Water and Environment Journal

Water and Environment Journal. Print ISSN 1747-6585

Relationships between landforms, soils and vegetation in the River Plate coastal plain, Argentina

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Keywords
Argentina; coastal plain; geomorphology; River Plate; soils; vegetation communities; wetlands.

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doi:10.1111/j.1747-6593.2010.00232.x

Abstract

The River Plate coastal plain is a 160-km-long, 3–10-km-wide strip, located to <5 m a.s.l. on the right bank of the estuary. It is formed by sediments and landforms generated by the littoral transport and marine ingressions and regressions during the Holocene. The coastal plain faces heavy pressures from Buenos Aires Metropolitan Area, with about 13 million inhabitants, industrial, mining and rural activities. Here, we analyse the relations existing between landforms, soils and vegetation. Despite the anthropogenic influence, the natural landscape is more or less preserved in some areas, such as patches of the southernmost gallery forest in the world in natural levees, the xerophytic forests located in well-drained soils of beach ridges and other units such as Inland and Coastal Mudflats with wetland soils and vegetation, Tidal Flats with contrasting soils and plant communities among others.

Introduction

The River Plate coastal plain is a 160-km long, 3–10-km-wide strip, located on the right bank of this estuary to <5 m a.s.l. It is located in the vicinity of, and in some cases partially including, the Buenos Aires Metropolitan Area, which constitutes the largest conurbation of Argentina, with about 13 million inhabitants (about 30% of the total population of Argentina). Some sectors, especially nearer the cities of Buenos Aires and La Plata, are occupied by uses derived from urban sprawl such as industries, sanitary fills, quarries, highways, roads and canals (Fig. 1). Some areas are devoted to rural uses such as horticulture, forestation and livestock production.

Despite the anthropogenic influence, the natural landscape is more or less preserved in some areas, such as patches of the southernmost gallery forest in the world, with a very high biodiversity (Cabrera & Dawson 1944) and, to the south, landforms resulting of sea transgressions and regressions (Fidalgo *et al*. 1973; Tricart 1973; Cavallotto 1995), which include xerophytic forests ('talares') surrounded by wetlands (Parodi 1940; Cabrera 1963–1968; Vervoost 1967). The unique characteristics of the talares and adjoining areas lead to the creation of the Biosphere Reserve 'Parque Costero del Sur' (MAB-UNESCO) in 1984, now considered a natural and cultural heritage site. This reserve, which covers about 270 km^2 is largely privately owned and productive activities are not regulated. The implementation of in situ and ex situ conservation strategies for native trees is considered absolutely necessary (Rivas *et al*. 2004).

Coastal plains are wetlands that fulfill several functions common to other wetlands such as, groundwater recharge/discharge, wildlife habitat, dissipation of storm wave energy, surface water storage, accumulation of sediments and organic matter (Brinson 2004). However, they will become critical areas in the future on account of the forecast of sea-level rise as a result of global warming, especially near densely populated regions (IPCC 2001). Some consequences include: elevation of water table, salinization of aquifers, upstream displacement of the saline wedge, increase of the intensity and frequency of storm effects along the coasts and increased erosion of shorelines (Rivas & Cendrero 1994). Storm surges will reach further inland also affecting upland areas.

Some of these processes are currently affecting the study area (Ainchil & Kruse 2002). In this respect, rising trends of sea level were detected by Lanfredi *et al*. (1988, 1998) in the River Plate coastal plain: 0.16 ± 0.1 mm/year (Buenos Aires city, period of record: 1913–1984); similar rises were found by these authors in the Atlantic coast of Buenos Aires province: 1.6 ± 0.2 mm/year (Puerto Quequén, 1926–1992) and 1.4 ± 0.5 mm/year (Mar del Plata, 1962–1984).

For an improved understanding of this coastal environment, it is essential to increase the knowledge about the interactions between biotic and abiotic components and human activities. Several studies have been conducted in relation with the different components of the environment (landforms, groundwater, soils, vegetation) in the region (Cappannini & Mauriño 1966; Goya *et al*. 1992; Auge 1995; Cavallotto *et al*. 1999; Ainchil & Kruse 2002; Vilanova *et al*. 2006). However, there are fewer works dealing with the interrelations between the components (Sánchez *et al*. 1976; Cavallotto 1995; Imbellone *et al*. 2002; Nabel & Pereyra 2002). The objectives of this work are to analyse the influence of landforms and soils in the distribution of plant communities of the River Plate coastal plain, including the effect of the hydroperiod in the development of soils and vegetation. Some assumptions concerning the effects of sea-level rise in soils and vegetation are presented. For the sake of comparison, a characterization of the upland region (High Plain) is also included.

Methods

The soils have been surveyed in two representative transects of the northern and southern areas, indicated N–N′ and S–S′, respectively (Figs 1 and 2). Morphological descriptions and drainage classes correspond to the Soil Survey Manual (Soil Survey Division Staff 1993). Chemical analyses were made according to the following methods, described in the Soil Survey Laboratory Methods Manual (National Soil Survey Center 1996): Reaction (pH): potentiometric measurement in the saturated paste. Electrical conductivity: measurement in the saturation extract. Organic carbon: Walkley–Black method (organic matter: %C × 1.724). Cation exchange capacity: cation displacement with ammonium acetate (1 N, pH 7) and measurement of ammonium. Exchangeable cations (Ca, Mg, Na and K): displacement with ammonium acetate and measurement by atomic absorption spectrophotometry. Carbonates: by the acid neutralization method. Particle-size analysis: pipette and densimetric methods. Infiltration velocity: using a double ring infiltrometer.

