HYPERSALINE TIDAL FLATS (*APICUM ECOSYSTEMS)*: THE WEAK LINK IN THE TROPICAL WETLANDS CHAIN

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Word count: 8,933

ABSTRACT

Hypersaline tidal flats (HTF) are transitional ecosystems commonly occurring in arid/semi-arid coastal regions. These ecosystems typically border mangrove forests. HTF perform important functions related to the maintenance of coastal biodiversity as well as support socio-economic and cultural activities in local communities**.** Despite their importance, HTF are rarely studied, especially with regard to the understanding of their formation and function. From the premise that the knowledge on the formation of HTF and soil contribute to the understanding of ecological relationships occurring in these ecosystems, a review is presented. Flat topography, coastal dynamics, pronounced hydric deficit, limited frequency, and duration of tidal flooding are the key factors for the formation of these coastal wetlands. The active pedogenetic processes (salinization, gleyzation, sulfidization and bioturbation) are highly influenced by these factors and present important ecological roles, specifically in regards to carbon and nutrient dynamics. This review presents evidence for the necessity of further studies on the ecological relationships in HTF's, as well as determining the ecological connection between HTF and other wetlands. Filling this knowledge gap is essential if we are to improve public policies and conservation laws on the protection of all coastal ecosystems.

Key words: tropical semiarid estuaries, saltflats, ecosystem formation, soil formation

INTRODUCTION

Wetlands are transitional ecosystems between terrestrial and aquatic environments which occur in areas where soils are naturally or artificially saturated by water due to ground or surface water saturation. Furthermore, the saturation may take place during part of or the entire year. These ecosystems are commonly found in river deltas, estuaries, floodplains, and tidal flats (Neue et al. 1997).

These ecosystems are important in terms of the global biogeochemistry, water balance, wildlife, food source (Neue et al. 1997, Mitsch et al. 2009) and carbon dynamics (Nelleman et al. 2009) covering, approximately, only 5 to 7% of the world's surface area (Neue et al., 1997) Because of environmental functions, these ecosystems are among the most important, yet vulnerable and endangered ecosystems (Mitsch et al. 2009). In fact, in terms of global economics, the degradation of wetlands results in monetary losses in the form of goods and services which total approximately $630 million US Dollars per year (Blankespoor et al. 2012).

Mangroves are typical tropical and subtropical wetland ecosystems situated where the land meets the sea and are characterized by a high degree of ecological stability but with interactive components (e.g. channels, ponds, islands, and hypersaline tidal flats) which promote high primary productivity. The biological productivity is stimulated by the exchange of water masses, sediment, nutrients, organic matter, and animal populations (Tomlinson 1986, Kjerfve 1990, Alongi 2002, Lacerda 2002, Lana 2003, Alongi 2008). Due to the coupling of multiple components, mangrove ecosystems are key elements for the flow of energy and nutrients between terrestrial environments and the ocean. The result of this coupling of components is the generation of ideal conditions for nurseries and refuge areas (Alongi, 2002; Aburto-Oropeza et al. 2008). Considering the various roles of mangrove ecosystems (fisheries, forestry, coastal protection, recreation and tourism, nutrient retention, carbon sequestration, biodiversity, and also non-use areas), the estimates suggest that the global economic value of mangrove ecosystems are approximately \$27,000 US Dollars ha^{-1} yr^{-1} (Salem and Mercer 2012).

In Brazil, a geoenvironmental unit called *apicum* (pl. *apicuns*; from indigenous language Tupi: “apecu” meaning saltwater marsh; Cunha 1999) can commonly be found associated with mangroves found in arid and semi-arid regions (Meireles et al. 2007, Lebigre 2007, Hadlich et al. 2010). *Apicuns* are defined as hypersaline tidal flats formed in marginal areas of mangrove forests (or inside them), with a unique flora composition (Table 1), particularly when compared to the mangroves (Lebigre 2007). Similar environments other than "*apicum*" or "*tanne*" (Lebrigre 2007) were characterized and studied in other semiarid regions of the world sharing similar genetic and ecosystemic traits (Bigarella 1947, Bigarella 2001, Lana 2003, Conesa et al. 2011).The literature reports the occurrence of these hypersaline tidal flats in Brazil (Lebigre 1999, Hadlich et al. 2008, Marques 2010), Africa (e.g., Gabon and Madagascar) and Oceania (New Caledonia; Lebrigre 2007).

The key characteristic of these ecosystems is that they are hypersaline and may reach salinity values up to five times greater than those found in the sea water (Ridd and Sam 1996, Sam and Ridd 1998, Ridd and Stieglitz 2002). Furthermore, the association of HTFs with mangroves is also a necessary condition for the characterization of this ecosystem (Lebigre 2007, Hadlich et al 2010).

When compared to other coastal ecosystems, the studies of these hypersaline tidal flats are recent (Lebigre 2007) and began with studies in Senegal (Vieillefon 1969, 1977, Marius 1985). In fact, Lebigre (2007) reported that the first study of hypersaline tidal flats (*tannes*) was carried out in Senegal and Gambia, followed by studies in

Madagascar, Australia, Nicaragua and Ecuador; all located in tropical climates with a three month dry season. According to Marius (1985), the hypersaline tidal flats are formed through flooding and drying cycles which culminate in increases salinities relative to entering sea water with the disappearance of mangroves and the colonization of soils by halophytes. Sadio (1989) reported that pedogenesis in these environments is driven by the water regime conditioning the occurrence of hydromorphism, and also includes gleying and sulfidization processes.

In southeast Brazil (the State of Espírito Santo), Marius (1985) performed the first pedological study in environments similar to the Senegalese *tannes*. The author found soils characterized by a sandy clay texture, grey colors, and colonies of *Philoxerus vermicularis*, *Sesuvium portulacastrum,* and *Eleocharis caribaea.* The region identified in southeast Brazil, however covered less area than the hypersaline tidal flats in Africa.

In spite of the limited number of studies, these ecosystems perform important functions in terms of the maintenance of the biodiversity of flora and fauna in coastal environments, as well as provide socio-economic and cultural activities for local communities (Nascimento 1993, Schmidt 2006). For example, local populations use these areas to harvest crustaceans (such as *Cardisoma guanhumi* [Leitreille]), for recreational activities, and also as grazing sites for domesticated animals (Ackermann et al. 2006). Furthermore, these environments allow access to the mangrove forest (Meireles et al. 2007). Although mangroves and *apicuns* perform a great number of similar social and ecological functions, the latter are still subjected to a great variety of human pressures, especially in northeastern Brazil (Meireles et al. 2007). This negative environmental impact is likely due to the fact that mangroves have always been explicitly protected by Brazilian laws whereas *apicuns* were poorly protected (Ucha et al. 2008, Hadlich et al. 2008).

Despite the importance of these HTF's, a great knowledge gap still exists, specifically with regard to ecosystem formation and soil genesis (Ucha et al. 2008, Hadlich et al. 2010). Determining how ecosystem and soil processes function in HTF's is crucial to understanding their function as a whole on an ecosystem level., Here we present a literature review in order to provide theoretical analysis on the processes that occur in these tropical wetlands, with specific reference to soils.

Hypersaline tidal flats: definitions and general characteristics

The Brazilian word "*apicum*" describes sandy areas close to mangroves (Cunha 1999, Hadlich et al. 2008). In reference to the *apicum* ecosystem, the words "*salgado*" (Salty, briny) and "*areal*" (Sandy area) were also reported by Schmidt (2006) as synonyms used by local populations to refer to hypersaline tidal flats from NE-Brazil. In addition, the words "*salt flats*", "*tidal flats*" and "*supratidal flats*" are used to reference environments which are similar to the Brazilian "*apicuns*", even though, there is some controversy on the best synonym for these terms in English. According to Lebigre (2007), the Brazilian *apicum* environments correspond to the French term "*tannes"*, also used to designate HTF's.

Apicuns are the transition zones found mostly between semiarid mangroves forests and the adjoining dry upland areas, i.e. Coastal Tablelands in Brazil (Fig. 1 and 2; Hadlich et al. 2008, Ucha et al. 2008, Marques 2010), also occurring within mangrove forests (Maciel 1991, Schmidt 2006, Hadlich et al. 2008) and whose limits are set by the mean level of the spring tides (Fig. 1 and 2; Maciel 1991, Pellegrini 2000).

The apicuns environments, which are always associated with mangroves (Schaeffer-Novelli 2002), are subjected to much less frequent tidal flooding periods compared to mangrove flooding frequency. This different flooding regime coupled with high evaporation and low precipitation rates causes the formation of hypersaline soils (Ridd and Sam 1996, Sam and Ridd 1998, Ridd and Stieglitz 2002), which frequently present salt crusts (Fig. 3A; Lebigre 2007, Hadlich et al. 2008). The less frequent tidal flooding regime is caused primarily by the transport of sediments into the estuaries by water and/or wind. Sediment transport promotes the formation of sediment banks and the subsequent obstruction of tidal creeks, thus limiting the flow seawater to tidal flooding during the spring tides. The rainfall regimes with long and well defined dry seasons also contribute to the development of the hyper-salinity.

The apicum differs from salt marshes and tidal marshes in that the latter flood daily on during high tide. The flooding results in strong chemically reducing conditions (Odum 1988) that dilutes the salinity. The lower salinity conditions in salt marshes and tidal marshes promote the development of grasses and sedges, while the HTF are primarily vegetated by extreme halophytes (Table 1; Fig. 3B; Marques 2010), or are devoid of vegetation (Fig. 3C; Hadlich et al. 2008). The sabakhas, on the other hand, are hypersaline flats which occur only in arid regions, are colonized by cyanobacteria (Attia 2013) and differ from the apicum in the mineral composition of the sediments, composed by well developed evaporites (Stanford and Wood 2001, Attia 2013).

The soil salinity in the HTF controls the species which colonize the soils: they are typically halophytic perennial herbaceous succulents (e.g., *Batis maritima;* Table 1; Fig. 3D), rather than mangrove. However, the seasonal climatic variations influence plant colonization patterns in hypersaline tidal flats soils. During the rainy season, rainfall dilutes the salts and allows the colonization of soils by typical mangrove species

(Nascimento 1999, Hadlich et al. 2010). In addition, during dry seasons, which are common along the NE-Brazilian semiarid coast, the expansion of *apicum* species may spread into mangrove ecosystems (Portugal 2002, Filho 2007).

