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Soil-geomorphology relationships and landscape evolution in a southwestern Atlantic tidal salt marsh in Patagonia, Argentina

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ABSTRACT

Salt marshes in Patagonia ecosystem are nowadays fully recognized by ecological, pollution and phytoremediation studies but a soil genesis and geomorphology approach is currently unknown. The aim of this study was to establish the soil-geomorphology relationship in Fracasso salt marsh and to determine the successional vegetation dynamics associated with the landscape evolution. This work was carried out in Fracasso salt marsh sited in Península Valdés, Argentina, where an integrated study on soil-geomorphology relationship and landscape evolution was performed along with sedimentological analysis and vegetation changes (C3 photosynthesis pathway vs. C4 photosynthesis pathway plants). This last was determined through the $\delta^{13}C$ composition from soil organic matter (SOM). Soil descriptions and laboratory analysis of soil samples were performed. A marked relationship between the vegetation unit, the dominant landform and the type of associated soil was found. *Limonium brasiliense* (Lb) and *Sarcocornia perennis* (Sp), both C3 plants, are dominant in levees associated with tidal creeks, and soils were classified as Typic Fluvaquents, while *Spartina alterniflora* (Sa) soils were classified as Sodic Endoaquents and Sodic Psammaquents. Although no sulfidic materials were identified by incubation test, they were identified by hydrogen peroxide treatment in Sa soils, and now are considered potential acid sulfate soils (PASS). Sedimentological analysis from deepest sandy C horizons indicates a beach depositional environment. On the other hand, the $\delta^{13}C$ stable isotope composition of SOM preserved into these buried soil acting as parent materials shows the dominance of C4 plants presumably belonging to *Spartina* species, suggesting a possible colonization and stabilization as the pioneer salt marsh.

1. Introduction

Tidal salt marshes are peculiar environments placed in the highest part of the intertidal zone where a muddy substrate generally supports a wide range of halophyte vegetation (Allen and Pye, 1992). These environments are formed according to the variations of sea level occurred during the Holocene and they are frequently flooded and subjected, not only to marine action, but also to the influence of water and continental sediments, either from estuary system or from surface runoff. This is why salt marsh soils have a very weak profile development, most of them belonging to Entisols Order and Aquents Suborder in places where aquic moisture regime prevails (Soil Survey Staff, 2014).

Anoxia and salinity conditions would be both sufficient to produce sulfidic materials (potential acid sulfate soils; Soil Survey Staff, 1999) due to the buildup and stability of sulphides, mainly pyrite, which comes from the biological reduction of sulphate dissolved in seawater and Fe^{3+} from marine sediments. This Fe^{3+} and SO_4^{2-} reduction is responsible for pH increase (Van Breemen, 1993; Konsten et al., 1994, Eqs. (1) and (2)). Therefore, sulfidic materials soils are classified as Sulfaquents (Great Group level, Soil Survey Staff, 1999).

$$Fe_2O_3 + 1/2CH_2O + 4H^+ \rightarrow 2Fe^{2+} + 1/2CO_2 + 5/2H_2O \quad (1)$$

$$SO_4^{2-} + 2CH_2O + 2H^+ \rightarrow H_2S + 2CO_2 + 2H_2O \quad (2)$$

Salt marsh soils are closely related with landforms, sedimentation processes and vegetation (Redfield, 1972; Fagherazzi et al., 2004). A first complete description of the main salt marsh landforms was made by Benito and Onaindia (1991) on the Mundaka-Urdaibai salt marsh (Basque Country, Northeastern Spain). They considered tidal channels as one the most important salt marsh landforms because of the exchange of matter and energy between the salt marsh and the ocean (Mitsch and Gosselink, 2000). In this way, linear channels are typical of the first stages of salt marsh evolution and, over the time, they evolve to more complex forms such as dendritic or meandriform-dendritic forms (Pye and French, 1993). Levees are another important salt marsh

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landform formed in the edge of the tidal channels as a consequence of sea water flow. In this way, during the flooding, a rapid sand sedimentation occur showing a pattern of grain size decreasing with the distance from the channel to the inner marsh (Friedrichs and Perry, 2001). As regards vegetation, Zedler et al. (1999) established a relationship between this variable and marsh elevation in California salt marshes. Therefore, Otero and Macias (2001) related the physiographic position with the dominant vegetation in order to characterize the main salt marsh soils.