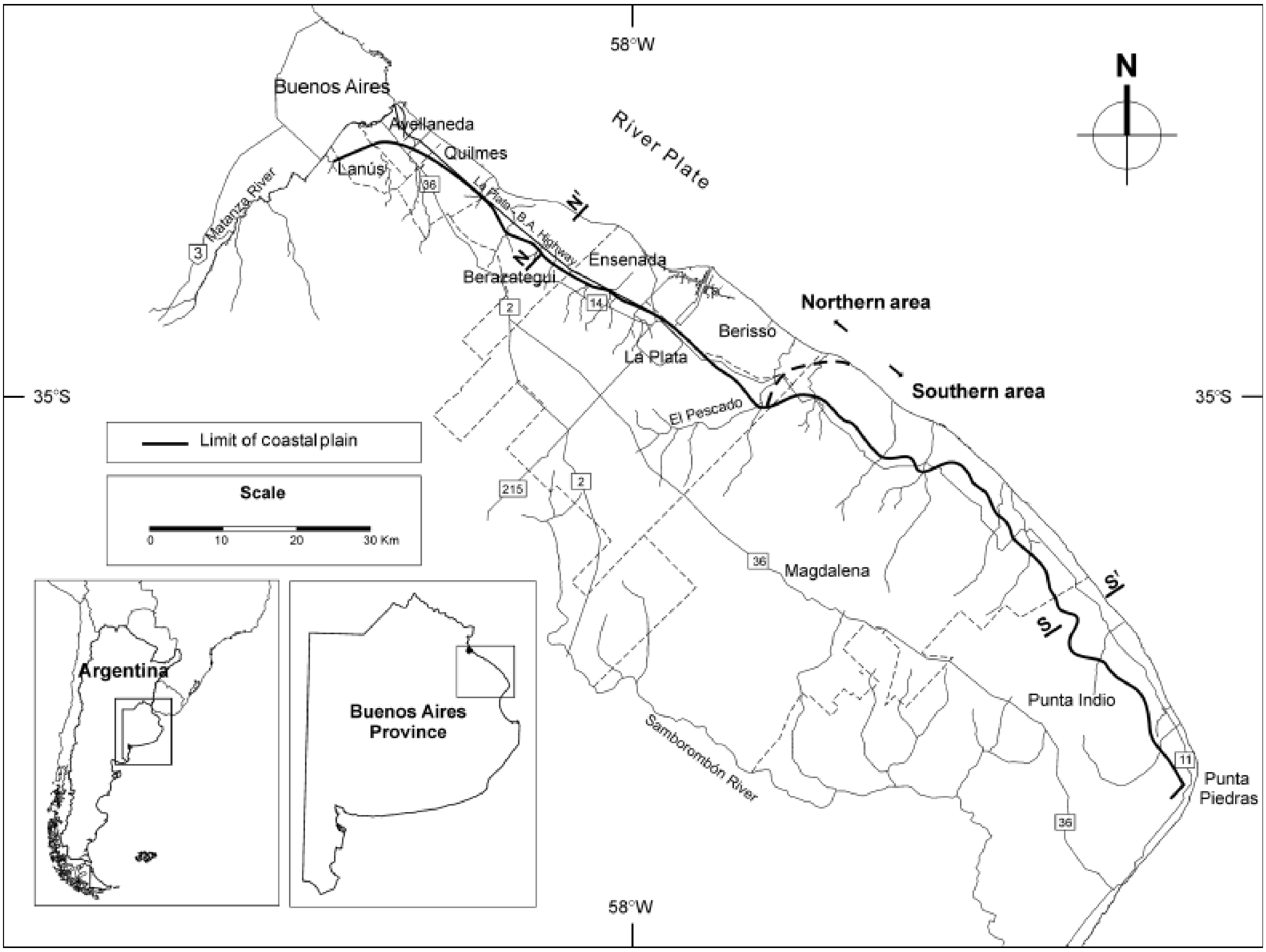

Fig. 1. Location map of the River Plate coastal plain.

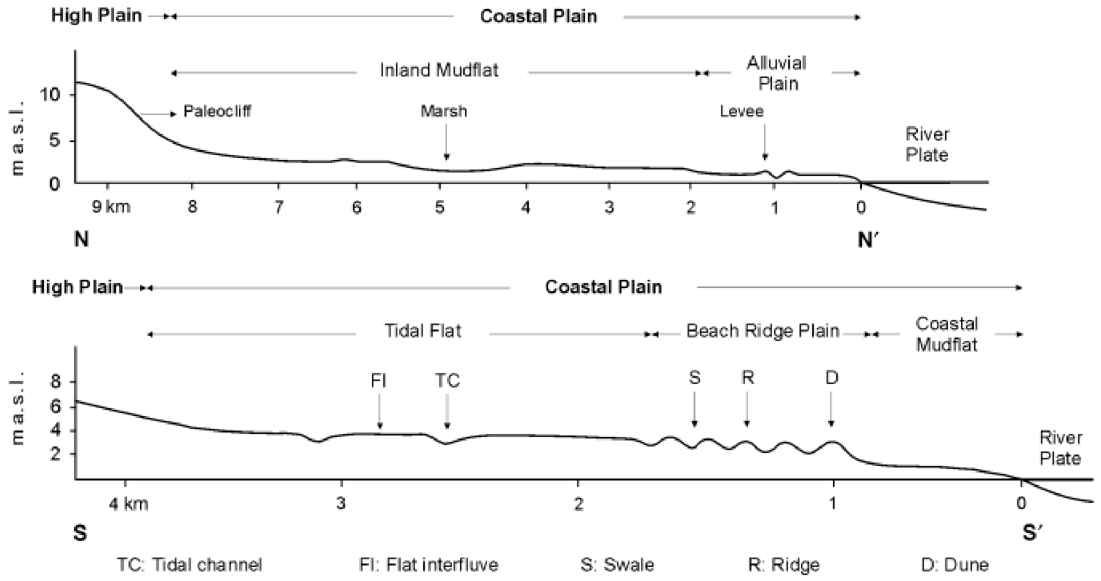

Fig. 2. Cross section of the transects showing the distribution of landforms.