Hypersaline tidal flats may interact with the adjacent ecological systems through ecological, geological, sedimentological, and pedological relationships (Lebigre 1999, Meireles and Silva 2002). However, hypersaline tidal flats clearly differ from other wetland ecosystems (e.g. salt marshes, swamps, mangroves, and lagoons) and therefore are important to the environmental variability and biodiversity in coastal zones.

Socio-ecological roles of hypersaline tidal flats

Hypersaline tidal flats provide refuge, nursery habitat, food resources for different animal species, primarily decapod crustaceans (Nascimento 1993, Schmidt 2006) (Fig. 3E and F, Fig. 4A). According to Nascimento (1993), large populations of fiddler crabs *Uca spp.* may be found in these ecosystems. During the rainy season, the population density of *Uca* may reach up to 250 individuals per square meter (ind m^{-2}), while in areas shaded by mangrove trees, the density of young *Ucides* specimens does not exceed 30 ind m^{-2}.

The *Cardisoma guanhumi* (Leitreille) land crab, which is an important food source for local populations (Fig. 3E and F), burrows in elevated sites where flooding is less frequent, specifically in the *apicum*, contrary to other typical mangrove crab species (e.g., *Uca maracoani* and *Ucides cordatus*; Oliveira 1946). Thus, the conservation and protection of *C. guanhumi* depends on the conservation of *apicuns* (Firmo et al. 2012). In addition, *Gecarcinidae* and juvenile *Callinectes* crabs are also found in these HTF's (Normann and Pennings 1998).

With respect to the edaphic perspective, these hypersaline tidal flats act as a nutrient reservoir to surrounding ecosystems providing organic matter, nutrients and ions (Nascimento 1999, Marques 2010). Moreover, HTF's represent a strategic region for protecting mangrove species in response to rising sea level (Portugal 2002) as well as other natural and/or anthropogenic disturbances.

Coastal wetlands, such as mangroves and salt marshes are known to store high amounts of organic carbon. Despite their relatively low area, in comparison to some other coastal communities, these environments may store up to 50% of the global terrestrial organic C (Gorham 1995, Lal 2004, Hopkinsonet al. 2012). For example, salt marshes represent the coastal wetlands with the highest burial rate (mean = 1.51 Ton C ha^{-1} y^{-1}), followed by mangroves (mean = 1.39 Ton C ha^{-1} y^{-1}) and seagrasses (0.83 Ton C ha^{-1} y^{-1} (Nelleman et al. 2009) (Table 3). Unfortunately, at this time data are not available for the organic carbon burial rate in *apicum* environments. However, since HTF represent a key role for the preservation of semi-arid mangrove forests, the anthropogenic impacts on these HTFs would also impact the ability of the mangrove to act as a carbon sink (Lacerda et al. 2007). Recently, the conception of the term "*Blue Carbon Sink*" was used to describe the importance of coastal wetlands in the global carbon cycle (Nelleman et al. 2009). The potential for carbon sequestration by *apicuns* occurs via mangrove burial processes during genesis; and therefore highlights the importance of protecting these and other coastal wetlands (Chmura et al. 2003, Nelleman et al. 2009).

The HTF also has a great socio-economic and cultural importance. The local populations (e.g., indigenous peoples, fishermen, shell fishermen) collect crustaceans, fish, and shellfish necessary to their diets from mangroves and associated areas; furthermore, they use the *apicum* regions to accesses the mangroves (Meireles et al

2007). However, some crustaceans, such as *Cardisoma guanhumi* (Leitreille), which have great economic value, are often collected primarily from *apicum* regions. In addition, the *apicums* close to the fishers' houses may be used for goat and cattle husbandry (Fig. 4B; Ackermann et al. 2006, Lebigre, 2007), as well as for recreational activities.

Despite its social and ecological importance, hypersaline tidal flats have been subjected to a great variety of anthropogenic stresses in different parts of the world due to economic activities, such as aquaculture (e.g. shrimp farming) and salterns (Fig. 1, and 2; Wilke and Fortuna 2003, Lebigre et al. 1990, Lebigre 2007, Ucha et al. 2008, Hadlich et al. 2008). According to Meireles et al. (2007), in the Brazilian states of Rio Grande do Norte and Ceará, where shrimp farming activity is intense, the deployments of production ponds occurs on hypersaline tidal flats (Fig. 1 and 2).

The Brazilian Forest Code (Brazil 1965) and the National Council of the Environment (CONAMA; Brazil 2002) consider the mangrove forests as permanent preservation areas. However, due to the legal interpretation, the enforcement of laws governing for the protection of *apicum* regions have been inadequately described (Schaeffer-Novelli 2002). Considering the close relationship between mangroves and *apicuns*, the latter should be considered as part of the mangrove ecosystem with regards to the applicability of conservation laws (Schaeffer-Novelli 2002). Although the New Brazilian Forest Code (NBFC; Brazil 2012) has included *apicum* regions, it also has allowed for an occupancy rate of 10 to 35% by shrimp farms and salterns, respectively. Furthermore, the saltern and shrimp farm activities initiated prior to July 22nd 2008 in *apicuns* were legalized (Brazil 2012).

Due to the reduced number of studies focusing on *apicuns* ecological functions, within their ecological boundaries and associated mangroves, it is virtually impossible to protect *apicuns* in Brazil (Rovai et al. 2012). Therefore, once anthropogenic activity is allowed to occur within these ecosystems, mangrove forests may also become threatened (Rovai et al. 2012).

Geomorphological aspects of hypersaline tidal flats

Apicuns and mangroves are contiguous ecological systems which present contrasting soils, with very different physical, chemical and mineralogical characteristics (Ucha et al. 2008, Marques 2010). From a geomorphological point of view, the HTF's are considered active areas which constantly receive sediments from dunes and adjacent higher terrains (e.g., Coastal Tablelands from the Brazilian coast). Sediments are delivered via three possible mechanisms: (1) wind action, which also affects mangroves and estuarine channels; (2) waves that deposit sediment during ebb flow; and (3) the riverine system which transports sediments from inland areas and deposits it along the coastal plains (Fig. 5; Meireles et al. 2007).

The sedimentary material forming HTF soils ranges from fine (clay and silt) to coarse (sand). However, the sand fractions composed of quartz and feldspars (Table 2; Marques 2010), may have different origins than the sediments deposited by the above mentioned processes. According to Hadlich and Ucha (2009), after the sediment deposition, the dispersion of colloids by sodium in seawater, combined with the high energy of tides and rainfall events, result in the clay removal, particularly in surface layers (Table 2). The relatively high sand content in Brazilian hypersaline tidal flat soils may also be related to the evolution of the coast during the Quaternary period. Many studies suggest that during the evolution of the Brazilian coastal plains, areas with lower elevation, such as the riverine plains, were covered with sand deposits from the

Pleistocene and were later reworked during a subsequent transgression (5,100 years BP; Funceme 2009, Villas Boas et al. 2001, Meireles and Raventos 2002).

Some studies using proxies, such as pollen (Behling et al. 2004), tannin (Benner et al. 1990), and pyrite (Roychoudhury et al. 2003, Nielsen et al. 2011), also suggest that HTF's originated from the burial of ancient mangroves. This hypothesis is supported by the presence of traces of mangrove plant tissues buried beneath different HTF's in Brazil and other parts of the world (Table 2; Fig. 4C). The expansion and regression dynamic between the mangrove forests and the HTF can also be confirmed based on the presence of remnants of oyster shells in deeper layers of HTF soils (Nascimento 1999, Hadlich et al. 2010) and preserved mangrove roots (Nascimento 1999, Hadlich et al. 2010, Marchand et al. 2011).

Bigarella (1947) studied the coastal plain from the Brazilian southern state of Paraná and described an environment similar to the HTF with a marked contrast between the rainy and dry seasons. The described HTF's were composed of sandy-clay soils, which evolved to sandy tablelands in response to the high inputs of sediments followed by colloid dispersion and removal. At the subsurface, an ancient buried mangrove called "*mangrovito*" was found. Further studies in Paraná reaffirmed that the HTF studied in 1947 was previously vegetated by a mangrove species. During a drier and hotter period past, a thin layer of salt crust precipitated on the soil surface (burying the mangrove), and thus promoting the establishment of the herbaceous vegetation present today (Bigarella 2001).

In Brazil, these ancient mangrove forests are located in upper physiographic position (due to transgressive processes) and were probably displaced by the restriction of tidal flooding and lower sea levels that occurred during the last regression period (Fig. 5B; Hadlich et al. 2010, Marques 2010). This last regression would also be responsible for the production of sediments present in diverse geomorphological features (e.g. dunes and fluviomarine plains; Tomazelli et al. 2008).

Another factor that is considered to contribute to the formation of HTF's, though detrimental to mangroves, is the input of sediment from adjacent elevated areas (e.g. Brazilian Coastal Tablelands). In the long term, terrestrial sediment transport may cause mangrove dieback (Ucha et al. 2004, Ackermann et al. 2006). The flat topography of hypersaline tidal flats, with slopes up to 0.4% when compared to the steeper slopes (> 3%) of contiguous areas, reinforces the hypothesis that HTF develops from the deposition of sediments from higher positions in the landscape (Hadlich et al. 2008).

Some authors suggest that the formation of HTF's may also be due to the formation of sand banks as a result of trapping of sediments by mangrove root structures (e.g. *Rhizophora mangle;* Cintrón 1978). The constant sediment input would raise the topographic level in relation to the mangrove, impeding tidal waters and promoting salt accumulation in soils (Vieillefon 1969, Pellegrini 2000). Other authors propose that the construction of dams in semiarid inland river basins would reduce freshwater delivery to estuaries, and therefore increasing the salt intrusion into freshwater regions (Knoppers et al. 2006, Hadlich and Ucha 2009). Similarly, shrimp farming activity and marine salt exploration in the salterns could also contribute to the development of HTF's, due to the fact that both activities promote changes in water flow in mangroves because of pond construction. After abandonment the regions affected by ponds construction may develop hypersaline soils (Meireles et al. 2010).

