 2016). Specifically, the palynological model developed along a transect in the lower section of the Salado River (Buenos Aires Province; Fig. 1. A) showed the salt marsh pollen zones that was compared with its fossil palynological counterpart. This comparison demonstrated that vegetation and environmental changes during the Holocene were mostly related to sea-level fluctuations.

Here we present the modern palynological spectra from four salt marsh areas located at the northeastern coastal plain of Argentina (Bahía Samborombón), whose wetlands have been declared RAMSAR sites. The aims of this study are: (1) to examine patterns of pollen deposition across

different salt marsh zones including tidal environments in order to generate a modern reference data for the north-central- sector of Bahía Samborombón; (2) to establish the representation of vegetation distribution based on the palynological assemblages along four transects perpendicular to the coast, encompassing the different salt marshes zones and microenvironments originated by microrelief variations and (3) to illustrate the use of modern palynological assemblages for the paleoenvironmental interpretation of the Bahía Samborombón coastal plain.

2. Study area

2.1. General description

Bahía Samborombón is a wide bay -about 150 km of shoreline- located in the northeastern coastal area of Buenos Aires Province,
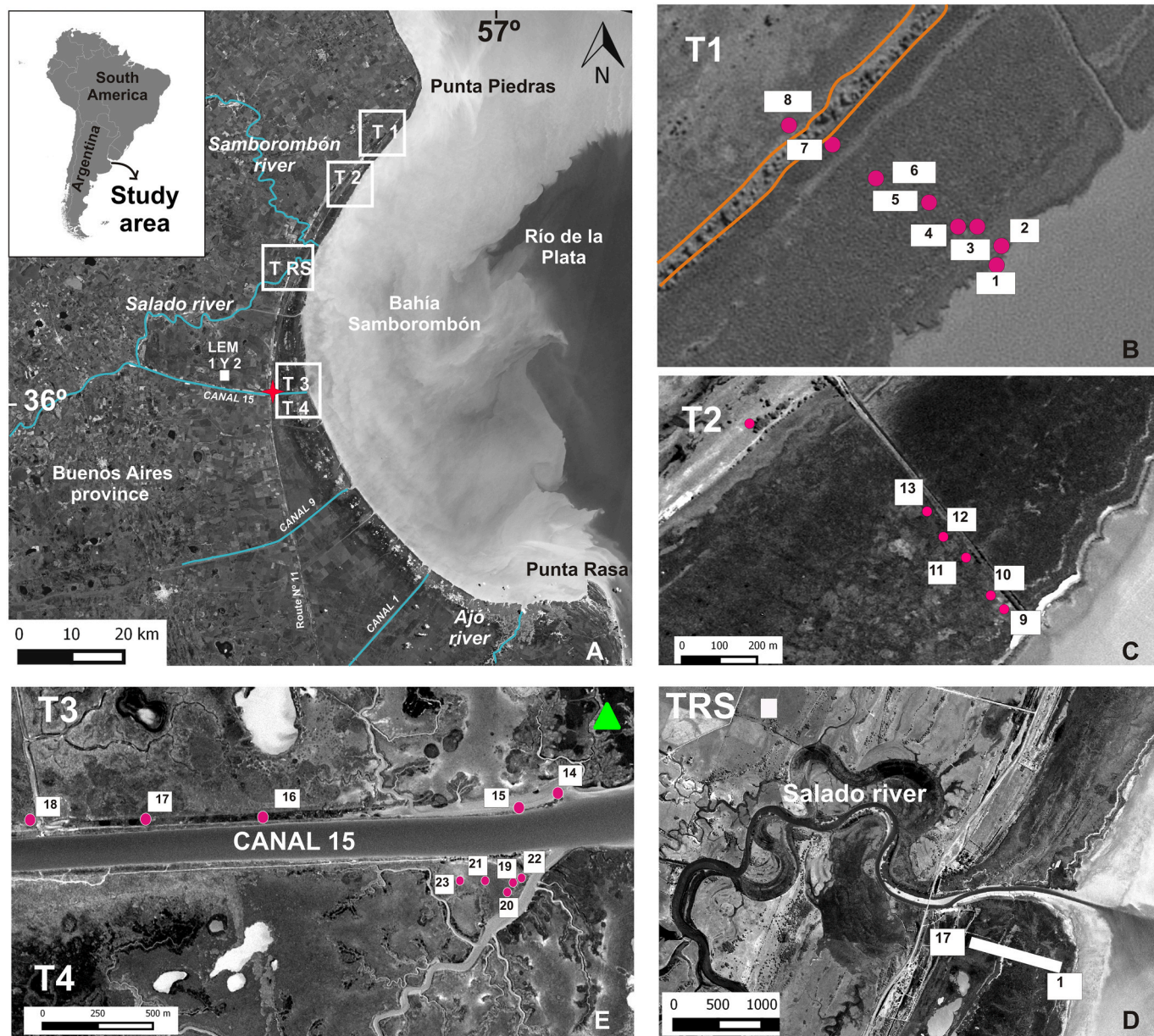

Fig. 1. Study area. A- Landsat 7 image of the coastal sector, north-east of the Buenos Aires Province, with location of the studied transects along the coastal fringe of Bahía Samborombón (T1 to T4), transect on the Salado River (TRS) (Vilanova and Prieto, 2012) and sediment section site PM1 (red asterisk) (Luengo et al., 2018). B- Transect 1; chenier surrounded in orange. C- Transect 2. D- Transect of the Salado River. E− Transects 3 and 4. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

2

Argentina. The bay is an extensive microtidal (0.46/0.52 m) wetland located in the outer reaches of Río de la Plata estuary; it is extended from Punta Piedras (35°27′ S/56°45′ W) to Punta Rasa (36°17′ S/56°46′ W), (Fig. 1. A). The Bahía Samborombón coastal plain is a flat surface (0.01% slope) and has a mean height of 2–3 m a.s.l (Violante et al., 2001). The coastal plain deposits were produced by the last sea level transgressive-regressive cycle during the Holocene (Violante et al., 2001). These deposits have been the subject of geological, stratigraphic, sedimentological and paleontological studies (e.g., Aguirre, 1993; Violante et al., 2001; Laprida and Bertels-Psotka, 2003; Violante and Parker, 2004; Fucks et al., 2010; Luengo et al., 2018). The climate of this region is temperate sub-humid to humid with influence of oceanity, decreasing towards the west and southwest. The average annual temperature is 16 °C and the average annual precipitation is about 950 mm. The highest rainfall occurs in summer, although with great interannual variability (Barros et al., 2000), which is related to the influence of the South American Monsoon System (SAMS) and the South Atlantic semi-permanent high pressure center (Garreaud et al., 2009). The most representative winds for the region are those from the north, northeast, east and southeast. A phenomenon that affects the Río de la Plata as well as Bahía Samborombón is locally known as *sudestada*, an event of climatic anomaly characterized by strong southeastern winds, accompanied or not by rainfall and temperature drop. Three main rivers flow into Bahía Samborombón: Samborombón, Salado and Ajó (Fig. 1 A). In addition, at the beginning of the 20th century, different water courses (e. g. Canal 15, Canal 9 and Canal 1, Fig. 1. A), which transport large volumes of freshwater, were channeled and have modified the original regime of the three mentioned rivers (Volpedo et al., 2005).

2.2. Salt marsh vegetation of Bahía Samborombón

Temperate salt marshes are characterized by a low specific richness and diversity (Cagnoni, 1999). All species are associated in communities along a gradient that determine salt marshes zonation patterns (low, middle, high). This zonation is established according to the distance from the coastline and the topography; both determine the range and frequency of the tides, the aerial exposure of the substrate and the contribution of continental water, thus generating a salinity gradient. In addition, the development and zonation of vegetation are related to numerous chemical factors. Among the most important there are: water salinity, nutrient availability, particularly nitrogen, and anaerobiosis degree, which controls the decomposition rate and nutrient availability (Cagnoni, 1999).

The Bahía Samborombón wetlands are ~100 m wide at the northern tip and more than 20 km wide at the southern. The salt marshes of the bay are characterized by the domain of *Sporobolus densiflorus* (Loisel.) Peterson and Saarela, *Sporobolus alterniflorus* (Brongn.) Peterson and Saarela (Poaceae), and *Sarcocornia perennis* (Mill.) A.J. Scott (Chenopodiaceae).