The soils were classified at the subgroup level according to the Soil Taxonomy system (Soil Survey Staff 2006). Geomorphological descriptions were based mainly on Cavallotto (1995). Characterization of vegetation communities was based on regional and local studies by different authors (Parodi 1940; Cabrera 1963–1968; Vervoost 1967; Dascanio & Ricci 1988; Goya *et al.* 1992). Groundwater information is based on Ainchil & Kruse (2002) and Auge (1995). Data on water table depths, Fe^{2+} contents and E_h correspond to Imbellone *et al.* (2002), who monitored two soils in different landforms monthly from April 1998 to July 2000.

Study area

The study area is a coastal plain located in the north-east of Buenos Aires province, Argentina. It is a 160-km-long, 3–10-km-wide strip along the right bank of the River Plate from the southern limit of the city of Buenos Aires to Punta Piedras (Fig. 1). Its limits are the River Plate coastline and a fall line (at 5 m a.s.l.) that marks the boundary with an upland region ('High Plain') constituted by loessial sediments. The study area includes the municipal districts of Avellaneda, Quilmes, Berazategui, Ensenada, Berisso, La Plata, Magdalena and Punta Indio.

The River Plate is a 300-km long, 50–200-km-wide estuary that collects the waters of Paraná–Paraguay and Uruguay Rivers and empties into the Atlantic Ocean. A large quantity of suspended solids originated mainly in the watersheds of the Paraná and Paraguay Rivers are transported. The coastal plain is covered with materials derived from the intense sedimentation and the littoral transport and marine ingressions and regressions that occurred after the last glaciation maximum. The relief is nearly level or concave, except for a slightly undulating sector with beach ridges in the south. The regional slope varies from 0.1 to 0.05%.

Cavallotto *et al.* (1999) summarize the history of the River Plate coastal plain as follows: (a) beginning of a transgressive event (18–20 000 years BP) when muddy facies filled up the ancient river palaeovalley; (b) the moment of highest sea level (6000 years BP) when accretion processes become important and the coastal plain began to form and (c) the final coastal progradation when the environmental conditions changed from estuarine to fluvial. These fluvial and estuarine actions have given rise to stratigraphic columns that represent different sedimentary settings or landforms.

The base of the stratigraphic column is occupied by the Ensenada Formation, loessial Pampean sediments deposited from the Upper Pliocene to the Upper Pleistocene. The top of the Pampean sediments is defined by an erosive unconformity overlain by Holocene sediments deposited after the last glacial maximum, as a consequence of the transgressive–regressive episodes related to the last deglacial–postglacial cycle. The Holocene sedimentary sequence is divided by an unconformity surface into two levels: (1) a lower level consisting of mud sediments deposited in an estuarine setting in the freshwater/saltwater interface in equilibrium during the sea level rise (deglacial half-cycle) and (2) an upper level corresponding to the sedimentary record deposited from the time when the sea reached the highest relative level up to the present sea level (postglacial half cycle).

Climate

Climatic information corresponds to the city of La Plata, located approximately in the middle of the study area (34°55′S; 57°57′W; elevation 15 m a.s.l.; period of record 1905–2005). Mean annual precipitation is 1040 mm, with a fairly uniform seasonal distribution (summer 27.8%, autumn 27.8%, winter 18.8% and spring 25.6%). Mean annual temperature is 16.4 °C; mean temperatures of January (mid summer) and July (mid winter) are 22.8 and 9.9 °C, respectively. Extreme temperatures are 41 and − 5 °C (Departamento de Sismología e Información Meteorológica, Facultad de Ciencias Astronómicas y Geofísicas, Universidad Nacional de La Plata).

The water balance (Thornthwaite & Mather 1957) shows that the mean annual evapotranspiration is 806 mm, water surplus is 242 mm, mainly between May (late autumn) and October (mid spring) and water deficit is 7 mm, in summer. Water table depths in the region are closely related to these surplus and deficit values; thus, the highest depths occur usually in September (early spring) and the lowest in February–March (end of summer) (Auge 1995).

According to Thornthwaite's classification (1948), the climate is C2 B3′ r a′: humid, mesothermal, with low or zero water deficit and low summer thermal concentration.

An important local meteorological phenomenon is the 'sudestada'. It is characterized by persistent, strong south-east winds, usually accompanied by rain or drizzle. It is produced by the combined action of a high-pressure system in the Atlantic Ocean, off the central Patagonia coast, and a low-pressure system to the east of Buenos Aires province and Uruguay. The winds hinder the flow of water towards the Atlantic Ocean, which causes a rise of water level and the flooding of a portion of the coastal plain, variable in extension according to the severity and duration of the storm. South-east winds produce water rises of 1.02, 1.14 and 1.26 m for wind velocities of 60, 70 and 80 km/h, respectively; for east-south-east winds, the rises are 1.14, 1.32 and 1.50 m, respectively (Balay 1961). The critical estuary level, when flood hazard is imminent, is about +2.70 m. 'Sudestadas' can occur any time, but the most severe concentrates between March and October. June is the month with a greater number of strong 'sudestadas' and the return period for this month is 4 years. The highest level recorded is +4.65 m (15 April 1940), when flooding affected most of the coastal plain. The estuary is also affected by tides because of its proximity to the Atlantic Ocean; it has a microtidal regime as the tidal range varies from 0.46 to 0.52 m (Cavallotto 1995).

Landforms

The High Plain in contact with the coastal plain is a part of the so-called 'Rolling Pampa'. It is a very gently rolling plain, with a well-developed drainage network of fluvial valleys, tributaries of the River Plate and Paraná River. Slopes are generally below 5%.

In the coastal plain, Cavallotto (1995) differentiates two sectors (northern and southern) based on differences in landforms and sediments. In the northern area, two major geomorphological units are distinguished: (1) Inland Mudflat and (2) Coastal Levee (Albardón Costero); this unit has been named 'Alluvial Plain' by us to avoid confusions with other minor units. In the southern area, three main units are distinguished: (3) Tidal Flat, (4) Beach Ridge Plain and (5) Coastal Mudflat (Fig. 2). For the sake of simplicity, other less extensive units have not been included in the discussion. For the purposes of comparison, a description of the High Plain is also included.