Pedogenesis in HTF's

In Brazil HTF's are frequently found in the states of Ceará and Bahia, due to the favorable climatic conditions (tropical arid and semiarid) for the formation of these ecosystems (Fig. 1). In fact, global HTF's are associated with semiarid climates (Table 2; Schaeffer-Novelli et al. 1990, Shaeffer-Novelli 2002, Hadlich et al. 2008, Ridd and Stieglitz 2002). At these sites, during the rainy season the amount of freshwater that supplies the aquifer is sufficient to dissolve salts and favors the reduction of soil salinity. However, during the dry seasons evaporation and capillary rise of water enhances the salinization process (Lebigre 2007; Table 2; Fig. 5) and may result in the formation of salt crusts (Fig. 3A) with the precipitation of calcium carbonate ($CaCO_3$), dolomite ($CaMg(CO_3)_2$), gypsum ($CaSO_4.2H_2O$), halite (NaCl) and sylvite (KCl; Ridd et al. 1997, Barbiéro et al. 2002). Thus, as a reflection of the marked climatic seasonality, the salinity in these environments presents significant seasonal variation, with an increase in salt concentration during dry periods (Hadlich et al. 2008, Lebigre 1983). According to Lebigre (2007), the translocation of salts associated with the formation of these HTF's may be referred to tannification, in reference to *tannes*.

The high content of exchangeable Na in HTF soils (Marques 2010) may also be a result of the salinization process, which would initially promote the precipitation of less soluble salts (e.g. $CaCO_3$), and the replacement of exchangeable Ca^{2+} by Na^+ (Langmuir 1997). The remaining high concentrations of sodium and bicarbonate would increase the concentration of CO_3^{2-}, and therefore leading to high pH values and clay dispersion (Table 2; Miller and Pawluk 1994, Barbiéro et al. 2002, Marques 2010). The occurrence of alkalinization has been described in other wetlands (e.g. mangroves and salt marshes) due to the fact that high pH is characteristic of HTF's where precipitation of carbonates is known to occur (Marques 2010).

The hypersaline conditions and tidal regime also determine some of the morphological features of soil and the vegetation. The structure of hypersaline tidal flat soils (Table 2) indicate that these soils are subjected to incipient soil ripening (dehydration, shrinkage, development of crack, and an increase in permeability and development of soil structure; see Ellis and Atherton 2003, Vermeulen et al. 2003) in response to tidal waters and a natural drainage deficit. Due to the hypersaline soils HTF's are heavily colonized by herbaceous succulents in a patchy vegetation pattern. The spatial distribution of vegetation may also act as a limiting factor for structure development in soils as well as for the input of organic carbon to these soils (Table 2; Pennings and Richards 1998). In some cases the first few millimeters of the HTF soils are characterized by a higher content of organic matter than in the subsequent layers. The higher concentrations in the surface layers is likely due to microalgae biomass found as a coherent-laminated structure known as microbial mats (Fig. 4D; Ridd et al. 1997, Meireles et al. 2007, Huerta-Díaz et al. 2011, Marchand et al. 2011). These structures, dominated by cyanobacteria, are widespread in nature but typically limited to extreme environments (Huerta-Díaz et al. 2011) and play an important role in bio-mineralization and nutrient dynamics (Pires and Lacerda 2008, Reimer and Huerta-Díaz 2011, Huerta-Díaz et al. 2011). On the other hand, the patchy vegetation cover may be related both to nutrient availability and flooding patterns which determine the spatial extent of salinity and redox conditions (He et al. 2011). Thus, site-specific soil conditions combined with tidal flow patterns may be the primary factors determining ecological relationships between plants and soil in an HTF.

In an HTF the water input occurs primarily during spring tides or due to drainage of adjacent continental areas (Hadlich et al. 2009, Marques 2010). The water regime in these soils is characterized by periodic water saturation and therefore hydromorphic conditions (Marques 2010). In response to waterlogging, HTF soils are prone to the anaerobic organic matter decomposition (Marchand et al. 2011). In the absence of O_2, the decomposition of organic compounds takes place with alternative electron acceptors (e.g. Fe^{3+}; Mn^{4+}; SO_4^{2-}) in a sequential cascade which reflects the energetic efficiency of the process (O_2> NO_3^-> Mn^{4+}> Fe^{3+}> SO_4^{2-}> CO_2; Reddy et al. 1986, Canfield et al. 2005).

In HTF soils the reduction of Fe (III) minerals (e.g. ferrihydrite; goethite; lepidocrocite; through the bacterial reduction of iron) causes the development of grey or neutral colored soils (with or without mottling). These soil colors are typical of reducing environments and of the gleying processes (or gleyzation; Fig. 5; Marques 2010). The variation in the water table may also result in the formation of brownish and reddish mottles (Fig. 4E). After Fe reduction the decomposition of organic matter occurs via sulfate reduction (or sulfidization; Fig. 5); which results in the formation of metallic sulfides, such as Acid Volatile Sulfide (AVS) and pyrite (Berner 1984, Rickard and Morse 2005). Sulfate reduction is an important microbial metabolic pathway in mangroves and coastal wetland soils (Table 2; Alongi 2002, Lambais et al. 2008, Otero et al. 2009), and may be evident in sea water as in the high concentrations of dissolved sulfate detected during tidal flooding (Otero and Macías 2002). The presence of iron sulfides in these soils may also be due to inheritance from pre-existing buried mangrove soils, rather than from active/recent sulfidization processes (Marques 2010). Therefore, iron sulfide formation (sulfidization), may be restricted to the deeper layers in HTF soils. Sulfidization may also occur in response to anoxic conditions caused by higher water levels in combinations with sulfate input by seawater, iron from ground and surface waters, as well as to the presence of existing organic matter (from ancient mangroves). Sulfidization is an important process in HTF's as it occurs with less intensity in comparison to other wetlands that undergo constant flooding (Marques 2010, Marchand et al. 2011).

Sulfidization may also play an important ecological role as it controls trace metal biogeochemistry and bioavailability through the co-precipitation of metals with pyrite or via the formation of metallic sulfides (Morgan et al. 2012, Huerta-Diaz and Morse 1990). However, these metallic sulfides are highly unstable under oxidizing conditions and may lead to oxidation and the release of associated metals: therefore increasing bioavailability of trace metals. Therefore, any natural or anthropogenic disturbance of the system may increase the contamination risk of the adjacent mangrove ecosystems (Morgan et al. 2012). Sulfides oxidation, due to changing in redox conditions, is also responsible for marked decreases in soil pH (typically to values less than 3.5; Equation 1; Otero et al. 2008, Burton et al. 2006).

$$4FeS_2 + 15\,O_2 + 14\,H_2O \rightarrow 4Fe(OH)_3 + 8SO_4^{2-} + 16H^+ \qquad \text{Equation (1)}$$

The oxidation of iron sulfides (which results in the formation of iron oxyhydroxides; Langmuir 1997; Otero et al. 2008, Burton et al. 2006) is the primary pathway for the accumulation iron oxyhydroxides in HTF soils (Marques 2010). Furthermore, the oxidation of dissolved iron (Fe^{2+}) in continental drainage waters is due to aerobic conditions and may also result in the accumulation ferric compounds in the superficial sediment layers.

Another conspicuous process in HTF soils is bioturbation (Fig. 5). This process causes the dispersion and/or displacement of soil particles by benthic organisms or plant species, and determines the biogeochemical state of the substrate (Gabet et al. 2003, Ferreira et al. 2007, Maire et al. 2008). In wetland soils, bioturbation leads to changes in the functioning of ecosystems by modifying physical, chemical, and biological characteristics of soils and sediments, oxygen diffusion, nutrient flow and, rates of organic matter mineralization (Jones et al. 2006, Meysman et al. 2006, Maire et al. 2008). Bioturbation differs from others pedogenetic processes because it promotes considerable changes not only due to biochemical processes, but also by the mobilization of particles and by the construction of channels (made by interstitial and superficial fauna) in the sediments through which water flows.

Kristensen et al. (2008) consider crabs to have a considerable impact on ecosystem functioning as they are responsible for the transfer of nutrients, for maintaining high functional diversity, and promote considerable biogeochemical heterogeneity within wetland soils. Similarly, it would be expected that the high density of crabs typically found in HTF's would also cause changes in its soils, as is indicated by observations of morphological features (Fig. 4F). However, to our knowledge, no studies are presently published on the effects of crab bioturbation in HTF soils. Therefore, while the importance of faunal activity is well established for other wetland soils (Smith et al. 1991, Thongtham and Kristensen 2003, Ferreira et al. 2007, Wang et al. 2011, Casariego et al. 2011, Araujo-Junior et al. 2012), studies on the effects of bioturbation specifically in HTF's are still not available.

Floral bioturbation results from the interaction between roots and soil due to root growth, root expansion, channel opening, water extraction, and exudate release (Schaetzl et al. 1989). Additionally, in the microregion of the soil rhizosphere, high rates of chemical and biological processes affect nutrient biogeochemical cycles (e.g., carbon, nitrogen, and phosphorus), greenhouse gases emission rates, and the immobilization of pollutants (Toal et al. 2000, Liangpeng et al. 2007, Richter et al. 2007, Dantas et al. 2009). Biogeochemical processes in sediment surface horizons are strongly influenced by rhizosphere activity. The relevant soil biogeochemical reactions between plant roots and the mineral phase of sediments of HTF's are: ion absorption, production of organic acids, changes on redox conditions and CO_2 production (Richter et al. 2007, Caçador et al. 2000).

CONCLUSIONS

Apicuns are HTF's and are unique ecosystems located adjacent to mangrove forests along arid and semi-arid coasts. These ecosystems are directly influenced by the coastal dynamic which control both past and present ecosystem processes. The available literature presents different theories on the formation of these ecosystems. The reduced tidal flooding associated to an evaporative environment and a hydric deficit seems to be the primary controlling factors for the formation of these hyper-saline coastal wetlands. Pedogenesis, salinization, gleyzation, sulfidization and bioturbation are the main processes that seem to occur in the soils from these ecosystems. Despite the great ecological and socio-economic importance of HTF's, very a few studies have focused on these endangered ecosystems; more specifically on the ecological relationships between soils, plants, and fauna. Further studies are necessary to delineate the ecological connection between HTF's and other highly ecologically important wetlands in order to improve public policies and conservation laws which should strive for the protection of the whole coastal ecosystem chain.