The low marsh is flooded twice a day and its extension is bounded to the limits of the influence of the daily tidal regime. The vegetation is composed mostly by *Sporobolus alterniflorus* populations located between the tidal plain and the low marsh environment.

The high marsh is irregularly flooded and its upper limit is conditioned to the extreme high tides flood extent (Cagnoni, 1999). The vegetation is composed by *Sarcocornia perennis* surrounded by *Sporobolus densiflorus*, accompanied by *Limonium brasiliense* (Boiss.) Kuntze (Plumbaginaceae) and *Juncus acutus* (Parl.) patches (*juncales*) (Vilanova and Prieto, 2012). Between the high and low zones, different vegetation composition and distribution allow the recognition of a transitional middle zone, characterized by *Limonium brasilensis*, intermingling among *S. densiflorus*.

In the middle and high zones *S. densiflorus* and *S. perennis* can be distributed in three different patterns: (1) *S. densiflorus* grasses only; (2) *S. perennis* only; and (3) a mixture of both species (Isacch et al., 2006). In these three patterns there are also species which tolerate brackish

conditions, forming strips of a few meters wide (Isacch et al., 2006), especially in the high salt marsh zone where there is a greater supply of fresh water such as *Carex* (Cyperaceae), *Pseudognaphalium gaudichaudianum* (DC.) Anderb., *Baccharis glutinosa* Pers., *B. salicifolia* (Ruiz & Pav.) Pers. (Asteraceae), *Heliotropium curassavicum* L. var. *argentinum* I. M. Johnst. (Boraginaceae), *Sesuvium portulacastrum* (L.) L. (Aizoaceae), *Centauriumpulchellum* (Sw.) Druce (Gentianaceae), *Euphorbia serpens* Kunth var. *serpens* (Euphorbiaceae), *Oxybasis macrosperma* (Hook. f.) S. Fuentes, Uotila & Borsch, *Atriplex prostrata* Boucher ex DC. (Chenopodiaceae), *Polygonum aviculare* L. (Polygonaceae), *Phyla nodiflora* (L.) Greene (Verbenaceae), *Melilotus indicus* L. All. (Fabaceae), *Solanum pseudocapsicum* L., (Solanaceae), *Paspalum vaginatum* SW. (Poaceae) and *Eryngium* sp. (Apiaceae). These marsh zones are extended along the Bahía Samborombón coastal area in different magnitude (length), depending on topography, mainly on the slope gradient that varies from north to south.

Although the coastal area is characterized by saline soils lowlands there are areas with local influence of freshwater conditions towards the north of the bay. There, an inverse pattern in the vegetation zonation is developed, where communities of hydrophytes (e.g., *Schoenoplectus californicus*, *Cyperus* sp., and *Typha*) are submerged by tides near the shoreline, and halophytic vegetation develops in higher elevation zones (Isacch et al., 2006). Arboreal patches of *Celtis tala* Gillies ex Planch develop on top of the beach ridges, cheniers, and other elevated landforms distributed along the tidal environments.

Regarding the tidal plain (intertidal) environment of Bahía Samborombón, its limits are given by the low and high tidal syzygy levels. This environment is non-vegetated but the high intertidal can be invaded by halophytic vegetation indicating an advance of the marsh over the high intertidal environment (Bértola et al., 1998).

3. Materials and methods

3.1. Field work and sampling procedure of surface soil sediment

A total of 23 surface sediment samples (upper 1–5 cm) were collected from April 2014 to December 2016 following Adam and Mehringer (1975) sampling techniques. Samples were taken along four transects perpendicular to the shoreline, at different local marsh vegetation zones. Moreover, for the selection of the sampling sites, the different tidal environments of the coastal area of Bahía Samborombón were taken into account. Three sources were considered: 1) a geomorphological map of the area (Bértola et al., 1998), 2) marsh vegetation detected using a Landsat 5 image by Isacch et al. (2006) and 3) vegetation distribution patterns for the Salado basin by Vervoorst (1967).

Transects 1 and 2 are located at the north of the bay, following a NE-SE direction (Fig. 1 A, B and C), with a length of 360 and 440 m respectively. Transects 3 and 4 are located at the central sector of the bay following an E-W direction parallel to Canal 15 (Fig. 1 A and E). Transect 3 is 3400 m long. Transect 4 comprises four series of samples which were taken in the proximity of an active tidal channel, located at 1000 m from the shoreline (Fig. 1 A and E). These samples were selected according to the different plant communities and microenvironments observed in the salt marsh. Transect 1 includes all the tidal environments: intertidal (samples 1 and 2), low marsh (sample 3), middle marsh (samples 4 and 5) and high marsh (samples 6, 7 and 8). The most inland sample (8) is located behind a chenier (Fig. 1 B). Transect 2 encompasses the low (sample 9), middle (samples 10, 11 and 12), and high marsh sectors (sample 13). In the intertidal sector no survey was possible since the anthropic activity disturbed the entire landscape, filled with construction debris. Transect 3 begins near the Canal 15 mouth in the low to mid-marsh (sample 14), and runs across the middle salt marsh (samples 15 and 16). Sample 16 is located in a depressed terrain. This transect finishes in the high salt marsh zone (sample 17 and 18). Finally, all transect 4 samples encompass the middle salt marsh sector (samples 19 to 23) and are distributed according to a microrelief linked to an active tidal

channel (Fig. 1 E). We have also examined an additional of two samples from the water-sediment interface from a shallow water body (LEM 1 and 2 sites, 35°56′16.93″S/57°36′7.65″W, 35°56′18.30″S/ 57°36′8.7″W, Fig. 1 A). This shallow lake environment is surrounded by *S. perennis* and characterized by the aquatic fern *Azolla filiculoides* which forms a layer on the surface.

3.2. Laboratory work

23 surface soil samples were considered for palynological content analysis (pollen, spores and dinoflagellate cysts -dinocysts-). Sediment (1–2 cm^3) per sample was sieved using a 250 and 150 μm mesh to remove coarse particles and was later processed using physical and chemical methods proposed by Faegri and Iversen (1989) and Mudie and Harland (1996), which include the use of KOH, HCL, HF and acetolysis. *Lycopodium clavatum* spore tablets (Stockmarr, 1971) were added before treatment to calculate pollen concentration (grains/cm^3).

A minimum of 300 pollen grains per sample were counted (except for those samples which resulted in low pollen concentration). The identification of pollen grains and spores was made according to Atlases and published keys (Heusser, 1971; Markgraf and D'Antoni, 1978; Prieto and Quattrocchio, 1993; Mourelle and Prieto 2016), and the reference collections at the BA_Pa (Museo Argentino de Ciencias Naturales BR) and Cátedra de Palinología, Universidad Nacional de La Plata, Argentina (Yáñez et al., 2014). Moreover, NPPs structures of algae such as *Pediastrum, Scenedesmus* and *Botryococcus* (colonials), *Debarya, Mougeotia* and *Zygnema* Type (zygospores) -the latter grouped as Zygnemataceae- were identified. Fungi (*Glomus, Tetraploa* conidia and fruiting bodies of *Microthyrium* and other undifferentiated spores) and microforaminifers were also recognized. These NPPs -including dinocysts- were determined following Van Geel (2002), Borel et al. (2003) and Borel (2007), among others. Other identified NPPs were bryophytes spores *Anthoceros, Phaeoceros tenuis, Phaeoceros bulbiculosus*, Ricciaceae and *Riella* (Prieto and Quattrocchio, 1993) along with glochidia and massulae of the *Azolla filiculoides* aquatic fern. Percentages of pollen grains were calculated on the total sum of pollen, whereas those of dinocysts, spores, algae and fungi were calculated considering both pollen grains and spores. Additionally, the aggregates of two or more pollen grains of the same type (clumps) were identified and counted. However, given their poor representation, they were disregarded from the pollen sum and relative percentages.