The Inland Mudflat is 5–7 km wide and extends between the High Plain and the Alluvial Plain. The landwards boundary with the High Plain (at about 5 m a.s.l.) is marked by a fall line or palaeocliff, which in some cases is not well discernible. The origin of this unit is linked to the deposition of predominantly clayey sediments (Villa Elisa Facies of Las Escobas Formation) flocculated as a consequence of a saline water–freshwater interface, under low energy and shallow water conditions. Cavallotto (1995) recognizes a succession of palaeocoastlines that indicate deposition stages, or coast advance, interrupted by erosion intervals. This results in relief variations reflected in differences in soil drainage conditions and vegetation. The drainage network is poorly developed because of the flat relief; thus, many streams originated in the High Plain are unable to cut their channels and the waters spread on the surface. This has given rise to a number of marshes and other waterlogging-prone areas. The water table is normally at 1.00–1.50 m depth, and it can outcrop in the lowest lying areas (marshes) (Ainchil & Kruse 2002). According to Imbellone *et al.* (2002), the average water table depth in the dominant soil (*imperfectly drained Natraquert*, at 4 m a.s.l.) is 1.23 m (extreme readings 0.95–1.80 m).

The Alluvial Plain is constituted of recent fluvial deposits of predominantly sandy particle-size composition (Sandy Facies of Río Santiago Formation). Clays were deposited in a fluvial environment, which determines a predominance of illites over smectites (Cavallotto 1995). The unit appears discontinuously along the River Plate coast ranging in width from 2 to 5 km. It extends between the Inland Mudflat (2–3 m a.s.l.) and the River Plate coast. It is flooded to a lesser or greater degree by tides and southeastern storms ('sudestadas'). Water table is above 1.00 m depth most of the year (Ainchil & Kruse 2002). The average water table depth in one of the most widespread soils (*Fluvaquent*, at 1 m a.s.l.) is 0.42 m (0.16–0.90 m) (Imbellone *et al*. 2002). The drainage network includes a number of creeks, that act as tidal channels, generally flanked by natural levees which are the highest sites in the unit.

The Tidal Flat extends from the vicinity of El Pescado stream in the north to Punta Piedras in the south, between the High Plain and the Beach Ridge Plain. The boundary with the High Plain is not marked by a palaeocliff, as in the northern area, but by a slight slope, similar to a pediment. The Tidal Flat is characterized by the presence of meandering tidal channels separated by slightly higher areas (flat interfluves). The channels are relicts of an area affected by tides during the maximum of the Holocene transgression and became inactive after the accumulation of the beach ridges; they were later infilled with alluvial sediments. The water table is commonly between 1.00 and 1.50 m depth (Ainchil & Kruse 2002).

The Beach Ridge Plain is better expressed in the southern area. It is a 1–3-km-wide area, constituted of a succession of subparallel ridges or shell bars, decreasing in altitude towards the coast. The succession of ridges (five to eight in the study area) and inter-ridge depressions or swales produces a gently rolling landscape. The individual ridges are 30–100 m wide and 1–2 m high with respect to the adjacent swales. They are constituted of sand and mollusc shells accumulated by storm waves during the sea regression (6000–3000 years BP) in response to the littoral drift. The more common mollusc species include *Mactra isabelleana*, *Erodona mactroides*, *Tagelus plebeus*, *Littoridina australis*, *Buccionanops cochlidiu* and *Adelomedon brasiliana*. In the outer border, adjacent to the Coastal Mudflat, there are also dunes formed with sand from nearby beaches when the sea level was higher. This sand has also affected the upper horizons of the soils located in the outer ridges.

The Coastal Mudflat is a narrow strip, 50–300 m wide or in some cases absent, located between the Beach Ridge Plain and the beach. It is level to the concave area slightly sloping towards the coast. It would correspond to a 'schorre' *sensu* Tricart (1973) and it is subject to floods and high water table (generally above 0.50 m). The sediments are mostly clayey as a consequence of the highest concentration of suspended solids in the estuary waters and the flocculation of clay because of the presence of the freshwater/saline water interface. The deposition of clays in an estuarine environment also determines the predominance of smectites (52%) over illites (33%) (Cavallotto 1995).

Results and discussion

The distribution of landforms, soils and vegetation communities are summarized in Table 1.

High Plain

The soils are formed in windblown loessial sediments, sometimes reworked by water. They are well-developed soils; two typical horizon sequences are: A-Bt-BC-C and A-Btss, BC-C. Melanization and lessivage (clay illuviation) are the main soil-forming processes, accompanied in many cases by vertisolization. Interfluve soils are mainly *Mollisols* (*Typic* and *vertic Argiudolls*). *Vertisols* (*Typic Hapluderts*) are also found. In low-lying areas, *Alfisols* and sodic/hydromorphic *Mollisols* (*Natraqualfs*, *Albacualfs*, *Natraquolls*, *Argialbolls*) occur.

Vegetation structure in interfluves corresponds to a prairie, largely modified by agriculture and livestock production. The dominant genera are *Bothriochloa*, *Stipa*, *Piptochaetium*, *Aristida*, *Paspalum*, *Briza* and *Melica* (Cabrera 1963–1968). Shrubs, forbs and sedges are interspersed among the grasses; some of the more common genera are *Baccharis*, *Eupatorium*, *Phyla*, *Carex*, *Conyza* and *Adesmia* (Soriano 1991).