ACKNOWLEDGEMENTS

The authors would like to thank the Conselho Nacional de Desenvolvimento Científico e Tecnológico (CNPq) and Coordenação de Aperfeiçoamento de Pessoal de Nível Superior (CAPES) for financial support. We also thank Dr. Janet J. Reimer for revision of the English of the final version of the manuscript.

REFERENCES

Aburto-Oropeza, O., Ezcurra, E., Danemann, G., Valdez, Murray, V.J., and Sala, E. 2008. Mangroves in the Gulf of California increase fishery yields. PNAS **105**(30):10456–10459. doi:10.1073/pnas.0804601105.

Ackermann, G., Alexandre, F., Andrieu, J., Mering, C., and Ollivier, C. 2006. Dynamique des paysages et perspectives de développement durable sur La petite cote et dans de delta du Sine-Saloum (Sénégal). Vertigo **7**(2):1 -18. Available from http://vertigo.revues.org/2206 [accessed 13 April 2013].

Alongi, D.M. 2002. Present state and future of the world's mangrove forests. Environ. Conserv. **29**(3):331–349. doi:10.1017/S0376892902000231

Alongi, D. M. 2008. Mangrove forests: Resilience, protection from tsunamis, and responses to global climate change. Estuarine, Coastal and Shelf Science **76**:1-13. doi: 10.1016/j.ecss.2007.08.024

Araujo-Junior, J.M.C., Otero, X.L., Marques, A.G.B., Nóbrega, G.N., Silva, J.R.F., and Ferreira, T.O. 2012. Selective geochemistry of iron in mangrove soils in a semiarid tropical climate: effects of the burrowing activity of the crabs *Ucides cordatus* and *Uca maracoani*. Geo-Mar Lett. **32**:289-300. doi: 10.1007/s00367-011-0268-5

Attia, O.E.A. 2013. Sedimentological characteristics and geochemical evolution of Nabq sabkaha, Gulf of Aqaba, Sinai, Egypt. Arab. J. Geosci. **6**:2045 2059. doi: 10.1007/s12517-011-0499-9

Barbiéro, L., Furian, S., Queiroz Neto, J.P., Ciornei, G., Sakamoto, A.Y., Capellari, B., Fernandes, E., and Vallès V. 2002. Geochemistry of water and ground water in the Nhecolândia, Pantanal of Mato Grosso, Brazil: variability and associated processes. Wetlands **22**:528–540. doi: 10.1672/0277-5212(2002)022[0528:GOWAGW]2

Behling, H., Cohen, M.C.L., and Lara, R.J. 2004. Late Holocene mangrove dynamics of Marajó Island in Amazonia, northern Brazil. Veget Hist Archaeobot **13**:73- 80. doi:10.1007/s00334-004-0031-1

Berner, R.A. 1984. Sedimentary pyrite formation: an update. Geochim. Cosmochim. Acta. **48**:605–615. doi:10.1016/0016-7037(84)90089-9

Benner, R., Hatcher, P.G., and Hedges, J.I. 1990. Early diagenesis of mangrove leaves in a tropical estuary: bulk chemical characterization using solid-state 13C NMR and elemental analysis. Geochim. Cosmochim. Acta. **54**:2003 – 2013. doi: 10.1016/0016-7037(90)90268-P

Bigarella, J.J. 1947. Contribuição ao estudo da planície litorânea do Estado do Paraná. Boletim Geográfico. *In* Transcrição de Arquivos de Biologia e Tecnologia. Instituto de Biologia e Pesquisas Tecnológicas, Curitiba **55**:747-779.

Bigarella, J.J. 2001. Contribuição ao estudo da planície litorânea do estado do Paraná. Braz Arch Biol Technology. pp. 65-110. Available from http://www.scielo.br/pdf/babt/vjubilee/a05vjub.pdf [accessed 10 April 2013].

Blankespoor, B., Dasgupta, S., Laplante, B. 2012. Sea-Level Rise and Coastal Wetlands Impacts and Costs. Policy Research Working Paper, pp. 27.

Brazil. 1965. Lei Federal nº 4771 de 15 de setembro de 1965. Available from the Código Florestal brasileiro. Brasília, DF: Diário Oficial da União, Poder Executivo, pp. 11.

Brazil. 2002. Resolução n. 312 de 10 de outubro de 2002. Available from the Conselho Nacional de Meio Ambiente. Brasília, DF: Diário Oficial da União, Poder Executivo.

Brazil. 2012. Medida provisória Nº571, de 25 de maio de 2012 que altera a Lei Nº 12.651, de 25 de maio de 2012. Brasília, DF: Diário Oficial da República Federativa do Brasil, 28 maio 2012. Available from http://www2.camara.gov.br/legin/fed/medpro/2012/medidaprovisoria-571-25-maio2012-613083-publicacaooriginal-136207-pe.html. [accessed 15 October 2012].

Burton, E.D., Bush, R.T., and Sullivan, L.A. 2006. Acid-volatile sulfide oxidation in coastal flood plain drains: iron-sulfur cycling and effects on water quality. Environ. Sci. Technol. **40**(4):1217–22. doi: 10.1021/es0520058

Caçador, M.I., Madureira, M.J., and Vale, C. 2000. Effects of plant roots on salt-marsh sediment geochemistry. *In* Muddy Coast Dynamics and Resource Management. *Edited by* B.W. Flemming, M.T. Delafontaine and G. Liebezeit. Elsevier Science. pp. 197-204.

Canfield, D.E., Thamdrup, B., Kristensen, E. 2005. Aquatic geomicrobiology. Elsevier

Casariego, A.M., Luppi, T., Iribarne, O., and Daleo, P. 2011. Increase of organic matter transport between marshes and tidal flats by the burrowing crab *Neohelice* (Chasmagnathus) *granulata* Dana in SW Atlantic salt marshes. J. Exp. Mar. Biol. Ecol. **401**:110-117. doi: 10.1016/j.jembe.2011.02.035

Chmura, G.L., Anisfeld, S.C., Cahoon, D.R., and Lynch, J.C. 2003. Global carbon sequestration in tidal, saline wetland soils. Global. Biogeochem. Cy. **4**:1–12. doi: 10.1029/2002GB001917

Cintrón, G., Lugo, A.E., Pool, D.J., and Morris, G. 1978. Mangroves of Arid Environments in Puerto Rico and Adjacent Islands. Biotropica. **10**(2):110-121. Available from http://links.jstor.org/sici?sici=0006-3606%28197806%2910%3A2%3C110%3AMOAEIP%3E2.0.CO%3B2-Z [accessed 12 April 2013].

Conesa, H.M., María-Cervantes, A., Álvarez-Rogel, J., and González-Alcaraz, M.N. 2011. Influence of soil properties on trace element availability and plant accumulation in a Mediterranean salt marsh polluted by mining wastes: Implications for phytomanagement. Sci. Total Environ. **409**:4470–4479. doi:10.1016/j.scitotenv.2011.07.049

Cunha, A.G. 1999. Dicionário Histórico das Palavras Portuguesas de Origem Tupi. 5ed., São Paulo: Melhoramentos. 397 p.

Dantas, J.S., Souza, A.P., Farias, M.F., and Nogueira, V.F.B. 2009. Las interaciones entre los grupos de microorganismos em la rizosfera. PA&T. **2**(2):249-273. Available from revistas.unicentro.br/index.php/repaa/article/download/113/808. [accessed 20 March 2013].

Ellis, S., and Atherton, J.K. 2003. Properties and development of soils on reclaimed alluvial sediments of the Humber Estuary, Eastern England. Catena **52**:129- 147. doi: 10.1016/S0341-8162(02)00179-0

Ferreira, T.O., Vidal-Torrado, P., Otero, X.L., and Macias, F. 2007. Are mangrove forest substrates sediments or soils? A case study in Southeastern Brazil. Catena **70**:79 – 91. doi: 10.1016/j.catena.2006.07.006

Filho, G.A.N. 2007. Desenvolvimento estrutural e padrão de zonação dos bosques de mangue no rio Ariquindá. Baía de Tamandaré, Pernambuco, Brasil. M.Sc. thesis, Departamento of Biology, The Federal Rural University of Pernambuco, Recife.

Firmo, A.M.S., Tognella, M.M.P., Silva, S.R., Barboza, R.R.R.D., and Alves, R.R.N. 2012. Capture and commercialization of blue land crabs (“guaiamum”) *Cardisomaguanhumi* (Lattreille, 1825) along the coast of Bahia State, Brazil: an ethnoecological approach. J Ethnobiol Ethnomedicine. **8:**12. doi:10.1186/1746-4269-8-12

FUNCEME. 2009. A zona costeira do estado do Ceará: compartimentação geoambiental e antropismo. Fundação Cearense de Meteorologia e Recursos Hídricos. (FUNCEME). Fortaleza, pp. 77.

Gabet, E.J., Reichman, O.J., and Seabloom, E.W. 2003. The effects of bioturbation on soil processes and sediment transport. Annu. Rev. Earth Planet. Sci. **31**:249–273. doi: 10.1146/annurev.earth.31.100901.141314

Gorham, E. 1995. The biogeochemistry of northern peatlands and its possible response to global warming. *In* BioticFeedback in the Global Climate System: will warning feed warning? *Edited by* G.M. Woodwell and F. T. Mackenzie. Oxford University Press, New York. pp. 169–186.

Hadlich, G.M., Ucha, J.M., and Celino, J.J. 2008. Apicuns da Baía de todos os Santos: distribuição espacial, descrição e caracterização física e química. *In* Avaliação de ambientes na Baía de Todos os Santos: aspectos Geoquímicos, Geofísicos e Biológicos. *Edited by* F.S. Queiroza and J.J. Celino. Brazil: Salvador, pp. 59-72.