3.3. Statistical analyses

Palynological diagrams of modern spectra were drawn using the TGView 2.0.4 software (Grimm, 2004). Cluster analysis (CONISS) (Grimm, 2004) was used to determine the palynological zones in two modes: constrained, for samples related with the shoreline distance (transects T1, T2, T3), and unconstrained, for samples not related with the shoreline distance (T4). For those analyses, pollen types present withat least 1% were selected.

In this study, we included 17 surface samples previously analyzed by Vilanova and Prieto (2012) from transect TRS (Fig. 1 A and D) in order to have a more comprehensive model and thereby to achieve a more accurate analysis and interpretations of the palynological distributions patterns in the different zones and environments.

To illustrate the use of modern palynological assemblages as analogues for the paleoenvironmental interpretation, 38 fossil samples from PM1 sediment section (35°58′14.86″S/57°24′49.72″W; Fig. 1 A) (Luengo et al., 2018), were combined with the 42 modern surface samples using a Detrended Correspondence Analysis (DCA). DCA was performed using the R studio application (R Core Team, 2013). The variables selected to make the comparison with the fossil pollen record were those which were shared species and with at least 1% of presence. The 15 selected palynological types were: Poaceae, Chenopodiaceae, *Limonium brasiliense*, Cyperaceae, *Typha*, Asteraceae, *Ambrosia*,

Solanaceae, *Pediastrum, Phaeoceros, Riccia, Botryococcus, Operculodinium, Spiniferites, Azolla filiculoides*.

4. Results

The palynological diagrams of each transect are expressed in relative percentages and total pollen concentration (grains/cm^3). Transects are described from north to south, that is from T1 to T4 (Fig. 1) and from shoreline inland (Figs. 2–4).

4.1. Transect 1.~360 m long (35°33′ S/57°13′ W) (Fig. 2)

Zone T1.1 (samples 1, 2 and 3): Chenopodiaceae (40%) and Poaceae (up to ~30%), accompanied by Cyperaceae 17%, Asteraceae 10%. *Ambrosia*, Ranunculaceae and the arboreal taxa *Celtis* are registered with ≤5%. The dinocysts *Operculodinium* spp. and *Spiniferites* spp. present the highest values along the transect (25–40% and ≤5% respectively). Microforaminferal linings are registered (~5–6%), presenting the highest values along the transect. *Tetraploa* conidium and *Microthyrium* fruit bodies are registered (≤5%). The total pollen concentration ranges between 5,202 and 17,403 grains/cm^3.

Sub-zone T1-2a (samples 4 and 5): Chenopodiaceae increases (60–70%) and Poaceae decreases (up to 10–15%), Cyperaceae (5–15%), Asteraceae, *Ambrosia*, *Typha* and other herbs (Convolvulaceae, Brassicaceae, Euphorbiaceae, Malvaceae, Verbenaceae) are registered as a traces (≤5%). *Operculodinium* decreases (5–15%) whereas *Spiniferites* maintains trace values. The total pollen concentration ranges between 77,357 and 31,970 grains/cm^3.

Sub-zone T1-2b (samples 6 and 7): Chenopodiaceae decreases (36–50%) while Poaceae increases (35–45%), accompanied by Cyperaceae, Asteraceae, *Ambrosia*, Apiaceae, *Celtis* (≤5%). *Operculodinium* and *Spiniferites* decreases, (~5% and ≤5% respectively). Microforaminferal linings, Bryophytes and *A. filiculoides* glochidia are recorded as traces. Undifferentiated fungal spores are registered in this zone (30%), and *Tetraploa* conidium reaches values up to 18% representing the highest values along transect. The total pollen concentration ranges between 33,389 and 96,758 grains/cm^3.

Sub-zone T1-2c (sample 8): Poaceae (~55%), Cyperaceae (18%), Apiaceae (10%), acompanied by Chenopodiaceae (6%), and Asteraceae (~5%). *Ambrosia, Celtis, Eryngium* and *Operculodinium* spp. are recorded as traces. Pollen clumps of Chenopodiaceae and Poaceae are found. *A. filiculoides* glochidia are present as traces. Total pollen concentration is 243,019 grains/cm^3, and constitutes the highest value along the transect.

4.2. Transect 2. ~440 m long (35°36′ S/57°15′ W) (Fig. 3)

Zone T2-1: Sub-zone T2-1a (9, 10 and 11): Cyperaceae (20–25%) and Poaceae (24–35%), accompanied by Chenopodiaceae (15–35%), *Typha* and Asteraceae (5%), *Ambrosia* (≤5%). Apiaceae, *Eryngium, Plantago, Celtis* spp. and *Schinus* are recorded as traces values, (≤5%). *Phaeoceros* spp. (≤5%), *A. filiculoides* glochidia (5%) *Pediastrum* and Zygnemataceae (as traces) are registered. *Operculodinium* spp. (22–24%) and *Spiniferites* spp. (≤5%), show the highest values along the transect and the microforaminferal linings are recorded with values of 5%. Seven Chenopodiaceae clumps were found. The total pollen concentration ranges from 18,971 to 22,716 grains/cm^3.

Sub-zone T2-1b (sample 12): Chenopodiaceae increases (up to 90%). Poaceae and Cyperaceae decreases to ≤5%. The total pollen concentration reaches 522,503 grains/cm^3 (the highest value along the transect). Seven Chenopodiaceae and Poaceae clumps are registered. *Operculodinium* and *A. filiculoides* are recorded as traces.

Zone T2-2 (sample 13): Poaceae (reaching 60%, the highest value along the transect), while Chenopodiaceae and Cyperaceae show values of 12 and 10%, respectively, accompanied by Asteraceae (10%) and Ambrosia (5%). *Operculodinium* spp. and *Spiniferites*s pp. decrease to
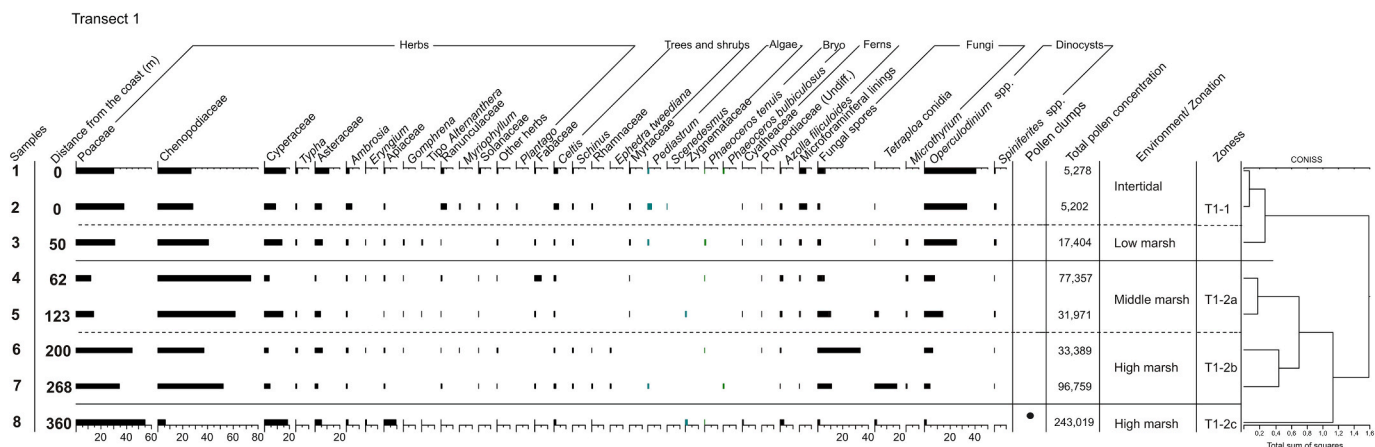
Fig. 2. Diagram of pollen and other palynomorphs (in percentage), total pollen concentration (grains/cm³) and zones resulting from constrained cluster analysis of Transect 1.
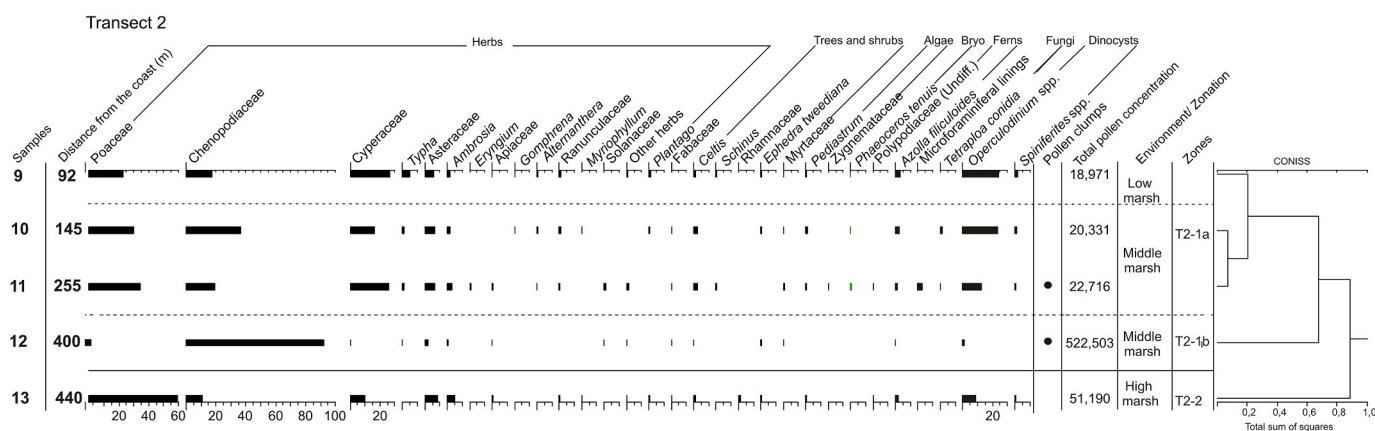