Inland Mudflat

The soils have formed in clays of the Villa Elisa Facies of Las Escobas Formation. An important part of these clays (30–50%) are smectites (Cavallotto 1995). This fact, and the very high percentage of total clay (60–80%) in the whole profile, account for the high swell-shrink potential of these soils (COLE > 0.1). This is reflected in well-expressed vertic features such as wide, deep cracks when dry, slickensides and wedge-shaped peds. Permeability is very slow when moist but when dry it can be initially rapid because of the presence of wide cracks (bypass flow). Drainage conditions are in general deficient, especially because of waterlogging. However, the slight differences of relief indicated above, produce some variations in drainage classes (from imperfectly drained to poorly drained). This is also reflected in the expression of the hydromorphic features (mottles, iron–manganese concretions, gley colours). The upper two horizons (0–30 cm) of an imperfectly drained soil have a mean E_h value (24 monthly readings) of 380 mV and 1.3 mg/kg of Fe^{2+} (Imbellone *et al*. 2002). In most cases, the soils are strongly alkaline (pH 8.5–9.5) because of the high content of exchangeable sodium. The sequence of horizons is A-Bngss-BCng-2Cg, and have been classified as *Typic Natraquerts*. The drainage differences were marked by the use of the 'phase' concept '*imperfectly drained phase*' for the

Table 1 Geomorphological units and subunits, lithostratigraphic units, soils and vegetation communities in the study areas

Geomorphology				
Unit	Subunit	Lithostratigraphic unit	Soils	Vegetation community
High plain (> 5 m a.s.l.)				
Interfluve		Fm. La Postrera Fm. Buenos Aires Loessial silts	Argiudolls (Hapluderts)*	Grassland
Coastal plain (0–5 m a.s.l.)				
Northern area				
1. Inland Mudflat 5.0–2.5 m a.s.l.		Fm. Las Escobas Fc. Villa Elisa Estuarine clays	Natraquerts (Epiaquerts)	Salt meadow
2. Alluvial Plain 2.5–0.0 m a.s.l.	2a. Natural levee	Fm. Río Santiago.	Fluvaquents	Gallery forest
	2b. Depression	Sandy Facies Fluvial sands (occas. clays)	Fluvaquents Hydraquents	Rush marsh, sauzal, ceibal, etc.
Southern area				
3. Tidal Flat 5.0–3.7 m a.s.l.	3a. Flat Interfluve	Fm Arroyo Espinillo	Natraqualfs	Salt meadow
	3b. Tidal Channel		Argialbolls	Hygrophilous meadow
4. Beach Ridges Plain 3.7–0.0 m a.s.l.	4a. Ridge	Fm. Las Escobas Fc. Cerro de la.Gloria Estuarine sands and shells	Haprendolls	Xerophytic forest (dense)
	4b. Swale	Fm. Las Escobas Fc.Punta Lara Estuarine silts	Epiaquolls	Hygrophilous grassland
	4c. Dune	Fm La Petrona Eolian sands	Udipsamments	Xerophytic forest (sparse)
5. Coastal Mudflat 2.5–0.0 m a.s.l.		Fm.Río Santiago Clayey Facies Estuarine/fluvial clays	Epiaquerts Natraquerts (Fluvaquents)	Rush marshes Wet prairies

*Soils in parentheses are subordinate.

soils in the higher positions and '*poorly drained phase*' for the soils in lower areas (marshes).

The dominant species are low grasses adapted to waterlogging and sodicity/salinity: salt grass (*Distichlis scoparia*, *Distichlis spicata*), Bermuda grass (*Cynodon dactylon*) and sedges (*Carex* sp., *Cyperus* sp.). A common naturalized weed is cardoon or artichoke thistle (*Cynara cardunculus*), usually found at slightly higher sites with better drainage.

There are also soils, especially in deeper depressions or marshes, which remain waterlogged most of the time and have lower contents of exchangeable sodium, classified as *Typic Epiaquerts*. Hygrophilous shrub species such as waxyleaf nightshade (*Solanum glaucophyllum*) and carda (*Eryngium eburneum*) are common in these sectors.

Alluvial Plain

The soils have formed in recent fluvial materials (Sandy Facies of Río Santiago Formation). Very fine and fine sand are the modal particle-size fraction, but clayey layers and buried organic materials are also found. Clay mineralogy is different from that of the mudflat soils: smectites decrease with respect to illite; there is a higher content of kaolinite, which would reveal the contribution of materials eroded from Oxisols and Ultisols of northern Argentina, Brazil and Paraguay and carried by the Paraná River.

The soils are poorly developed, with horizon sequences such as A-C-(2Oib)-3Cg. They are generally acid (pH 5–6), with low contents of soluble salts and exchangeable sodium. Drainage conditions are in general poor, because of susceptibility to waterlogging and flooding. However, differences produced by relief variations are observed; for example, soils located in natural levees bordering some creeks have slightly better drainage conditions. Most soils have well-expressed redoximorphic features (Fe mottles and Fe–Mn concretions) in the upper part of the profiles (above 40 cm approximately), where water table fluctuations are more frequent; gley colours appear in deeper horizons (below 40–50 cm) affected by the water table for a longer time. This differences in aeration are reflected in the redox potential (E_h) and Fe^{2+} contents of a typical soil: mean E_h is 341 mV in the two upper horizons (0–27 cm) and 190 mV in the third horizon (27–50 cm); Fe^{2+} contents are 2.9 and 48.2 mg/kg, respectively (Imbellone *et al*.

Fig. 3. Alluvial Plain. (a) Soil profile of a Typic Fluvaquent. (b) Gallery forest.

2002). *Typic Fluvaquents* are the dominant soils, which are found in natural levees and slightly lower areas (Fig. 3a). *Hydraquents* occur in areas that are waterlogged most of the time.