Hadlich, G.M., and Ucha, J.M. 2009. Apicuns: aspectos gerais, evolução recente e mudanças climáticas globais. Rev Bras Geomorf. **2**(10):13- 20. Available from www.lsie.unb.br/rbg/index.php/rbg/article/download/126/120 [accessed 18 January 2013].

Hadlich, G.M., Ucha, J.M., and Oliveira, T.L. 2009. Distribuição de apicuns e de manguezais na Baía de Todos os Santos, Bahia, Brasil. *In* Proceedings of XIV Simpósio Brasileiro de Sensoriamento Remoto, Natal, Brasil, pp. 4607-4614.

Hadlich, G.M., Celino, J.J., and Ucha, J.M. 2010. Physical-Chemical differentiation between supratidal salt flats, mangroves and hillsides in the Todos os Santos Bay, Northeast Brazil. *Geociências* **4**(29):633-641. Available from http://ppegeo.igc.usp.br/pdf/geosp/v29n4/v29n4a16.pdf [acessed 20 Apri 2013].

He, Y., Li, X., Craft, C., Ma, Z., and Sun, Y. 2011. Relationships between vegetation zonation and environmental factors in newly formed tidal marshes of the Yangtze River estuary. Wet. Ecol. Ma. **31**(19):341-349. doi: 10.1007/s11273-011-9220-8

Hopkinson, C.S., Cai, W.J., and Hu, X. 2012. Carbon sequestration in wetland dominated coastal systems - a global sink of rapidly diminishing magnitude. Curr. Opin. Env. Sust. **4**(2):186-194. doi:10.1016/j.cosust.2012.03.005

Huerta-Diaz, M.A., and Morse, J.W. 1990. A quantitative method for determination of trace metal concentrations in sedimentary pyrite. Mar. Chem. **29**:119–144. doi:10.1016/0304-4203(90)90009-2

Huerta-Diaz, M.A., Delgadillo-Hinojosa, F., Otero, X.L., Segovia-Zavala, J.A., Martin Hernandez-Ayon, J., Galindo-Bect, M.S., and Amaro-Franco, E. 2011. Iron and Trace Metals in Microbial Mats and Underlying Sediments: Results From Guerrero Negro

Saltern, Baja California Sur, Mexico. Aquat. Geochem. **17**(4-5):603–628. doi:10.1007/s10498-011-9126-3

Jones, C.G., Gutiérrez, J.L., Groffman, P.M., and Shachak, M. 2006. Linking ecosystem engineers to soil processes: a framework using the Jenny State Factor equation. Eur. J. Soil Biol. **42**:S39-S53. doi: 10.1016/j.ejsobi.2006.07.017

Jones, C.G. 2012. Ecosystem engineers and geomorphological signatures in landscapes. Geomorphology. **157**:75-87. doi: 10.1016/j.geomorph.2011.04.039

Kjerfve, B. 1990. Manual for investigation of hydrological processes in Mangrove Ecosystems. New Delhi: UNESCO/UNDP, pp 79.

Knoppers, B., Medeiros, P.R.P., Souza, W.F.L., and Jennerjahn, T. 2006. The São Francisco Estuary, Brazil. *In* Handbook of environment chemistry. Part H **5**. Springer: Verlag Berlin. pp. 51-70.

Kristensen, E., Bouillon, S., Dittmar, T., and Marchand, C. 2008. Organic carbon dynamics in mangrove ecosystems: a review. Aquat. Bot. **89**:201–219. doi: 10.1016/j.aquabot.2007.12.005

Lacerda, L.D. 2002. Mangrove ecosystems: function and management. Edited by Springer, pp. 292.

Lacerda, L.D., Menezes, M.O.T., and Molisani, M.M. 2007. Changes in mangrove extension at the Pacoti River estuary, CE, NE Brazil due to regional environmental changes between 1958 and 2004. Biota Neotropica **7**(3):68-72.

Lal, R. 2004. Soil carbon sequestration impacts on global climate change and food security. Science (New York, N.Y.) **304**:1623–1637. doi:10.1126/science.1097396

Lambais, M.R., Otero, X.L., and Cury, J.C. 2008. Bacterial communities and biogeochemical transformations of iron and sulfur in a high saltmarsh soil profile. Soil Biol. Biochem. **40**(11):2854–2864. doi:10.1016/j.soilbio.2008.08.014

Lana, P.C. 2003. Salt marshes of Paranaguá Bay (Southern Brazil): ecological characteristics, modes of appropriation and implications to environmental legislation. Rev. Desenv Meio Amb. **8**:11-23. Available from http://ojs.c3sl.ufpr.br/ojs2/index.php/made/article/view/22044/14407 [accessed 20 March 2013]

Langmuir, D. 1997. Aqueous environmental geochemistry. Edited by Simon and Schuster: New Jersey, pp. 600.

Lebrigre, J.M. 1983. Les tannes, approche geographique. Mad. Rev Géographie **43**:41-63. Available from http://madarevues.recherches.gov.mg/IMG/pdf/rev-geo43_3_.pdf [accessed 15 April 2013].

Lebigre, J.M., Marius, C., and Larques, P. 1990. Les sols des marais maritimes du littoral occidental malgache. Cahiers Orstom **3**(25):277-286. Available from http://cat.inist.fr/?aModele=afficheN&cpsidt=4565956. [Accessed 20 April 2013].

Lebigre, J.M. 1999. Natural spatial dynamics of mangals through their margins: diagnostic elements. Hydrobiologia **413**:103–113. doi: 10.1023/A:1003894927650

Lebigre, J.M. 2007. Les marais à mangrove et lês tannes [online]. Available from http://www.futura-sciences.com/fr/doc/t/geographie/d/les-marais-a-mangrove-et-les tannes_683/c3/221/p1/#xtor=AL-40 [accessed 10 January 2013].

Liangpeng, Y., Jian, M., and Yan, L. 2007. Soil salt and nutrient concentration in the rhizosphere of desert halophytes. Acta Ecol. Sin. **9**(27):3565-3571. doi: 10.1016/S1872-2032(07)60074-2

Maciel, N.C. 1991. Alguns Aspectos da Ecologia do Manguezal. Available from Alternativas de uso e proteção dos manguezais do Nordeste, CPRH: Série Publicações Técnicas, Recife. pp. 9-37.

Maire, O., Lecroart, P., Meysman, F., Rosenberg, R., Duchêne, J.C., and Grémare, A. 2008. Quantification of sediment reworking rates in bioturbation research: a review. Aquat. Biol. **2**:219-238. Available from http://anchsvr.vub.ac.be/public/pubs/2008%20 Aq%20Bi ol%20Maire%20et%20al.pdf [accessed 12 January 2013].

Marchand, C., Lallier-Vergès, E., and Allenbach, M. 2011. Redox conditions and heavy metals distribution in mangrove forests receiving effluents from shrimp farms (Teremba Bay, New Caledonia). J Soils Sediment. **11**:529-541. doi: 10.1007/s11368-010-0330-3

Marius, C. 1981. Acid Sulphate soils of the mangrove area of senegal and Gambia. in: proceedings of the Bangkok Simposium on acid sulphate soils. edited by H. Dost and N. von Bremen. Bankok Thailand. p. 103-136.

Marius C. 1985. Mangroves du Senegal et de la Gambie: ecologie, pédologie, géochimie. Mise en valeur et aménagement. Cahiers. Orstom Série Pédologique. Paris, pp. 357.

Marius, C., Archanjo, D., and Larque, P. 1987. Les sols de mangroves de la baie de Vitória (Brésil). Cahiers. Orstom Série Pédologique. **3**:211-216. Available from http://cat.inist.fr/?aModele=afficheN&cpsidt=7038479 [accessed 17 March 2013].

Marques, A.G. 2010. Characterization and genesis of mangrove, apicum salt flat and coastal tableland of Acaraú (Ceará State) coastal region. M. Sc. Thesis, Departament of Agronomy, The Federal University of Ceará, Fortaleza, Ceará.

Meireles, A.J.A., and Silva, E.V. 2002. Abordagem geomorfológica para a realização de estudos integrados para o planejamento e gestão em ambientes flúvio-marinhos. Scr Nova. **6**:105-132. Available from http://www.ub.edu/geocrit/sn/sn-118.htm [accessed 19 April 2013].

Meireles, A.J.A., and Raventos, J.S.I. 2002. Um modelo geomorfológico integrado para a planície costeira de Jericoacoara/ Ceará. Mercator. **1**:79-94. Available from http://www.mercator.ufc.br/index.php/mercator/article/view/197/163 [accessed 19 April 2013].

Meireles, A.J.A, Cassola, R.S., Tupinambá, S.V., and Queiroz, L.S. 2007. Impactos ambientais decorrentes das atividades da carcinicultura ao longo do litoral cearense, nordeste do Brasil. Mercator. **12**(6):83-106. Available from http://www.mercator.ufc.br/index.php/mercator/article/view/48/22 [accessed 18 April 2013].

Meireles, A. J. A., Silva, E. V., and Thiers, P. R. L. 2010. Environmental impacts of the Activities of Shrimp farming in mangrove ecosystem of the Ceará state, Northeastern Brazil. J Integ Coastal Zone Mannagement **8**:1-11. Available from http://www.aprh.pt/rgci/pdf/rgcimang81_Meireles.pdf [accssed 14 January 2013].

Meysman, F.J.R., Middelburg, J.J., and Heip, C.H.R. 2006. Bioturbation: a fresh look at Darwin's last idea. Trends Ecol. Evol. **12**(21):687-695. doi:10.1016/j.tree.2006.08.002.

Millennium Ecosystem Assessment. 2005. *Ecosystems and Human Well-Being: Wetlands and Waters Synthesis*. World Resources Institute, Washington, DC. pp. 80.

Miller, J.J., Pawluk, S. 1994. Genesis of solonetzic soils as a function of topography and seasonal dynamics. Can. J. Soil Sci. **74:**207-217.