Fig. 3. Diagram of pollen and other palynomorphs (in percentage), total pollen concentration (grains/cm³) and zones resulting from constrained cluster analysis of Transect 2.
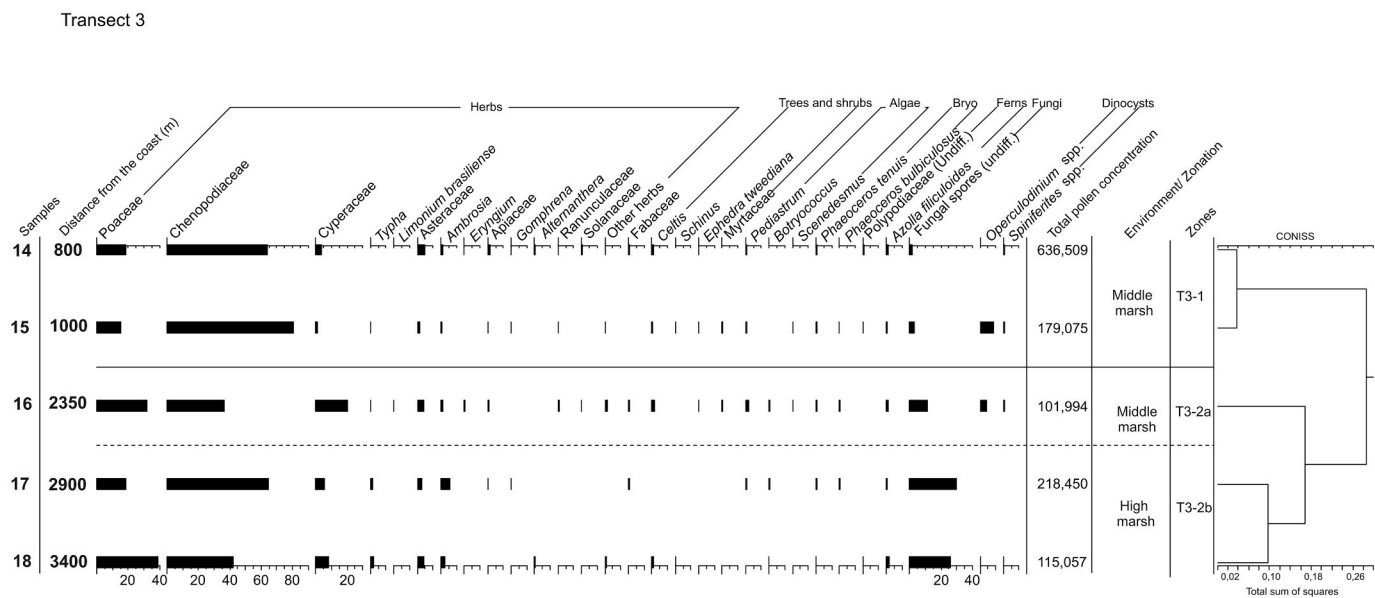

Fig. 4. Diagram of pollen and other palynomorphs (in percentage), total pollen concentration (grains/cm³) and zones resulting from constrained cluster analysis of Transect 3.

10% and traces respectively. *A. filiculoides* glochidia also decrease as traces value. The pollen concentration decreases to 51,190 grains/cm³.

4.3. Transect 3. ~3400 m long (35°58′ S/57°23′ W) (Fig. 4)

Zone T3-1 (samples 14 and 15): Chenopodiaceae (64–80%) and Poaceae (15–19%) dominate the spectrum, accompanied by Asteraceae (2–5%), Cyperaceae, *Ambrosia* and Apiaceae with values ≤5%. *Phaeoceros* spores, *A. filiculoides* and *Pediastrum* are registered as traces (≤2%). *Operculodinium* spp. values reach 10% and *Spiniferites* spp. has trace values. The pollen concentration varies from 636,509 to 179,075 grains/cm³.

Zone T3-2: Sub-zone T3-2a (sample 16): Cyperaceae and Poaceae increase (up to 20% and 32%, respectively), Chenopodiaceae decreases to 36%. *L. brasiliense* is present in this zone. *Operculodinium* spp. decreases to 5% and *Spiniferites* spp. continues with low values. Furthermore, *A. filiculoides,* the colonial algae *Pediastrum*, *Botryococcus* and *Scenedesmus* are recorded as traces values (1%), while fungi spores reach 12%. The total pollen concentration is 101,994 grains/cm³.

Sub-zone T3-2b (samples 17 and 18): it is characterized by Chenopodiaceae (42–65%), Poaceae (19–40%), Cyperaceae (5–8%) and *Ambrosia* (6%); along with *Typha*, Asteraceae and *A. filiculoides* (≤3%). The fungi spores reach the highest values along the transect (25–30%). The total pollen concentration varies between 115,057 and 218,450 grains/cm³.

4.4. Transect 4. around a tidal channel (35°58′ S/57°23′ W) (Fig. 5)

Zone T4-1: (samples 19, 20 and 21): Chenopodiaceae (70–73%), Poaceae (12–15%), Cyperaceae (4–6%), Asteraceae, *Ambrosia* and *Celtis* (≤3%), and *L. brasiliense* (≤2%). *Operculodinium* and *Spiniferites* show values between 10 and 17% while *A. filiculoides* and microforaminifera continue as traces. Pollen clumps are recorded. The total pollen concentration ranges between 35,357 and 93,856 grains/cm³.

Zone T4-2 (samples 22 and 23): Chenopodiaceae (~43%), Poaceae (27–32%) and Cyperaceae (8–15%), accompanied by Asteraceae, *Ambrosia*, Apiaceae, *Eryngium*, *Typha* and other herbs, are all recorded as traces (≤5%). *Operculodinium* reaches the highest values along the tidal channel samples (~19–23%) and *Spiniferites* is present as traces (≤2%). *Pediastrum* (4%), *Scenedesmus* and *Botryoccocus*, Zygnemataceae, *A. filiculoides*, microforaminifera and fungi spores are recorded as trace values. The total pollen concentration ranges between 17,310 and

33,453 grains/cm³.

4.5. Shallow water body site: LEM 1 and LEM 2 (Fig. 1 A and 6)

The palynological spectrum is represented by Chenopodiaceae (~67–75%), Poaceae (12–17%), Cyperaceae and Asteraceae (3–5%). Apiaceae, *Ambrosia*, Asteraceae, *Typha*, Solanaceae and *Celtis* are recorded as traces (≤5%). Values of the aquatic fern *A. filiculoides* vary between 15 and 20%. *Botryococcus* and Zygnemataceae, Ricciaceae, microforaminifera and undifferentiated fungal spores are registered in this zone as trace values (~3%). Chenopodiaceae pollen clumps are recorded. The total pollen concentration of the two samples is 161,130 and 81,847 grains/cm³ respectively.