Particularly, botanical zonation is the most common salt marsh characteristic worldwide which can be observed in a generalized cross-section of the salt marsh coastline, where soil conditions such as salinity, saturation, immersion and anoxia are highlighted by a pattern roughly parallel to the coast (Pennings and Callaway, 1992; Silvestri et al., 2005). This pattern could reflect ecological succession assuming that bare soils of the tidal flats are colonized by typical low marsh species that promote soil accretion by trapping sediment and producing land elevation. This would enable the colonization of other species and eventually, the first colonizing plants would disappear, possibly settling in the lower levels of the marsh (Leeuw et al., 1993; Steers, 1977). However, changes in vegetation may also be due to changes in sea level, continental water and sediment discharges or any other possible event (e.g. storminess) or geomorphological and sedimentological processes (e.g. changes on depositional regimes and sediment autocompactation) which took place during Holocene (Allen et al., 2006; Choi et al., 2001; Goman et al., 2008; Lamb et al., 2006, 2007).

One way to determine past changes in the vegetation and the geomorphology is by assessing the proportion of plants C4/C3 through $\delta^{13}C$ isotopic compositions from soil organic matter (SOM) which is recorded in the soil profile (Chmura and Aharon, 1995; Choi et al., 2001; Lamb et al., 2006, 2007). This is based on the discrimination of plants with respect to CO_2 during the process of photosynthesis, which is due to the biochemical properties of primary enzymes that fix carbon and to the diffusion process that controls the CO_2 entry in leaves (Farquhar et al., 1989). This type of discrimination varies according to the photosynthetic cycles C3, C4 and CAM of the terrestrial plants. C3 plants reduce CO_2 to phosphoglycerate (3C) via the ribose bisphosphate/oxygenase enzyme (Rubisco). That is why the plants with this type of photosynthesis have a $\delta^{13}C$ of −32‰ to −22‰ with an average of −27‰ (Boutton, 1991). They are best adapted to cool and wet environments. Unlike C3 plants, C4 plants reduce CO_2 to aspartic or malic acid (4C) via the enzyme phosphoenolpyruvate carboxylase (PEP). These plants discriminate less $^{13}CO_2$ so they have higher values in $\delta^{13}C$ than the C3 plants. The isotopic range for this plant type is −17‰ to −9‰ with an average of −13‰. (Boutton,1991). They are best adapted to hot, sunny environments which implies an evolutionary advantage on C3 plants regarding to global warming. For example, in a northern Patagonia salt marsh, in the low position, where waterlogging conditions prevail almost permanently, *Spartina alterniflora* (C4 pathway) species is dominant and tolerant to salt stress (Mendelssohn and Morris, 2002; Bortolus et al., 2015) and soil anoxia (Bertness, 1991; Idaszkin et al., 2011). Whereas in the high marsh position, where the water table is about tens centimeters deep, *Sarcocornia perennis* (C3 pathway) are dominant (Bortolus et al., 2009; Idaszkin et al., 2011).

In addition, in order to determine if the SOM is autochthonous (i.e. it contains terrestrial components such as lignin, cellulose and humic substances) or allochthonous (it contains marine components), the weight ratio of organic carbon to total nitrogen (C:N) is used. Lamb et al. (2006) established that C:N ratios higher than 12 suggest that organic matter is from terrestrial sources. On the contrary, the allochthonous component coming from aquatic organisms tends to balance at a C:N ratio ranging from 4 to 10, indicative of organic matter without cellulosic structures from algae and phytoplankton.