Mitsch, W.J., Nahlik, A., Wolski, P., Bernal, B., Zhang, L., and Ramberg, L. 2009. Tropical wetlands: seasonal hydrologic pulsing, carbon sequestration, and methane emissions. Wetl. Ecol. Manag. **18**(5):573–586. doi:10.1007/s11273-009-9164-4

Morgan, B., Rate, A.W., and Burton, E.D. 2012. Trace element reactivity in FeS-rich estuarine sediments: Influence of formation environment and acid sulfate soil drainage. Sci. Total Environ. **438**:463–476. doi:10.1016/j.scitotenv.2012.08.088

Nascimento, S.A. (1993). Biologia do caranguejo-uçá (*Ucides cordatus*). *In* Relatório Técnico Preliminar. Edited by ADEMA, Brazil: Aracajú, pp. 48.

Nascimento, S.A. (1999). Estudo da importância do “apicum” para o ecossistema de manguezal. *In* Relatório Técnico Preliminar. Edited by Governo do Estado do Sergipe, Brazil: Sergipe, pp. 27.

Nellemann, C., Corcoran, E., Duarte, C.M., Valdés, L, De Young, C., Fonseca, I., and Grimsditch, G. 2009. Blue carbon. *In* A rapid Response Assessment. United Nation Environment Programme. GRID-Arendal.

Neue, H.U., Gaunt, J.L., Wang, Z.P., Becker-Heidmann, P., and Quijano, C. 1997. Carbon in tropical wetlands. Geoderma **79**:163-185. doi: 10.1016/S0016-7061(97)00041-4

Nielsen, S.G., Goff, M., Hesselbo, S.P., Jenkyns, H.C., Larowe, D.E., and Lee, C.T.A. 2011. Thallium isotopes in early diagenetic pyrite – a paleoredox proxy? Geoc. Cosmoc. Acta **75**:6690-6704. doi: 10.1016/j.gca.2011.07.047

Normann, B.E., and Pennings, S.C. 1998. Fiddler crab-vegetation interactions in hypersaline habitats. J Experim Marine Biology Ecology **225**:53-68. Available from http://www.bchs.uh.edu/~steve/CV/publications/nomann%20and%20 pennings%201998%20jembe%20%20fiddler%20crabs.pdf [accessed 13 April 2013].

Odum, W.E. 1988. Comparative Ecology of Tidal Freshwater and Salt Marshes. Annual Review of Ecology and Systematics **19**: 147-176.

Oliveira, L.P.H. 1946. Estudos ecológicos dos crustáceos comestíveis Uça e Guaiamú, *Cardisoma guanhumi* Latreille e *Ucides cordatus* (L). *Gecarcinidae, Brachyura*. Mem. Inst. Oswaldo Cruz. **2**(44):295-322. Available from http://www.academicoo.com/texto-completo/estudos-ecologicos-dos-crustaceos-comestiveis-uca-e-guaiamu-cardisoma-guanhumi-latreille-e-ucides-cordatus-l-gecarcinidae-brachyura [accessed 18 April 2013].

Otero, X.L., and Macias, F. 2002. Variation with depth and season in metal sulfides in salt marsh soils. Biogeochemistry. **61**:247–268. Available from http://link.springer.com/article/10.1023%2FA%3A1020230213864 [accessed 21 febuary 2013].

Otero, X.L., Ferreira, T.O.,Vidal- Torrado, P., Macias, F., and Chesworth, W. 2008. Thionic Soils. *In* Encyclopedia of Soil Science. Edited by W. Chesworth, Berlin: Springer. pp. 777-780.

Otero, X.L., Ferreira, T.O., Huerta-Díaz, M.A., Partiti, C.S.M., Souza, V., Vidal-Torrado, P., and Macías, F. 2009. Geochemistry of iron and manganese in soils and sediments of a mangrove system, Island of Pai Matos (Cananeia - SP, Brazil). Geoderma **148**:318–335. doi:10.1016/j.geoderma.2008.10.016

Pellegrini, J.A.C. 2000. *Caracterização da planície hipersalina (apicum) associada a um bosque de mangue em Guaratiba*. M.Sc. Thesis, São Paulo University, São Paulo.

Pennings, S.C., and Richards, C.I. 1998. Effects of wrack burial in salt-stressed habitats: *Batis maritima* in a southwest Atlantic salt marsh. Ecography **21**:630-638. doi: 10.1111/j.1600-0587.1998.tb00556.x

Pires, L.C. and Lacerda, L.D. 2008. Piritas flamboidais associadas ao biofilme em sedimentos de manguezal de coroa grande, Baía de Sepetiba, RJ. Geochimica Brasiliensis **22**(3):201-212.

Portugal, A.M.M. 2002. Manguezais de Guaratiba frente à perspectiva de elevação do nível médio relativo do mar, Baía de Sepetiba, Estado do Rio de Janeiro – Brasil. M. Sc. Thesis, São Paulo University, São Paulo.

Reddy, K.R., Feijtel, T.C., and Patrick, W.J.R. 1986. Effect of soil redox conditions on microbiological oxidation of organic matter. *In* The role of organic matter in modern agriculture. Edited by Y. Chen and Y. Avnimelech. Kluwer Academic Publish, Hinghan-USA, pp. 117-156.

Reimer, J.J. and Huerta-Díaz, M.A. 2011. Phosphorus Speciation and Sedimentary Fluxes in Hypersaline Sediments of the Guerrero Negro Salt Evaporation Area, Baja Clifornia Sur, Mexico. Estuaries and Coasts **34:**514–528.

Richter, D.B., Oh, N.Y., Fimmen, R., and Jackson, J. 2007. The rhizosphere and soil formation. *In* The rhizosphere: an ecological perspective. Edited by Z. G. Cardon and J.L. Whitbeck, Elsevier Science, pp. 179-198.

Rickard, D., and Morse, J.W. 2005. Acid volatile sulfide (AVS). Mar Chem. **97**:141–197. doi:10.1016/j.marchem.2005.08.004

Ridd, P.V., and Sam, R. 1996. Profiling groundwater salt concentrations in mangrove swamps and tropical salt flats. Estuar Coast Shelf Sci. **43**:627–635. doi:10.1006/ecss.1996.0092

Ridd, P., Sam, R., Hollings, S., and Brunskill, G. 1997. Water, salt and nutrient fluxes of tropical tidal salt flats. Mangroves Salt Marshes. **1**:229–238. doi: 10.1023/A:1009944507334

Ridd, P.V., and Stieglitz, T. 2002. Dry Season Salinity Changes in Arid Estuaries Fringed by Mangroves and Saltflats. Estuar. Coast Shelf Sci. **54**:1039–1049. doi:10.1006/ecss.2001.0876

Rovai, A.S, Menghini, R.P., Schaeffer-Novelli, Y., Cintron, G., and Coelho-JR, C. 2012. Protecting Brazil s Coastal Wetlands. Sci Magazine. **335**:1571-1572. doi: 10.1126/science.335.6076.1571

Roychoudhury, A.N., Kostka, J., and Cappellen, P.V. 2003. Pyritization: a palaeoenvironmental and redox proxy reevaluated. Estuar. Coast Shelf Sci. **57**(5-6):1183-1193. doi: 10.1016/S0272-7714(03)00058-1

Ruivo, M.L.P., Amaral, I.G, Faro, M.P.S, Ribeiro, E.L.C., Guedes, A.L.S., and Santos, M.M.L. 2005.Chemical caracterization of the organic surfasse layer and light organic matter in diferente types of soil in a toposequence. *In* Boletim do Museu Paraense Emílio Goeldi. Ciências Naturais, pp. 227-234.

Sadio, S. (1989). Pédogenèse et potentialities forestières des sols sulfatés acides salés des tannes du Sine Saloum, Sénégal. Landbouw universiteit, Wageningen, Proefschrift van de Landbouwuniversiteit te Wageningen. Available from http://horizon.documentation.ird.fr/exl-doc/pleins_textes/divers09-04/35011.pdf [accessed 10 January 2013].

Salem, M.E., and Mercer, D.E. 2012. The Economic Value of Mangroves: A Meta-Analysis. Sustainability **4**:359-383. doi:10.3390/su4030359

Sam, R., and Ridd, P.V. 1998. Spatial variations of groundwater salinity in a mangrove-saltflat system, Cocoa Creeks, Australia. Mangroves Salt Marshes**.** **2**:121–132. doi:10.1023/A:1009919411508

Sanford, W.E. and Wood, W.W. 2001. Hydrology of the coastal sabkhas of Abu Dhabi, United Arab Emirates. Hydrogeology Journal **9**:358–366. doi: 10.1007/s100400100137

Schaeffer-novelli, Y., Cintron-molero, G., Adaime, R.R., and Camargo, T.M. 1990. Variability of Mangrove Ecosystems Along the Brazilian. Coast Estuaries **2**(13):204-218. doi: 10.2307/1351590

Schaeffer-Novelli, Y. 2002. Manguezal, marisma e apicum (Diagnóstico Preliminar). *In:* Avaliações e ações prioritárias para conservação da biodiversidade das Zonas Costeira e Marinha. Edited by Fundação Bio – Rio et al, Brasília: MMA/SBF, pp.119.

Schaetzl, R.S., Johnson, D.L., Burns, S.F., and Small, T.W. 1989. Tree uprooting: review of terminology, process and environmental implications. Can. J. For. Res. **19**:1-11. doi: 10.1139/x89-001

Schmidt, A.J. 2006. Estudo da dinâmica populacional do caranguejo-uçá, *Ucides cordatus cordatus (*Linnaeus, *1763) (Crustacea-Decapoda-Brachyura*), e dos efeitos de uma mortalidade em massa desta espécie em manguezais do Sul da Bahia. M. Sc. Thesis, Departament of Oceanographic Institute, The University of Sao Paulo, Sao Paulo.

Thongtham, N., and Kristensen, E. 2003. Physical and chemical characteristics of mangrove crab (Neoepisesarma versicolor) burrows in the Bangrong mangrove forest, Phuket, Thailand; with emphasis on behavioural response to changing environmental conditions. Vie Milieu. **53**:141–151. ID: 24774b40-ba9a-11dc-9626-000ea68e967b

Toal, M.E., Yeomans, C., Killham, K., and Meharg, A.A. 2000. A review of rhizosphere carbon flow modeling. Plant Soil. **222**:263-281. doi: 10.1023/A:1004736021965

Tomazelli, L.J., Dillenburg, S.R., Barboza, E.G., and Rosa, M.L.C.C. 2008. Geomorfologia e potencial de preservação dos campos de dunas transgressivos de Cidreira e Itapeva , litoral Norte do Rio Grande do Sul, Brasil. Rev Pesq Geoc. **35**(2):47-55. Available from: http://www.lume.ufrgs.br/bitstream/handle/10183/22670/000735381.pdf?sequence=1 [accessed 15 January 2013].