4.6. Stratigraphic profile PM1

According to CONISS cluster analysis, PM1 fossil palynological diagram is divided in three palynological zones and two subzones (Fig. 7) (Luengo et al., 2018). The PM1-P1.1 zone (ca. 2,700 to 1,660 cal yr BP) is characterized by Chenopodiaceae 55% and Poaceae 35%; accompanied by Cyperaceae, Asteraceae and *L. brasiliense*, and by the highest values of *Operculodinium* and *Spiniferites* (60% and 10%, respectively). PM1-P1.2 zone (1,660–950 cal yr BP) is characterized by the increase of Chenopodiaceae and the decrease of Poaceae. *A. filiculoides* increases up to 40–50%; whereas *Operculodinium* and *Spiniferites* gradually decrease. Finally, PM1-P2 zone (950 cal yr BP to the present) is co-dominated by Chenopodiaceae and Poaceae, accompanied by Cyperaceae and *Ambrosia*. *A. filiculoides* increases up to 80% and *Operculodinium* and *Spiniferites* diminish considerably.

4.6.1. Detrended correspondence analysis (DCA)

The ordering of modern and fossil samples by DCA analysis is shown in Fig. 8. Fossil samples grouped in PM1-P1.1 sub-zone, characterized by *Operculodinium* spp. and *Spiniferites* spp., are located in the left quadrants of the two-dimensional graph, where it can be observed that these fossil samples do not show similarity with the modern environments samples.

Fossil samples grouped in PM1-P1.2 sub-zone are divided into two groups along axis 1 (Fig. 8). One group is located in the upper left quadrant along with the samples from PM1 sub-zone and two modern samples representing the middle salt marsh. The other group is located in the upper right quadrant and has similarities with samples of the middle salt marsh, characterized by Chenopodiaceae (Fig. 8).
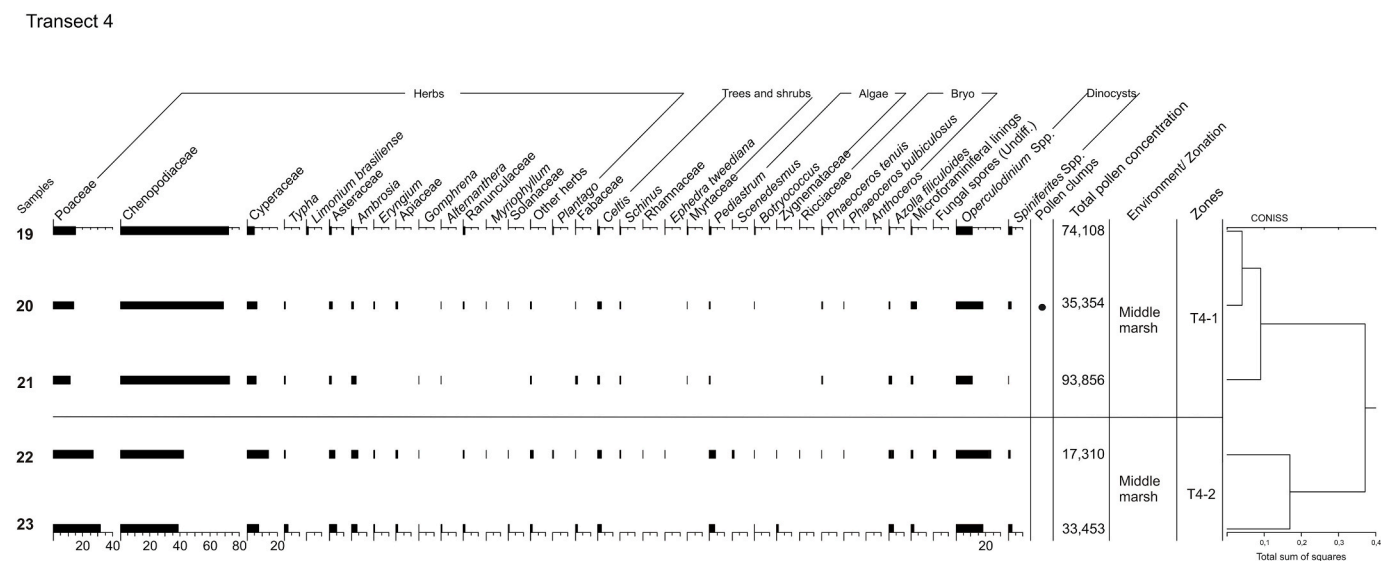
Transect 4

Fig. 5. Diagram of pollen and other palynomorphs (in percentage) , total pollen concentration (grains/cm³) and zones resulting from unconstrained cluster analysis of Transect 4.

Finally, the fossil samples grouped as PM1-P2, located in the upper right quadrant, have no similarity to the modern environment except for those that represent the shallow water body environment, which is determined by *A. filiculoides*.

5. Discussion

The predominant pollen taxa in the surface sediment samples from the Bahía Samborombón salt marshes are Chenopodiaceae, Poaceae and Cyperaceae (Fig. 9). This pollen assemblage reflects salt marshes observed not only in Bahía Samborombón and Laguna Mar Chiquita, both located in the coastal area of Buenos Aires province; but also in other South American coastal areas such as Lagoa dos Patos in southern Brazil (Isacch et al., 2006). Chenopodiaceae, Poaceae and Cyperaceae pollen taxa present taxonomic limitation, i. e. they cannot be identified at genus level (Medeanic et al., 2016). Although the determination and identification of pollen types is generally of low resolution, the relative proportions of pollen taxa along with taxa/ecological markers and NPPs, could enhance and improve the information to recognize the different salt marsh zones that is useful to infere and interpret the past salt marsh zones distribution.

5.1. Palynological representation of tidal environments

5.1.1. Intertidal environment
The palynological spectrum from the intertidal environment is co-dominated by Poaceae and Chenopodiaceae (Figs. 2 and 9). Poaceae represents populations of *S. alterniflorus* that can be found not only as patches in the intertidal zone but also in close proximity to the depositional environment. Chenopodiaceae pollen is also transported from the higher zones since parent plants (mainly *S. perennis*) are mostly located in the middle and higher salt marsh zones. This species is wind-pollinated and produces abundant pollen. This fact may explain the proportions of Chenopodiaceae pollen found in the intertidal zone. Pollen taxa associated with Poaceae and Chenopodiaceae samples are Cyperaceae, Asteraceae, *Ambrosia*, Ranunculaceae and other herbs (Fig. 2). These pollen taxa came from the high and middle salt marsh zones and were transported by the wind, freshwater creeks or channels and the marine tidal action.

A very important aspect to remark here, which can be a diagnostic indicator characterizing the environmental conditions is the highest frequency of dinocysts (25–40%).

Another similar indicator is represented by the microforaminiferal linings (~5–6%) that are the inner organic remnants of the benthic microforaminifera. The presence of this linings in palynological assemblages are commonly considered reliable indicators of marine transgressions and as proxies for paleosalinity and water pollution (Mudie and Yanko-Hombach, 2019; Arun, 2020). In this study, microforaminifera linings occur with low frequency in almost all the samples. Medeanic (2006), through the palynological analysis of the surface sediments of intertidal marshes on the margin of the Dos Patos Lagoon estuary, concludes that the frequency variations of these marine indicators in the samples are connected with a marine influence.

In addition, the high fragmentation degree of pollen grains and spores reflects the re-suspension, re-sedimentation and even re-work by the action of the tides and the greater energy of the daily flooded environment; which is could be the cause for the lowest total pollen concentration (5,278–5,202 grains/cm^3 of sediment) in the salt marsh ecosystem, but also reflecting the non-vegetated or scarce vegetation in this intertidal zone. However more samples are required for a better understanding of the palynological fingerprint from the tidal plain environment.

5.1.2. Low salt marsh
In this zone, Poaceae (30–70%), Chenopodiaceae (5–35%) and Cyperaceae (20–25%) are the main components of the pollen spectra.