In view of the foregoing, research on salt marshes on Extra-Andean Patagonian coast has focused mainly on ecological, pollution and phytoremediation aspects (Bortolus et al., 2009; Idaszkin and Bortolus, 2011; Idaszkin et al., 2011, 2014, 2015, 2017). As regards the pedology and geomorphology approach, Bouza et al. (2008) carried out a preliminary study describing salt marsh soils and classified the main Patagonian salt marshes. In addition, Playa Fracasso, a salt marsh of great ecological interest (Bala et al., 2008; Idaszkin et al., 2011), has only been focused from multi-disciplinary studies such as soil-plant relationship, hydrological-geomorphological relationship, and salinization processes (Ríos, 2015; Alvarez et al., 2015, 2016). Moreover, integrated studies on soil – geomorphology relationship and geo-ecology are scarce, mainly those aimed at elucidating landscape evolution, ecological processes (e.g. ecological succession) and geochemical processes. Considering all the above mentioned, the aim of this study was to establish the soil-geomorphology relationship in Playa Fracasso salt marsh and to determine the successional vegetation dynamics associated with the landscape evolution. The results will substantially increase the knowledge about salt marsh soils and eco-geomorphology, and will be useful to apply successful conservancy strategies for these environments in the protected area of Península Valdés.

1.1. Study area

Península Valdés (PV) is a 3600 km^2 area located on the Patagonia east coast between parallels 42°05′ and 42°53′S and meridians 63°05′ and 64°37′W connected to the mainland by the Istmo Carlos Ameghino (Carlos Ameghino Isthmus) which is only 11 km wide and less than 30 km long (Fig. 1). That is the reason why PV is almost an island that belongs to the Patagonian steppe, a cool semi-desert environment which surrounds it. It has a dynamic coastal zone with active sand dunes, numerous cliffs, spits, bays and coastal lagoons. The inside land is a desert steppe with dry climate and strong winds. UNESCO designated PV as a World Heritage Site list in 1999 because its coast and gulfs have global significance for the conservation of marine mammals (e.g. southern right whale). And following the ecological approach, PV is considered a transition area between two phytogeographic provinces (Monte and Patagonia) and two marine biogeographic regions (Argentina and Magallanica) which results in the richest diversity of marshes with both, muddy and rocky bottoms. In particular, the *Spartina*-dominated muddy bottom marshes are found in PV northern area (≤42°S) and the *Sarcocornia*-dominated muddy marshes in the south (> 42°S) (Bortolus et al., 2009).

The study area corresponds to the so-called Playa Fracasso (PF) salt marsh, northeast of the Istmo Carlos Ameghino (Fig. 1) on the Golfo San José (San José Gulf) margins. This gulf splits longitudinally into two hydrographic domains (east and west) by a climatic frontal system. The west circulation domain of the current is driven by well-defined vortices at the edge of the mouth whereas in the east domain -where the present study was performed-the conditions are more stagnant (Amoroso and Gagliardini, 2010). Fracasso salt marsh had a muddy plain built up by deposition of very fine grains produced by decantation and retention of halophyte plants. This salt marsh was protected by high sand bars, presumably due to both an exceptional storm and an extraordinary tide. The salt marsh was dominated by tides and exhibits a pattern of accretion. This pattern was largely controlled by the distribution of tidal channels and creeks and ephemeral alluvial sediment inputs from the mainland. The surrounding salt marsh geologic units are represented mainly by tertiary marine rocky sediments of Puerto Madryn Formations (Middle Miocene), and by the sandy-gravel deposits called "Rodados Patagónicos" (RP) of Plio-Pleistocene age (Haller, 1981; Haller et al., 2001). These Neogene-Quaternary units outcrop both on active cliffs and on erosion scarps of the littoral piedmont. The Holocene, which partially covered these geological units, is formed by colluvial, alluvial, aeolic, and coastal marine deposits. In the study area the average annual precipitation is 246 mm and the average annual temperature is 12.5 °C. The tidal regime is semi-diurnal with an average value of amplitude between 7.01 and 4.57 m.a.s.l. (SHN, Servicio de Hidrografía Naval Argentino, 1983).