Tomlinson, P.B. 1986. The Botany of Mangroves. Cambridge Tropical Biology Series. Australia: Cambridge University Press, pp.419.

Ucha, J.M, Santana, P.S, Gomes, A.S.R., Barreto, E.D.N., Vilas-Boas, G.S., and Ribeiro, L.P. 2004. Apicum: gênese nos campos arenosos e degradação dos manguezais em dois municípios baianos. Rev. Edu, Tec e Cult. **3:**26-27. Available from: http://www.cefetba.br/comunicacao/etc2a5.htm [accessed 15 January 2013].

Ucha, J.M., Hadlich, G.M., and Celino, J.J. 2008. Apicum: transição entre solos de encosta e manguezais. Rev. Edu, Tec e Cult. pp.58-63. Available from: http://www.nea.ufba.br/apicum/UCHA_ETC2008.pdf [accessed 25 January 2013]

Vermeulen, J., Grotenhuis, T., Joziasse, J., and Rulkens, W. 2003. Ripening of dredged sediments during temporary upland disposal. A bioremediation technique. J. Soils Sediment. **3**:49–59. doi: 10.1007/BF02989469

Vieillefon, J. 1969. La pédogénèsedans les mangroves tropicales. Un exemple de chronoséquence. Science du Sol, Supl. Au Bll. Assoc. Franç. pour Et. du sol. p.115-148. Available from: http://horizon.documentation.ird.fr/exl-doc/pleins_textes/pleins_textes_5/b_fdi_12-13/13927.pdf [accessed 17 February 2013]

Vieillefon, J. 1977. Les sols des mangroves et des tannes de Basse-Casamance (Senegal). Importance du comportement geochimique du soufre dans leur pédogénèse,. Paris: ORSTOU, coll. Mémoires. pp.291

Vilas Boas, G., Sampaio, F.J., and Pereira, A.M.S. 2001. The Barreiras Group in the Northeastern coast of the State of Bahia, Brazil: depositional mechanisms and processes [on line]. An. Acad. Bras. Ciênc. **3**(73):417-427.Available from: http://www.scielo.br/pdf/aabc/v73n3/v73n3a10.pdf [accessed 4 January 2013].

Wang, J.Q., Zhang, X.D., Jiang, L.F., Bertness, M.D., Fang, C.M., Chen, J.K., Hara, T., and Li, B. 2010. Bioturbation of Burrowing Crabs Promotes Sediment Turnover and CArbon and Nitrogen Movements in an Estuarine Salt Marsh. Ecosystems. **13**: 586-599.

FIGURE CAPTIONS

Figure 1. Hypersaline tidal flat ecosystems located in NE-Brazilian states which are known to be influenced by various anthropogenic impacts. (1) Maranhão; (2) Piauí; (3) Rio Grande do Norte; (4) Paraíba; (5) Pernambuco; (6) Alagoas; (7) Sergipe; and (8) Bahia.

Figure 2. (A) Schematic of geophysical distribution along a transect through a hypersaline tidal flat in northeast Brazil (*apicum*): from the mangrove forest at the land-sea interface up to the Coastal Tableland. The numbered positions are in reference to: the spring tide level (1), mean high tide level (2) and mean low tide level (3). (B) Satellite image of a hypersaline tidal flat ecosystem in the transition between Coastal Tablelands and mangrove forests (Ceará State, NE-Brazil); (C) A general panorama of a hypersaline tidal flat ecosystem.

Figure 3. (A) Typical salt crusts commonly found in hypersaline tidal flat ecosystems; (B) “patchy” vegetation pattern in a hypersaline tidal flat; (C) region with poor vegetation cover; (D) *Batis maritima,;* (E) *Cardisoma guanhumi* (land crab) burrow; and (F) *Cardisoma guanhumi* (land crab) and trap used to collect land crabs; a dietary staple of local populations.

Figure 4. (A) *Ucides cordatus* found in hypersaline tidal flats; (B) domestic animals grazing in a hypersaline tidal flats; (C) typical sediment layer with preserved mangrove residue; (D) microbial mats found on the surface of sediments; (E) reddish mottling indicating variations in the redox conditions in sediments; (F) iron oxide precipitation in sediments as a result of bioturbation. by crabs.

Figure 5. General characteristics of hypersaline tidal flats; (A) sediment accumulation from dunes and adjacent areas; (B) flooding period during spring tides; (C) seawater evaporation and salt accumulation during low tides.

TABLE CAPTION

Table 1. Floral composition of *apicum* and *tannes.*

Table 2. Site location, climatic characteristics (temperature, precipitation, and climate classification), mean organic carbon content, granulometric composition (sand, silt, and clay), pH, electrical conductivity (EC), presence of mangrove plant tissues and sulfidic material of different hypersaline tidal flats around the world.

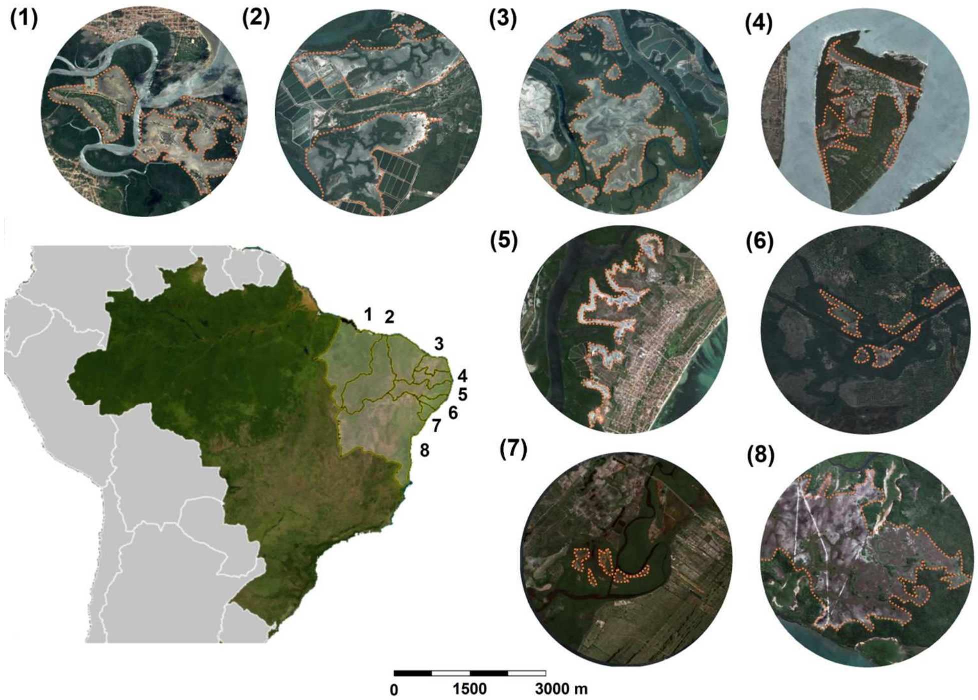

Figure 1. Hypersaline tidal flat ecosystems located in NE-Brazilian states which are known to be influenced by various anthropogenic impacts. (1) Maranhão; (2) Piauí; (3) Rio Grande do Norte; (4) Paraíba; (5) Pernambuco; (6) Alagoas; (7) Sergipe; and (8) Bahia.
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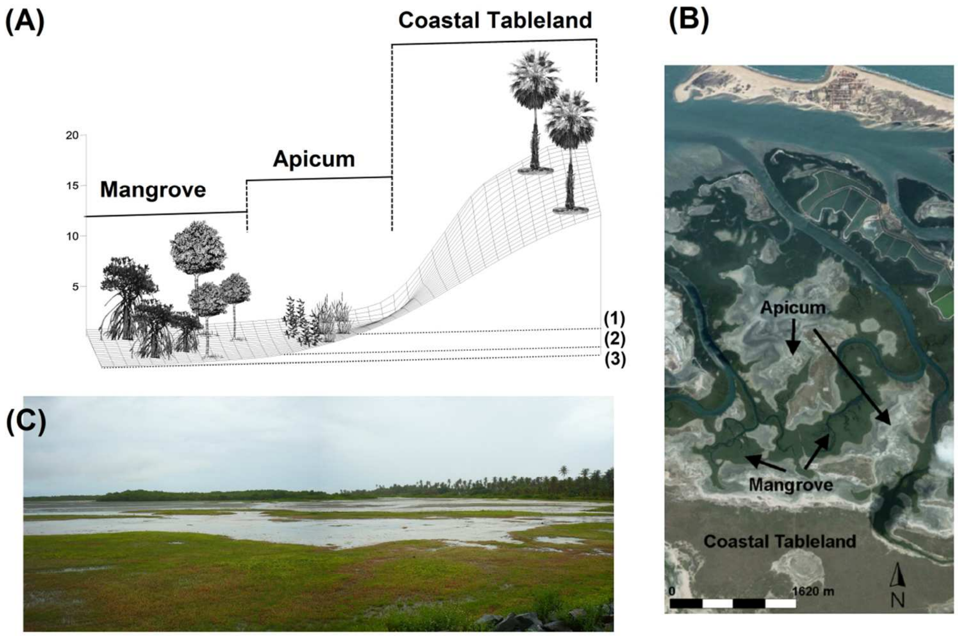