Poaceae corresponds to the dominant parent source of the vegetation cover of this narrow salt marshzone. The low marsh in transect 1 is represented in the palynological sapectrum with a specific range of Cyperaceae values (20–25%). This pollen spectrum may be reflecting the pattern of inverse vegetation zonation described by Isacch et al. (2006) for the northern coastal sector of Bahía Samborombón. However, values of Cyperaceae between 10 and 15% may be more related to freshwater influence through artificial channels discharge (e. g. sample 9 Fig. 2). Cyperaceae pollen is reflecting plants such as *Schoenoplectus californicus, Cyperus* sp. which inhabits soil depressions where water accumulates (Rodríguez-Gallego et al., 2012) and is considered as pollen deposited *in situ*. Therefore, in Bahía Samborombón marsh environments, Cyperaceae species can be found where these conditions develop regardless the marsh zones, e. g. sample 3 in the low marsh of T1 and sample 16 in the middle marsh of T3 where Poaceae and Cyperaceae co-dominate their pollen assemblages (Figs. 2 and 4). Also, in this low marsh zone the presence of *Pediastrum* and Zygnemataceae are indicators of shallow freshwater small ponds.

Another characteristic of the low marsh zone are the records of the dynocysts such as *Operculodinium* spp. that gradually diminish with increasing distance from the coast, and *Spiniferites* spp. that reflect the influence of tides. The decrease in the proportions of dinocysts and microforaminifers remains with increasing distance suggests lower tidal influence (Fig. 2). The record of fungi (fungal spores, *Tetraploa* conidia) in this zone may be related to pedogenetic processes. Moreover, the increase in pollen concentration (more than three times in regard to intertidal environment) may be explained by its closer proximity to the pollen source (*in situ*). Pollen from Chenopodiaceae may come from higher adjacent areas, (from the middle to high marsh zone). In this zone it is also transported and probably re-suspended and re-sedimented by the action of tides. The overrepresentation of this pollen taxa could be associated to the high pollen productivity by parent plants and the high pollen capacity to be transported by the wind (Vilanova and Prieto, 2012; Medeanic et al., 2016).

5.1.3. Middle salt marsh
The Chenopodiaceae pollen, most likely representing *S. perennis* is predominant in the spectra with percentages between 70 and 90% and is commonly found in pure populations. Other pollen types of the spectra are Poaceae 5–15%, Cyperaceae, Asteraceae and *L. brasiliense,* all with values ≤ 5%.

The higher values of Chenopodiaceae (up to 90%) in relation to those of Poaceae and Cyperaceae (Fig. 2), are probably due to overrepresentation related to a high pollen production, but also to the lower anemophily dispersion of Chenopodiaceae due to the effects of Poaceae height canopy and high coverages (Stutz and Prieto, 2003). In addition, the high pollen concentration may be explained by the high pollen clumps related to the proximity to the source and to the weak action of the agent (winds or tides). Pollen clumps record in this zone, may be related with more stable conditions at 255–400 m from the shoreline (Fig. 3), and are deposited *in situ.*

At the mouth of Canal 15, the palynological record from the edge of the marsh is characterized by high values of Chenopodiaceae pollen (Fig. 4) that would correspond to the middle zone in a particular situation, probably caused by erosion and fragmentation of the marsh, due to the formation and dynamics of the tidal channels and the water discharge of Canal 15. For this reason, the low saltmarsh with populations of *S. alterniflorus* (*espartillar*) are not present.

Low relative abundance of *Operculodinium* spp. and *Spiniferites* spp. reflects slighter influence of tides; whereas the increase of fungal elements suggests stable conditions and accumulation of organic matter on a depressed depositional environment.

In the particular case of T4, the pollen spectra shows variations that reflect the different vegetation patterns as a response to microrelief within a middle salt marsh environment. In levees of the main course and lesser flows, the dominance of Poaceae and Chenopodiaceae reflects

populations of *S. densiflorus* arranged as a fringe limiting with depressed areas where population of *S. perennis* occur, as reflected by Chenopodiaceae (up to ~80%, Fig. 5). The record of *L. brasiliense* involves middle to high salt marsh environments. The record of this pollen type can be considered as indicator taxa for the middle-high salt marsh because the pollen grains are extremely linked with the proximity to the source (*in situ*).

5.1.4. High salt marsh

The pollen spectra are characterized by the dominance of Poaceae (15–60%) and Chenopodiaceae (5–40%), Cyperaceae (5–20%), Asteraceae (5%). Accompanying taxa are: *Ambrosia, Eryngium* and Apiaceae, which are related to the higher diversity of vegetation. The two main characteristics that could contribute to differentiate the high marsh zone are: 1- the higher number of pollen types that reflect the higher diversity of the communities and 2- the high total pollen concentration.

The low pollen taxonomic resolution of Poaceae, which represents the dominant taxa of the low and the high salt marsh, generates difficulties to distinguish these environments through the pollen assemblages as Mourelle and Prieto (2016), and Medeanic et al. (2016) pointed out for grasslands from Uruguay and southern Brasil, respectively. For example, in a high salt marsh at 360 m from the coastline (T1), the Poaceae dominate the pollen spectra (Fig. 2), representing the salty grasslands of *Distichlis* spp. that develop behind a chenier in a stable environment protected from the direct action of extreme high tides. In this regard, high marsh environments colonized by *Distichlis* have similar pollen spectra to those of the low marsh colonized by *S. densiflorus* so they cannot be distiguished by the pollen fingerprint. Nevertheless, this can be overcome by the record of fungal elements increase (up to 40%), including the record of *Tetraploa* (Fig. 2), that suggests a higher stabilization of the surface and a greater accumulation of organic matter and thus lower influence of the tides due to the longer distance from the coast. Specifically, the conidia of *Tetraploa* suggest an alkaline-tolerant microbiota that decomposes the remains of the salt grass *Distichlis* (Elíades et al., 2014). Thefore, through the identification of this spore the presence of salty grass can be inferred, that is indistinguishable in pollen morphology from the rest of grasses.

The absence of *J. acutus* in the high salt marsh pollen assemblages is related to the low pollen preservation (Peglar et al., 2001) and also the destruction of Juncaceae pollen during acetolysis of sediment samples (Fontana, 2005). The under-representation of this taxa in high salt marsh pollen spectra constitutes a disadvantage in the recognition of this zone.

Regarding the high total pollen concentration, according to Grindrod (1988), the optimal conditions for the high pollen accumulation in salt marshes are most likely along muddy, low energy shores which support luxuriant plant communities containing high pollen producers, and where sediment accumulation, either inorganic or organic, is not excessive.

Concerning the low to null record of *Operculodinium* spp. in this zone, it may reflect scarce transport by extraordinary tides and *sudestadas* (Bértola, 1994). Between 2,900 and 3,400 m from the coastline (T1), no dinocysts were recorded, which is related to the higher topographic position and hence, the higher distance from the coast, where the tides are extremely rare.

5.1.5. Talares pollen representation

Arboreal pollen (mainly *Celtis*) is found in all tidal environments with low frequency (Figs. 2–5). *Celtis* pollen represents *C. tala* which is the dominant species located on the beach ridges along the coastal fringe. In particular, the highest values of *Celtis* (TRS, Fig. 9) reflect the arboreal taxa founded in chenier (Vilanova and Prieto, 2012). Although these beach ridges go all along the coastal fringe, they do not correspond to a particular tidal environment; for instance, cheniers formation occur along the whole bay, in channel and river mouths in particular, that influence the chenier genesis (Bértola, 1994). This may explain the

greater representation of Celtis along the RS transect, which is parallel to the Salado river mouth, where cheniers are well constituted.