Soil and topographic differences determine variations in plant communities. The natural levees, which cover a small part of the unit, generally support a gallery forest, in many cases modified by forestry activities and invasive plants (Fig. 3b). The gallery forest has a 10–12-m-high tree stratum, in addition to shrub, herbaceous and muscinal strata with abundant lianas and epiphytic plants. It is the southernmost relict of the gallery forest extending along the Paraná and Uruguay Rivers. Its presence at this latitude is as a result of favourable edaphic and climatic factors. Some of the more abundant tree species are: mata ojo (*Pouteria salicifolia*), laurel (*Ocotea acutifolia*), (*Lonchocarpus nitidus*), canelón (*Rapanea lorentziana* and *Rapanea laetevirens*), chal-chal (*Allophylus edulis*), anacahuita (*Blepharocalyx tweediei*), coronillo (*Scutia buxifolia*), palo amarillo (*Terminalia australis*) and blanquillo (*Sebastiana brasiliensis*). In some areas, the forest is almost totally dominated by tree privet (*Ligustrum lucidum*) and in other cases a mixed forest codominated by tree privet and the above-mentioned native species is observed (Dascanio & Ricci 1988; Montaldo 1993). Other plant communities found in lower areas are seibales of *Erythrina crista-galli*, sauzales of *Salix humboldtiana* and riparian shrub lands of *Sesbania punicea*.

Tidal Flat

The contact with the High Plain is marked by the soils of the two subunits recognized in the Tidal Flat (flat interfluves and tidal palaeochannels) (Fig. 4a). They have different soils and vegetation communities. The soils of the flat interfluves have developed in sandy-clayey silts of Arroyo Espinillo Formation deposited in a mixohaline littoral setting. The soils have high contents of exchangeable sodium (30–60%) and are strongly alkaline (pH 8.5–9.5). Sodium has favoured clay illuviation and Btn (natric) horizons are found. This cation has also induced a reduction of aggregate stability and the formation of a sealing crust at the soil surface that causes a reduction of water infiltration and is an impediment to plant emergence. The soils are subject to frequent waterlogging and have well-expressed redoximorphic features (mottles, Fe–Mn concretions) and gley colours (2.5Y and 5Y hues). A typical horizon sequence of these soils, classified as *Typic Natraqualfs*, is An-Btng-BCng-Cng (Fig. 4b). The A horizon is usually thin, light in colour and has low amounts of organic matter because of the low vegetation cover of these areas; it is generally overlain by a 2–5-mm-thick sealing crust.

In the palaeochannels, the soils have developed from infilling alluvial materials. These soils remain saturated for a longer time than those of the flat interfluves as a result of the concave relief and the higher infiltration. This high water input has produced the translocation of clay in the profile, with the appearance of well-expressed eluvial and illuvial horizons (E and Bt horizons, respectively). Besides, a great part of the exchangeable sodium and soluble salts has also been leached to lower horizons. The presence of sodium in the past is revealed by the columnar structure of the Bt horizon. The soils are acid in most of the profile. The A horizon is dark with a high content of organic matter. At some sites, thin organic horizons (Oi) are observed because of the deficient mineralization of organic materials. A typical sequence is A-E-Bt-BC-C; the soils have been classified as *Argiaquic Argialbolls* (Fig. 4c).

In the profile pits of both soils, about 30 m apart, water table depth was measured and samples were taken for chemical analysis. The water table is shallow most of the time in both soils. However, some important differences in water properties between them are observed (Table 2). The differences are ascribable to the higher permeability and lower position of the tidal channels; thus, more rainwater is collected here, which accumulates as a lens

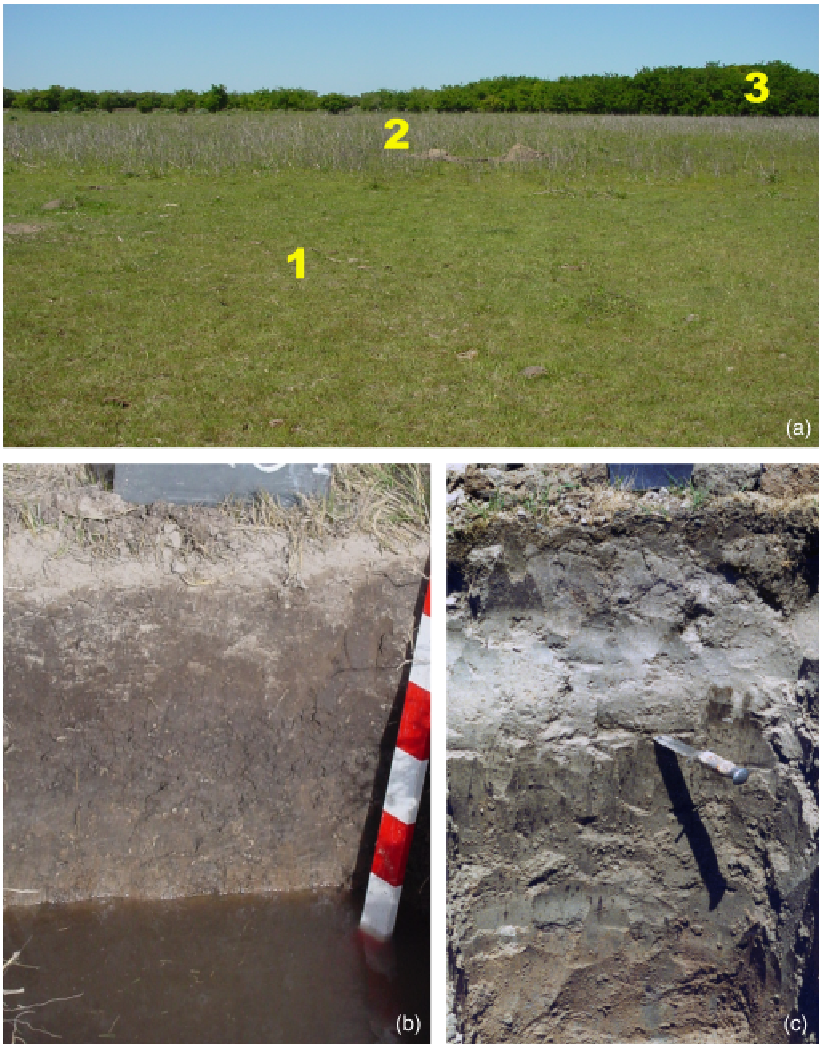

Fig. 4. Tidal Flat. (a) Landscape showing: 1, flat interfluve; 2, tidal paleochannel; 3, ridge in the adjoining Beach Ridge Plain. (b) Soil profile of a Natraqualf. (c) Soil profile of an Argiaquic Argialboll.

because of its lower density over the saline phreatic water (Ghyben-Herzberg lens, Ward 1975). The lower contents of exchangeable sodium and soluble salts of the *Argialbolls* also have an influence.