Figure 2. (A) Schematic of geophysical distribution along a transect through a hypersaline tidal flat in northeast Brazil (apicum): from the mangrove forest at the land-sea interface up to the Coastal Tableland. The numbered positions are in reference to: the spring tide level (1), mean high tide level (2) and mean low tide level (3). (B) Satellite image of a hypersaline tidal flat ecosystem in the transition between Coastal Tablelands and mangrove forests (Ceará State, NE-Brazil); (C) A general panorama of a hypersaline tidal flat ecosystem.
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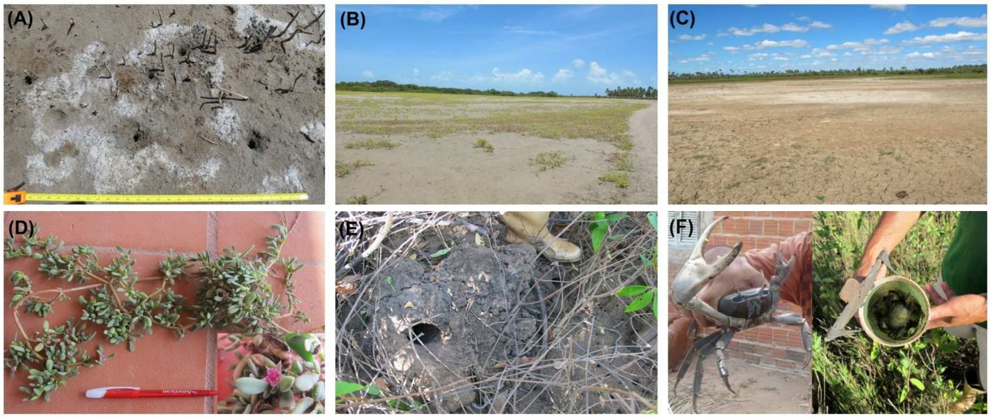

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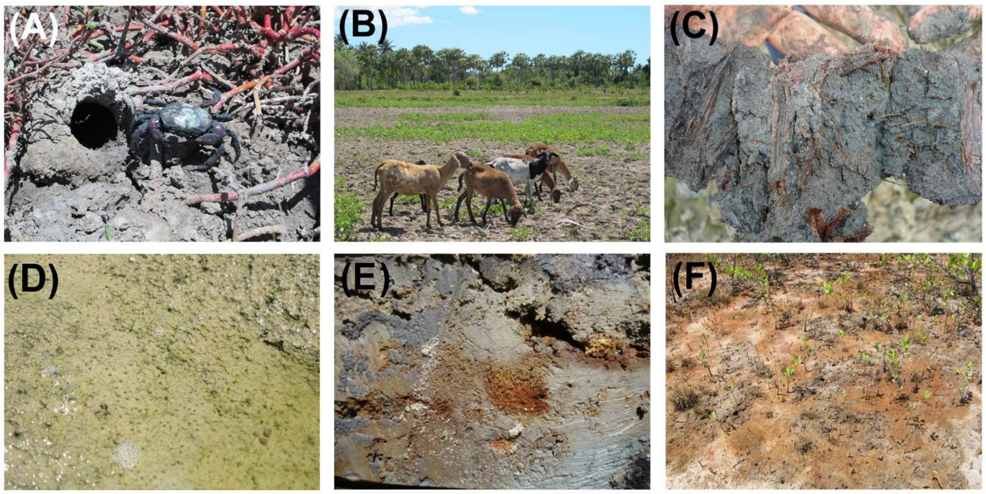

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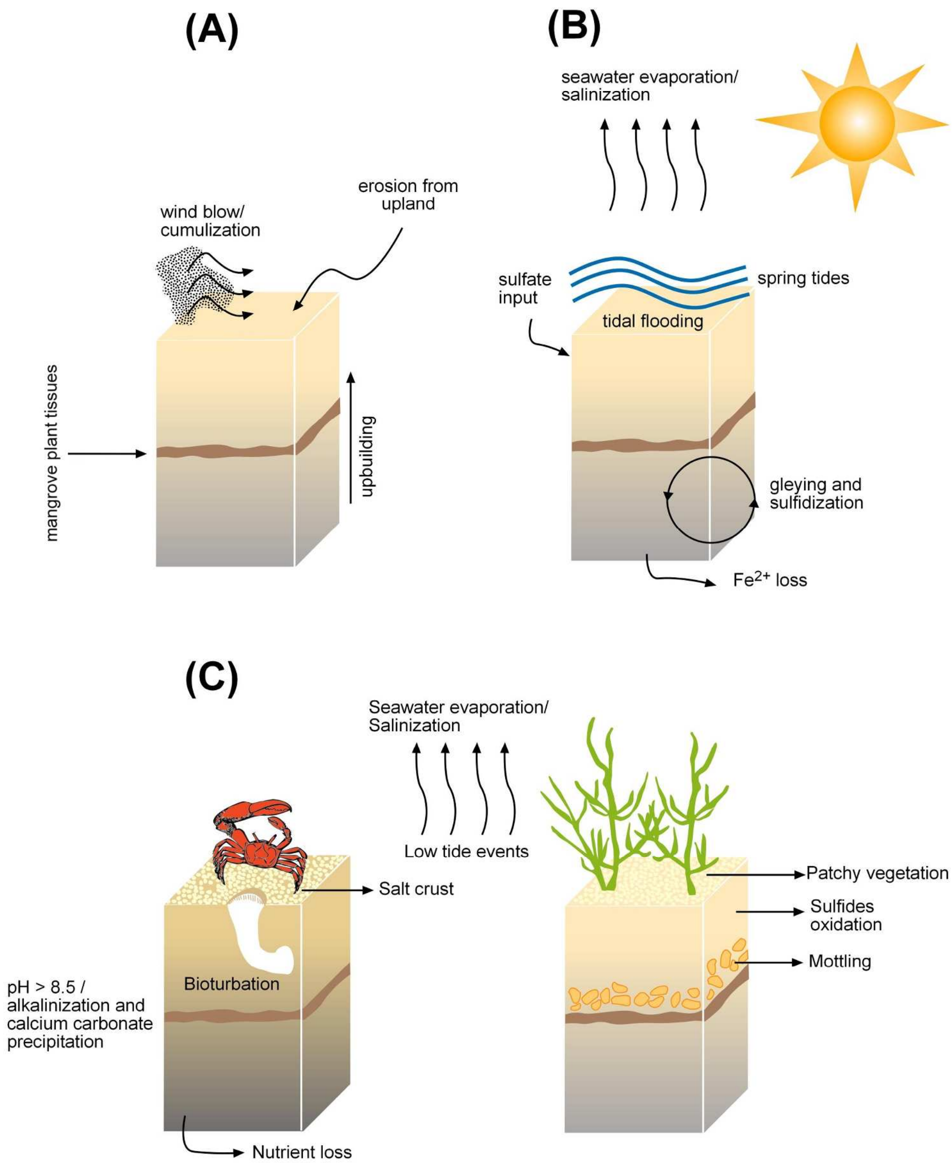
458x231mm (96 x 96 DPI)



192x234mm (300 x 300 DPI)

Table 1. Floral composition of *apicum* and *tannes*.

Family	Species	References
Aizoaceae	*Sesuvium portulacastrum* (L.) L.	*Marius (1981);Marius (1987); Lebigre (2007)*
Chenopodiaceae	*Arthrocnemum indicum*(Wild.)Moq.	*Lebigre (2007)*
	Atriplex spp. (L.)	*Lebigre (2007)*
	Halosarcia indica subsp. leiostachya (Benth.) Paul G.Wilson	*Lebigre (2007)*
	Salicornia spp.(L.)	*Lebigre (2007)*
	Salsola littoralis Moq.	*Lebigre (2007)*
	Sarcocornia sp. (A.J. Scott)	*Lebigre (2007)*
	Suaeda spp. Scop.	*Lebigre (2007)*
Poaceae	*Aeluropus lagopoides* (L.)	*Lebigre (2007)*
	Cynodon dactylon (L.) Pers.	*Lebigre (2007)*
	Paspalum vaginatum Sw.	*Marius (1981)*
	Sclerodactylon macrostachyum (Benth.) A. Camus	*Lebigre (2007)*
	Sporobolus robustus Kunth	*Lebigre (2007)*
	Sporobolus virginicus (L.) Kunth	*Lebigre (2007); R. L. Cabral (personal communication, 2013)*
Convolvulacae	*Cressa australis* R. Br.	*Lebigre (2007)*
Cyperaceae	*Cyperus laevigatus* (L.)	*Lebigre (2007)*
	Eleocharis caribaea (Rottb. Blake)	*Marius (1981); Marius (1987)*
	Eleocharis mutata (L.)	*Marius (1981)*
	Fimbristylis sp. Vahl	*Lebigre (2007)*
Amarantaceae	*Blutaparon portulacoides* (A. St.-Hil.) Mears	*R. L. Cabral (personal communication, 2013)*
	Philoxerus vermicularis (Linn.) P. Beauv	*Marius (1981); Marius (1987); Lebigre (2007)*
Bataceae	*Batis marítima* (L.)	*R. L. Cabral (personal communication, 2013)*

Table 2. Site location, climatic characteristics (temperature, precipitation and climate classification), mean organic carbon content, granulometric composition (sand, silt and clay), pH, electrical conductivity (EC), presence of mangrove plant tissues and sulfidic material of different hypersaline tidal flats around the world

Site location	Temperature	Preciptation	Climate	Organic carbon	Sand	Silt	Clay	pH	EC	MPT	Sulfidic material	Reference
	°C	mm		g kg^{-1}					dS m^{-1}			
Madagascar	30,0	500	BSh	-	-	-	-	7±1	12±11	-	-	Lebigre et al., 1990
Bahia, Brazil	26,5	1650	Awi	7±1*	758±36	93±17	149±28	6±0	-	yes	-	Hadlich; Ucha; Celino 2008
Ceará, Brazil	34,0	1.131	BSh	7±8	712±177	135±89	153±92	8±2	33±6	yes	yes	Marques 2010
TerembaBay, New Caledonia	28,1	83	Cfa	59±50	-	-	-	7±0	-	yes	yes	Marchand; Lallier-Vergès; Allenbach 2011
Murcia.Spain	19,1	24	BSh	41±16	225±149	365±92	145±134	7±0	11±8	-	-	Conesa et al., 2011

*Organic Carbon value = organic matter divided by1.724;

** Standard deviation calculated according to the mean values in the references.

MPT- mangrove plant tissues; Awi- Tropical hot and humid; BSh- Semi-arid hot; Cfa- Subtropial humid; (-) not analyzed