6. Application of modern palynological assemblages in Holocene paleoenvironmental reconstructions

The distribution of fossil and modern palynological samples along axis 1 reflects the salinity gradient as the main driver of paleoenvironmental changes (Fig. 8). This salinity gradient involves marine tidal influence environments and fresh water predominant environments. In turn, the results indicate that the fossil samples of the PM1-P1.1 zone (ca. 2,700- 1,660 cal yr BP) do not have a modern analogue. The absence of analogy with modern spectra in the palynological spectra of the basal samples of PM1 is related to the high amount of marine elements, especially the high proportion of dinocysts corresponding to a subtidal-intertidal environment, which implies a greater marine influence than the one at the present time. Within PM1-P1.2 zone (ca. 1,660-950 cal yr BP), the basal samples do not have a modern analogue either; except for the top samples that are similar to modern ones representing the halophyte communities dominated by Chenopodiaceae from the middle saltmarsh (Fig. 8). This similarity suggest that the establishment of a mature salt marsh began ca. 1,520 cal yr BP and not at 1,660 cal yr BP years as a previous study had shown (Luengo et al., 2018).

Samples from PM1-P2 zone (ca. 950 cal yr BP to the present) are grouped with modern samples from shallow lakes depositional environments (Figs. 6 and 8). These water bodies are typical in the Bahía Samborombón coastal plain region. They are isolated from the tidal action and are usually developed in spaces between successive shell ridges (inter ridges) and/or on ancient tidal channelsrelated to coastal progradation during the late Holocene (Luengo et al., 2018).

7. Conclusions

The study of surface palynological assemblages through four transects perpendicular to the coast of Bahía Samborombón allowed to differentiate and characterize the tidal environments from the palynological point of view. Although the determination and identification of pollen types is generally of low resolution (at family and genus levels), the relative proportions of pollen taxa along with indicator taxas/ ecological markers and NPPs, complete the information to infer the different salt marsh zones. For example, *L. brasiliense* can be considered as an indicator taxon for the middle-high salt marsh because the pollen grains are extremely linked with the proximity to the source (*in situ*).

Concerning other aspects determining the palynological assemblages, small changes in the ground (microrelief) such as the presence of tidal channels and associated deposits, cheniers, and low depressions areas, modify the local vegetation and therefore the final palynological assemblage, as well as human impact e.g. channelization.

Fungal spores are among the NPPs that could help differentiate between the low salt marsh in relation to the middle and high zones.

Regarding the dynocists distribution (*Operculodinium* and *Spiniferites*), results demonstrate that are useful indicators, as well as the microforaminifera remains, for characterizing the intertidal zone and inferring this environment in the past. Nevertheless, further research and more samples are required in order to establish palynological assemblages that could represent the tidal plain environment.

Pollen concentration is another characteristic of modern pollen associations that contributed to the environmental differentiation.

Other indicators, which are not specific of a salt marsh zone but contribute to establishing environmental conditions are: colonial algae such as *Pediastrum, Botryococcus, A. filiculoides* glochidea all of them related to aquatic environments (depressions, temporary shallow lakes, shallow waters).

DCA ordination of fossil and modern samples reflects that the paleoenvironmental changes are mainly in salinity related to the tidal influence, providing further evidence of the applicability of modern
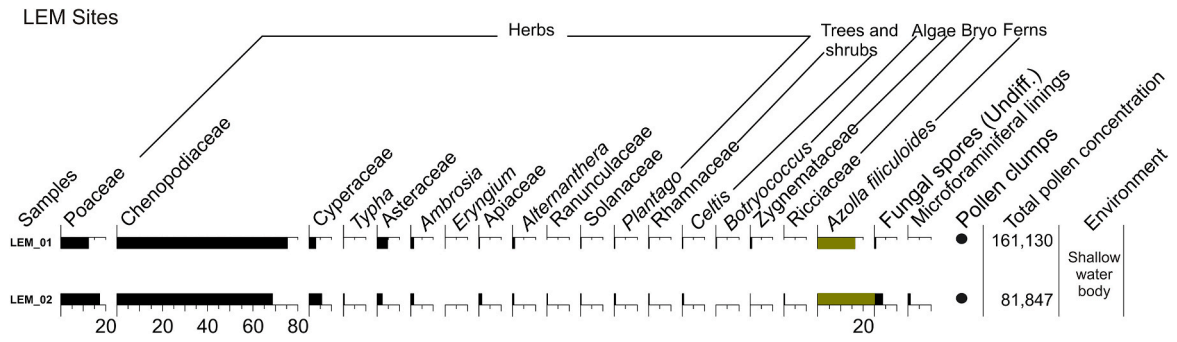
Fig. 6. Diagram of pollen and other palynomorphs (in percentage) and total pollen concentration (grains/cm³) of LEM 1 and 2.
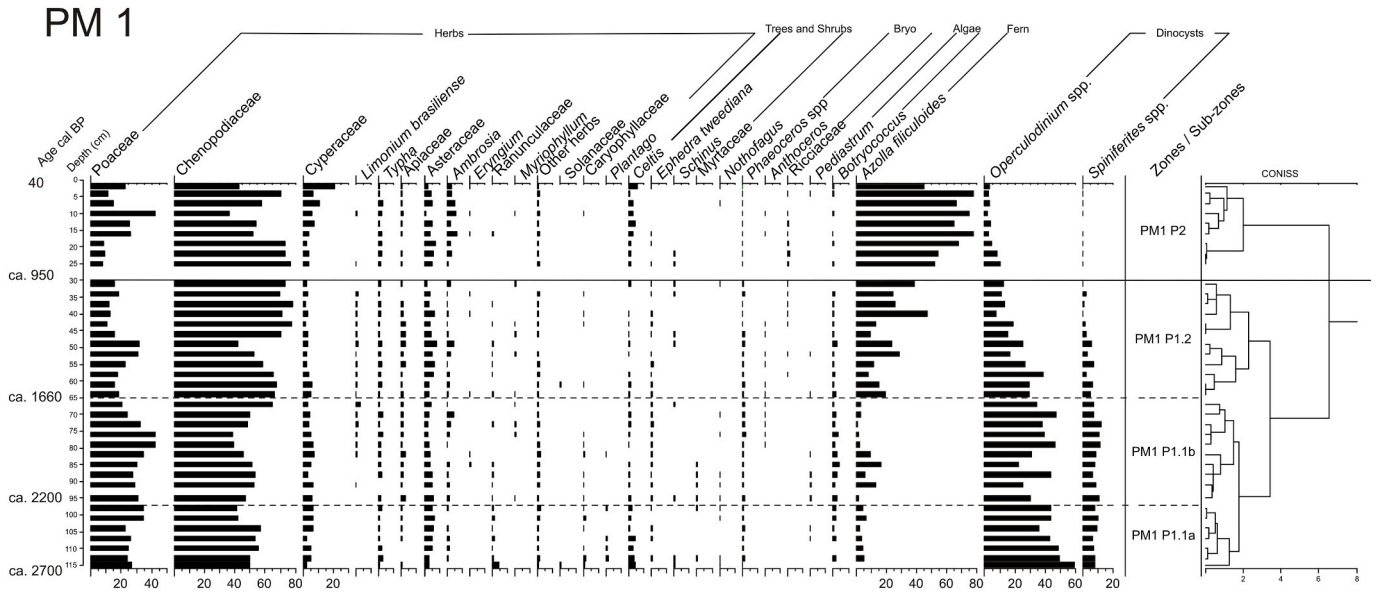