Plant communities differ markedly between both landforms and soils. Species tolerant to sodium and waterlogging are predominant in the *Typic Natraqualfs* of the flat interfluve. The most common species are salt grass (*D. scoparia, D. spicata*) and Bermuda grass (*C. dactylon*); colonies of a cyanobacterium (*Nostoc* sp.) are usually found on the surface. Vegetation cover is generally low (10–50%) because of the physical and chemical conditions of the soils (sealing crust, sodicity/salinity) and partially to salinity of phreatic water. The low plant density accounts for the reduced contents of soil organic matter.

Table 2 Phreatic water properties in the Natraqualf and the Argialboll

Soil Geomorphological subunit	Natraqualf Flat interfluve	Argialboll Tidal channel
Depth (cm)	120	94
Electrical conductivity (dS/m)	10.34	1.06
pH	8.1	7.3
Calcium (cmolc/L)	0.20	0.80
Magnesium (cmolc/L)	4.30	1.10
Sodium (cmolc/L)	131.25	8.52
Sodium adsorption ratio (SAR)	87.5	8.74

The tidal palaeochannels support a denser vegetation cover composed of hygrophilous species. The dominant plants are two herbaceous species: rush (*Schoenoplectus californicus*) and carda (*E. eburneum*) and a shrub: waxyleaf nightshade (*S. glaucophyllum*) (Vervoost 1967).

Beach Ridge Plain

The soils are distributed according to the three geomorphological subunits: ridges, swales and dunes. Ridge soils have formed in mollusc shells and sand, intermingled in the upper layers with loessial eolian materials. This mixture is revealed by the mineralogy of the modal fraction (50–100 μm) in the A horizon: 40% are shell fragments and calcic concretions and 60% have similarity with the loessial materials (volcanic glass, plagioclases, quartz and scarce heavy minerals). The soils are slightly developed as a result of the flocculating effect of calcium and the coarse texture. They are well-drained soils, with high infiltration velocity (11 cm/h). They are not usually affected by flooding or waterlogging; the water table does not affect the rooting system normally. The A horizon is dark, with a high content of well-humified organic matter (5–10%) and a granular or crumb structure. It overlies a transition horizon (AC) or more often, the C horizon consisting of shells and sand. These soils have been classified as *Typic Haprendolls* (Fig. 5a).

These soils support one of the few woody communities of the Pampean region: the tala forest or 'talares', which include two main species tala (*Celtis tala*) and coronillo (*S. buxifolia*). Other species of the tree stratum include sombra de toro (*Jodina* rhombifolia), molle (*Schinus longifolius*), elderberry (*Sambucus australis*), ombú (*Phytolacca dioica*) and curupí (*Sapium haematospermun*). The shrub stratum includes*:* *Pavonia malvacea*, brusquilla (*Discaria longispina*), escoba dura (*Sida rhombifolia*), quina (*Colletia spinosissima*), duraznillo negro (*Cestrum parquii*), etc. A number of creepers (*Clematis denticulata*, *Passiflora coerulea*, *Partenocissus quinquefolia*) and an epiphytic plant (*Tillandsia aeranthos*) are found on trees and shrubs. The herbaceous stratum is dense and include *Oplimenopsis najada*, *Parietaria debilis*, *Euphorbia portulacoides*, *Ambrosia tenuifolia*, *Bromus unioloides*, etc. (Parodi 1940; Dascanio & Ricci 1988; Goya *et al*. 1992; Cagnoni & Faggi 1993; Cagnoni *et al*. 1996) (Fig. 5b).

The tala forests are typical of the *Espinal* phytogeographic province, which covers about 310 000 km^2 in Argentina, mainly under subhumid and semiarid climates (ustic soil moisture regime). Even though all the species of the tala forest belong to this phytogeographic province, some species (*S. buxifolia, S. australis, P. dioica* and *S. haematospermun*) are also found in more humid provinces, such as the Paraná forests and their extensions in gallery forests. Likewise, other species (*C. tala*, *J. rhombifolia* and *S. longifolius*) also grow in drier phytogeographic provinces such as Monte and Chaco (Cabrera 1963–1968). These forests are degraded in many areas as a result of shell mining, firewood extraction, livestock production and deforestation (Goya *et al*. 1992).

The swales are occupied by poorly drained soils, subject to frequent waterlogging and high water table. They are finer in texture than the ridge soils, generally ranging from silt loam to silty clay. Typically, the surface horizon is dark with a high content of organic matter, and the underlying horizons have gley colours (2.5 or 5Y hues), partly inherited from the parent material and partly because of the influence of the water table. Shells are scarce or absent, but

Fig. 5. Beach Ridge Plain. (a) Soil profile of a Typic Haprendoll in a ridge. (b) Tala forest on a ridge. (c) Soil profile of a Typic Endoaquoll. (d) Hygrophilous grassland of a swale between 'tala' forests on the ridges.

the soil material is moderately calcareous throughout. A typical horizon sequence is A-(AC)-Cg1-Cg2. These soils are classified as *Typic Endoaquolls* (Fig. 5c).

These areas support hygrophilous grasslands that commonly have a high coverage. In the depressions nearer the coast, communities of *Eryingium cabrerae* and *Lolium multiflorum* are found, whereas in the drier areas *Stipa charruana* and *E. cabrerae* are present (Cagnoni *et al*. 1996). Other species are also found, such as *Puccinellia glaucescens*, *C. dactylon* and *Cyperus* sp. (Fig. 5d).

