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Burial of mangroves by mobile dunes: a climate change threat in semiarid coasts

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Background

In the northeastern coast of Brazil, between the states of Maranhão and Rio Grande do Norte, the semiarid climate extends to the littoral. This sector of the Brazilian coast, known as the "dune coast", also harbours mangroves located along estuaries and coastal lagoons. At the extreme west of this sector, the semiarid conditions transits into humid equatorial climate, typical of the Amazon region. In this transition, there is located the enormous Parnaíba Delta, the largest open sea delta in the Americas, covering about 270,000 ha. The Delta is encircled by an Environmental Protection Area (EPA), a 313,809-ha federal conservation unit established in 1996 and located at 02°37'– 03°05' S and 42°29'– 41°09' W (Figure 1). Within the Delta, the "Reserva Extrativista (RESEX) Delta do Parnaíba" was created by the Federal Government in 2000. This 27,021-ha extractive reserve was constituted by 3,600 families of local fishermen which depend mostly on mangrove products. Uca-crab, *Ucides cordatus*, is the most explored resource and the RESEX has the largest concentration of crab catchers in Brazil. The EPA, apart from preserving over 100,000 ha of mangroves and associated ecosystems, protects the IUCN Red List, Red-handed Howler Monkey *Alouatta belzebul*; a relatively large cetacean diversity and a highly diversified avifauna, including colonies of the iconic scarlet ibis *Eudocimus ruber*.

Figure 1 The Parnaíba Delta in the northeastern Brazilian coast. Dark green areas are mangrove forests. The white stripes bordering the regional littoral are mobile dune fields. Note the dunes on the right inferior corner advancing over mangrove forests (see Figure 3 for details).

The entire region is a unique example of a pristine delta, basically not affected by anthropogenic activities. Along the EPA's eastern sector, actively migrating coastal dune fields frequently advance over mangroves. At the western portion, the region is characterized by tidal channels under estuarine conditions, and tidal flats occur between mangrove islands and deltaic plains. This climatic transition zone is influenced by the Intertropical Convergence Zone (ITCZ) and the South Atlantic anticyclone. There are two marked seasons, a dry period when semiarid conditions dominate, from July-August to December, and a wet season from January to May-June, when higher rainfall results in large riverine contribution (Szczygielski *et al*., 2015).

The total extension of mangrove forests in the EPA of the Parnaíba Delta is still unknown but may reach over 150,000 ha. The dominant tree species are *Rhizophora mangle*; *Avicennia germinans* and *Laguncularia racemosa*. Trees are tall, reaching over 20 m (Figure 2) and since the region is located in a transition climate zone, many typical Amazon species from flooded forests, such as the aquatic macrophytes *Montrichardia linifera* and *Eichhornia azurea*, and palms (mostly Arecaceae) abound, mixed with mangroves at the higher estuary.

Figure 2 Tall *Rhizophora mangle* trees at the Parnaíba Delta in northeastern Brazil.

Response of the region's mangroves to climate change

Recent evaluations of the impact from climate change on mangroves of the semiarid northeastern region of Brazil suggest that major pressures are from the decreasing continental runoff due to diminishing annual rainfall, but strengthened by river damming, and from sea level rising. These affect freshwater supply and sediment dynamics, resulting in saline intrusion and sedimentation along river banks and enlargement of estuarine islands. Mangroves respond to these pressures by migrating landward, substituting freshwater macrophytes and colonizing new available tidal flats. As a consequence, in many areas of the northeastern coast, the extension of mangroves is increasing. These responses occur on a decadal scale (Godoy & Lacerda, 2015). At the Parnaíba Delta, however, although sea level is also rising and annual rainfall is decreasing, the large freshwater contribution from the Parnaíba River, which varies from 240 to nearly 3,000 $m^3.s^{-1}$ (average 600 $m^3.s^{-1}$), which represents at least one order of magnitude higher than the sum of all fluvial contribution form the entire dune coast, results in a continental runoff too high to allow significant saline intrusion and therefore, the landward migration of mangrove species by outcompeting freshwater vegetation. This larger flow also maintains the continental sediments contribution to the estuary. This situation avoids mangrove migration and colonization of new areas and exposes mangroves to be encroached by the mobile dunes. Thus, knowing the response of these dunes to climate change is of key importance to the conservation of the Parnaíba Delta mangroves and their high diversified associated fauna, as well as of the fishermen families from the extractive reserve (RESEX) who depend on mangrove ecosystems goods and services, in particular those from artisanal fisheries.