Fig. 7. Pollen diagram in percentage of stratigraphic profile PM1 (Luengo et al., 2018).
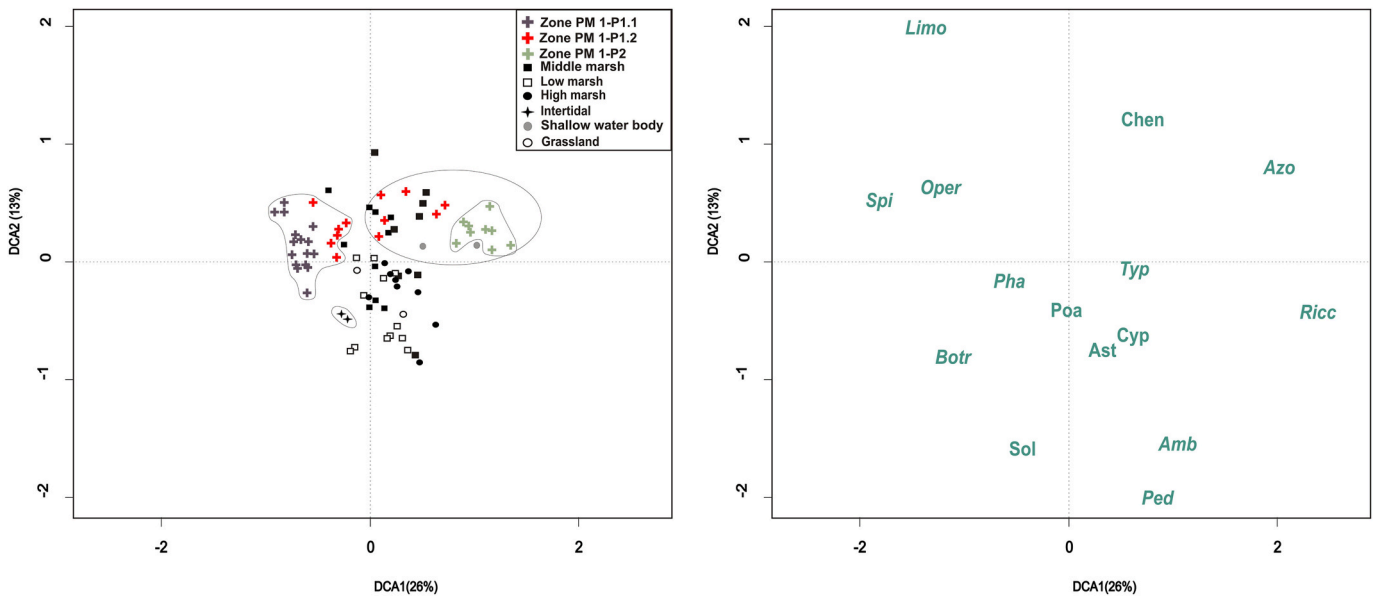

Fig. 8. DCA of the 42 surface samples: T1, T2, T3, T4, LEM 1, LEM 2, TRS (Vilanova and Prieto, 2012) and 38 fossil samples (Luengo et al., 2018). B- Spatial distribution of the 15 palynological types considered for this analysis, along the two firsts axes. References: Poa: Poaceae, Cheno: Chenopodiaceae, Limo: *Limonium brasiliense*, Cyp: Cyperaceae, Typ: *Typha*, Ast: Asteraceae, Amb: *Ambrosia*, Sol: Solanaceae, Ped: *Pediastrum*, Pha: *Phaeoceros*, Ricc: *Riccia*, Botr: *Botryococcus*, Oper: *Operculodinium* spp., Spi: *Spiniferites* spp., Azo: *Azolla filiculoides*.
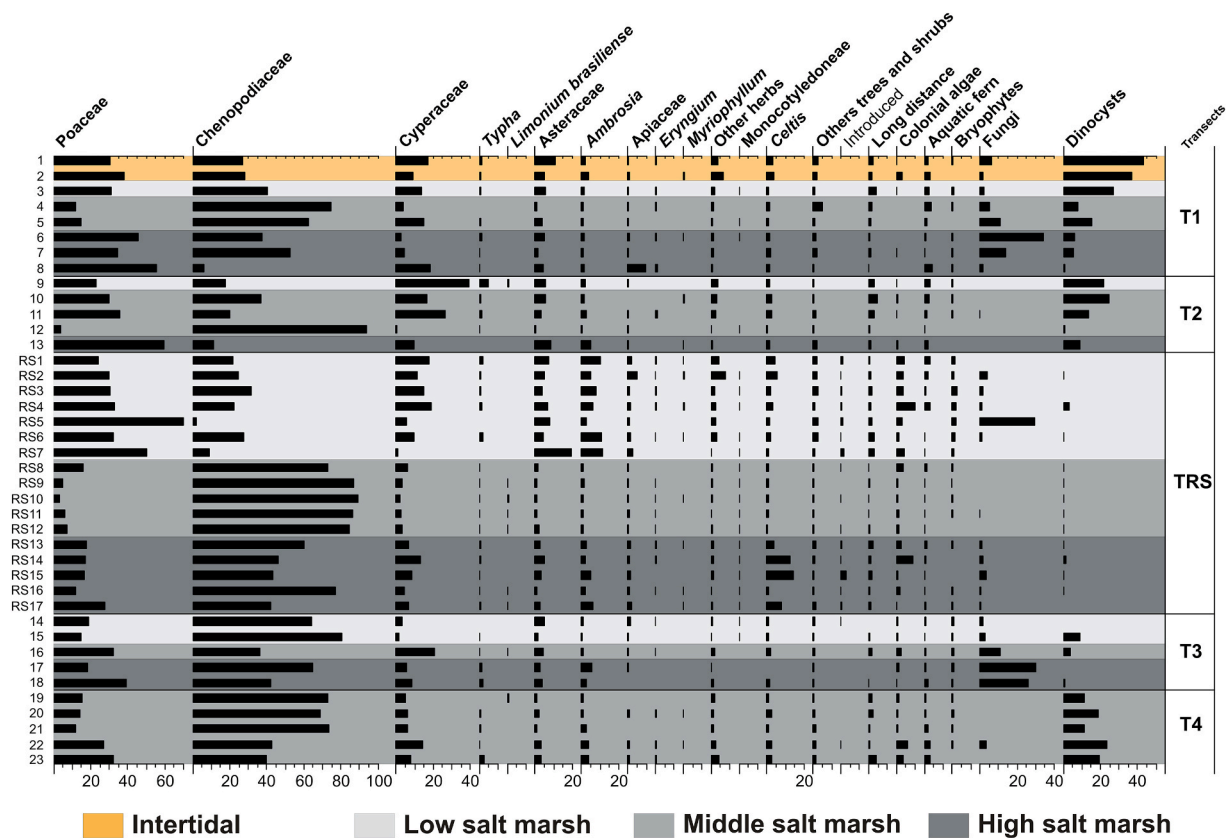
Fig. 9. Pollen diagram in percentage (summarized) of the 40 surface samples: T1, T2, TRS, T3, T4 and TRS (Vilanova and Prieto, 2012) of the central-north zone of Bahía Samborombón. Asteraceae include the types *Baccaris, Senecio* and Cichorioideae. Other herbs: Brassicaceae, Convolvulaceae, Euphorbiaceae, Geraniaceae, *Gomphrena,* Malvaceae, Onagraceae, *Oxalis, Plantago,* Ranunculaceae, *Alternanthera, Plumbago* type*, Polygonum,* Verbenaceae. Other trees and shrubs: *Acacia, Ephedra tweediana,* Fabaceae (Caesalpinioidae and Papilionoideae), *Jodina rhombifolia, Salix, Sambucus, Schinus,* Solanaceae, Rhamnaceae. Long distance: *Alnus, Betula,* Myrtaceae*, Nothofagus,* Pinaceae/Podocarpaceae. Colonial algae: *Botryococcus, Pediastrum, Scenedesmus,* Zygnemataceae. Impact: Type *Carduus* and *Rumex.* Bryophytes: Ricciaceae, *Phaeoceros tenuis, P. bulbiculosus* and *Anthoceros.* Fungi: *Glomus* and undiff. spores.

palynological assemblages to interpret Holocene fossil sediment sequences from the Bahía Samborombón coastal plain.

This study provides new modern palynological data for Bahía Samborombón and may constitute an important tool to interpret local and regional fossil palynological assemblages. This data could be used in future paleonvironmental reconstructions in coastal plain deposits whose evolution are linked to relative sea-level fluctuations.

CRediT authorship contribution statement

Mariel S. Luengo: Conceptualization, Methodology, Formal analysis, Investigation, Resources, Writing - original draft, Writing - review & editing, Visualization, Supervision, Project administration. **Isabel Vilanova:** Supervision, Project administration, Resources, Writing - original draft, Writing - review & editing, Funding acquisition. **M. Florencia Pisano:** Methodology, Investigation, Writing - review & editing, Visualization. **Gabriela D'Amico:** Methodology, Investigation, Writing - review & editing, Visualization. **Nicole Pommarés:** Methodology, Writing - review & editing, Visualization. **Enrique Fucks:** Resources, Supervision, Project administration, Methodology, Writing - review & editing, Funding acquisition.

Declaration of competing interest

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

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