The dune soils are poorly developed, with A-AC-C sequences. The A horizon is light in colour, with a low amount of organic matter (about 1%) and without structure (single grain). The texture is sandy throughout, with very fine and fine sand as the modal fractions. Cation exchange capacity is low (5–7 cmolc/kg) and the reaction is acid (pH 5.5–6.5), except below 2 m depth, where shell fragments are found. At about 1 m depth, a number of 1–3-mm-thick subparallel lamellae, formed by clay and silt illuviation, are observed. Some water can accumulate above these lamellae. These are excessively drained soils with a high infiltration velocity (30–35 cm/h), classified as *Lamellic Udipsamments* (Fig. 6a).

The woody, shrubby and herbaceous vegetation is similar to that of the beach ridges but sparser. *C. spinosissima* can form dense thickets in places where the tala forest is thinner (Fig. 6b). The low vegetation cover can favour wind erosion in areas under livestock production or where the population of tucu-tucus (*Ctenomys talarum*) is higher (Sánchez *et al*. 1976). The activity of this rodent is revealed by the frequent presence of krotovinas (infilled burrows) in the soils of the beach ridges and the dunes.

Coastal Mudflats

The soils of this unit have developed in recent estuarine materials (Clayey Facies of Río Santiago Formation). The high clay content (60–70%) in the whole profile, dominated in many cases by smectites, determines a high shrink-swell potential, revealed by vertic features like slickensides and wide cracks when dry. These are poorly or very poorly drained soils because of flooding and a high water table, classified as *Typic Epiaquerts* or, when exchangeable sodium and soluble salts are high, as *Typic Natraquerts*. Other soils with a coarser texture (*Fluvaquents*) are also found.

A complex of hygrophilous plant communities are found in the unit. They are distributed mainly in relation to topographical gradients, which mainly affect flood duration. Some of these communities include cord grass (*Spartina* sp.); rush marshes of *S. californicus*, cattail (*Typha* sp.), bulrush (*Scirpus giganteus*) and espadaña (*Zizaniopsis bonariensis*) and wet prairies of *Scirpus americanus* and *Cyperus obtusatus* (Cabrera 1963–1968; Vervoost 1967; Cagnoni *et al*. 1996). Some of these communities have been invaded by yellow iris (*Iris pseudacorus*), which in some places is the dominant species (Cagnoni *et al*. 1996; Kalesnik & Malvárez 2003; Kalesnik *et al*. 2005).

Conclusions

Wetlands are complex ecosystems and the range of variation in wetland habitats is greater than in terrestrial habitats for the same climatic–geographic region. Further, more factors are responsible for the control of the environments in wetlands than in terrestrial ecosystems; in addition to landform, soil and fire frequency, common to both, wetlands are also controlled by hydroperiod and water source (Brinson 2004).

The River Plate coastal plain is an example of such complexity. The Holocene transgressions and regressions during the Holocene period have given rise to a variety of landforms, built of different materials. The combination of these two factors (topography and parent material) produced different soils, which determined the spatial patterns of vegetation. The boundaries of plant communities are largely determined by the hydroperiod, because soil water content is dependent on topography and materials

Fig. 6. Dunes. (a) Profile soil of a Lamellic Udipsamment. (b) Landscape of the dunes.

related to the maximum elevation in which different plant communities evolved. Changes of topography and materials are observed within very short distances, without ecotones in most cases.

(1) In the Inland Mudflat, the diversity of vegetation is low as a result of the limitations imposed by the relief, and the soils. The level or concave relief favours waterlogging, whereas the soils, derived from marine–estuarine clays, are a poor substrate for root growth, from the physical and chemical viewpoint. Consequently, the area is dominated by a limited number of herbaceous species adapted to waterlogging and sodicity/salinity.

(2) The Alluvial Plain, located in the northern area of the coastal plain, is subject to tides and floods from the River Plate and has a shallow water table. However, it possesses a greater diversity of plant communities than the Inland Mudflat because of the better physical and chemical conditions of the soils: coarser textures and low levels of exchangeable sodium and soluble salts. Further, its direct contact with the estuary dynamics favours the spread of seeds and propagules from the subtropical environments located upstream to the north.

(3) In the Tidal Flat, the distribution of plant communities are governed primarily by landforms and soils, showing two well-defined situations. In the slightly higher parts, the exchangeable sodium inherited from estuarine parent materials has been largely preserved in the soils, which support only species tolerant to this cation. In the tidal channels, sodium affected soil evolution to a lesser degree, partly because of the fact that these areas are infilled by alluvial materials from the uplands and partly because of sodium leaching, as a consequence of very frequent ponding. The differences in phreatic water properties may have also had an influence.

(4) Perhaps, the most striking contrast in the study area is the edaphic influence in the presence of xerophytic communities, which are climax in drier regions of Argentina. The presence of xerophytic forests on a coastal plain under a humid climate can be explained by the fact that they are edaphic communities, developed in shell ridges and dunes, where water retention is low because of the coarse particle-size soils and the convex topography. In the swales, subject to frequent waterlogging and with finer particle-size soils, the forests abruptly disappear and are replaced by hygrophilous species. Consequently, the boundary between both communities constitutes an edaphic limit between coarse and fine texture soils and a geomorphological limit, separating high, well-drained areas and low-lying areas subject to waterlogging following heavy rains. *C. tala* is usually considered a calcicole plant as it generally grows on shell bars. However, this and other species of the forest are more aptly considered plants of well-drained soils, because they are also found in nearby dunes or in loessial upland soils, where reaction is mainly acid. Tala forest species are sensitive to water saturation in the root zone, even for short periods. The water table increase as a result of sea-level rise may affect the roots of the xerophytic wood communities causing their decline, considering they are species sensitive to anoxia in the soil root zone, even for short periods.

Acknowledgements

The authors are grateful to David Edward for style corrections. We especially thanks to J. P. Bravard and an anonymous reviewer for your valuable comments and suggestions.

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