Response of the local mobile dunes to climate change

Mobility of the dunes in the Delta area displays an annual cycle. Their displacement over varying distances depends on climate conditions, in particular a conjunction of wind speed and annual rainfall. These two variables are linked through teleconnections with two large-scale phenomena; the ICTZ in the Atlantic and ENSO in the Pacific. During the wet season, with the southward migration of the ICTZ, trade winds running E-W along the coast decrease in intensity. The ICTZ also brings high humidity and rainfall. During this period, mobile dunes absorb water from a higher water table and are immobilized. On the other hand, when the ICTZ moves north, winds intensify and rainfall decreases, lowering the groundwater table and allowing the dunes to move. The magnitude of their displacement will, therefore, depends on the balance between these two phenomena. The average yearly displacement rate estimated for these dunes is 19 $m.yr^{-1}$, varying from 9.5 to 37 $m.yr^{-1}$, depending on the intensity and duration of the dry season, the longer and stronger the drought conditions, the larger the annual displacement of these dunes (Maia *et al*., 2005).

There is a relationship that links dune migration in northeastern Brazil with El Niño events. As ENSO induces major climatic perturbation, its effects are transferred to all the dynamical processes controlled by the regional climate. Maia *et al.* (2005) observed a significant relationship between the annual displacements of mobile dunes in the region with the South Oscillation Index (SOI) in the Central Pacific. Since mobile dunes respond to the actual rainfall and wind regimes, El Niño years will result in faster than normal dune displacement, whereas La Niña years will result in lower than normal dune migration. The volume of sand transport will also respond to ENSO events in a manner similar to dune displacement rates.

Strengthening arid conditions and the fate of mangroves in the Parnaíba Delta

Recently, Marengo *et al.* (2017), based on historical registers of extended droughts in the NE region of Brazil in the past 400 years, observed a relationship with ENSO through influencing the northward migration of the ICTZ, due also to warming of the North Atlantic. Both large-scale phenomena that ultimately control rainfall and wind speed, and therefore dune displacement at the Parnaíba Delta have been strongly affected by global climate change. The historical analysis reported by these authors showed an intensification in the number and duration of extended droughts in NE Brazil, from 1 to 3 per century during the 1600's and 1700's to more than 14 in the 2000's. Other authors have also reported a progressive decrease in the annual rainfall over the region of about

6% per decade (5.3 mm.yr^{-1}) between 1961 and 2003 (Moncunill *et al*., 2006). Salati *et al.* (2007) estimated a total annual rainfall decrease in the same region of about 11.6%, between 1991 and 2004, and Andrade *et al.* (2018) estimated a decrease in the annual rainfall in the past 30 years of about 4.9 mm.yr^{-1}, quite consistent with the previous estimates. All these observations suggest an increase in frequency and extension of semiarid conditions as a response to global climate change in NE Brazil and as a consequence, an acceleration of dune displacement and the faster suffocation of mangrove forests (Figure 3).

Figure 3 Mobile dune field at the Parnaíba Delta (A); mobile dunes approaching fringe mangroves (B); mobile dunes encroaching mangroves (C).

This response to climate change is not specific to the Parnaíba Delta. It does happen along the entire "dune coast". However, the very small fluvial contribution along most of the region, results in saline intrusion and a landward migration of mangroves, which compensates the area lost to the dune advance. At the Parnaíba Delta, mangrove migration landward is prevented by the large freshwater flow of the Parnaiba River, keeping salinity low and allowing a luxuriant freshwater vegetation to colonize riverbanks and islands. Also, dune displacement is an annual scale phenomenon, too fast to allow any mitigation response such as replanting. With the acceleration of global warming, the Delta dune fields can migrate a few kilometres in a decade, encroaching and suffocating a large extension of forest, which becoming a real danger to this unique environmental reserve and to the local people depending on mangrove goods and services.

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