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RECENT DUNE MIGRATION ALONG THE COASTAL PLAIN OF CANOA QUEBRADA, CEARÁ STATE, NORTHEAST BRAZIL

Adriana Albuquerque Pedrosa[1], Vanda Claudino-Sales[2]*, IItabaraci Nazareno Cavalcante[3], Alexandre Medeiros Carvalho[4]

[1]Secretary of Education of the State of Ceará, Avenida General Afonso Albuquerque Lima, 60822-325 Fortaleza, Ceará, Brazil
[2]Department of Geography of the Federal University of Ceará (UFC), and Master of Geography of the State University of Acaraú Valley (UVA), Bloco 911, Campus do Pici, 60.440-544 Fortaleza, Ceará, Brazil
[3]Department of Geology, Federal University of Ceará, Bloco 912, Campus do Pici, 60.440-544 Fortaleza, Ceará, Brazil
[4]Marine Sciences Institute (LABOMAR), Federal University of Ceará, Avenida da Abolição 3207, 60.165-081 Fortaleza, Ceará, Brazil
*Corresponding author, e-mail: vcs@ufc.br

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Abstract

In the coastal area of Ceará State, northeast Brazil, there are large mobile dunefields, including barchans, barchanoid dunes and sandsheets. The migration rate of these dunes, as measured by several studies, varies between 32 m/y and 9 m/y. This paper analyzes the migration of the dunes in Canoa Quebrada Beach, located in the eastern coast of Ceará State, using remote sensing of aerial photos and satellite imagery from 1988 to 2013 (25 years). The resulting data indicate an average migration rate varying from 1.8 m/y to 9.3 m/y. This is the lowest rate of migration measured for large and undeveloped mobile dunes in Ceará State. The analysis indicates that the element responsible for this low rate is the low wind speed. However, the installation of wind power turbines in the area – which demanded the fixation of part of the dunes to prevent the equipment from being buried and from aeolian erosion – might be another reason for the decreasing dune migration. The dune migration decrease may increase the sedimentary deficit in the coastline downdrift of Canoa Quebrada Beach.

Keywords: dune migration, coastal dynamics, Northeastern Brazil, coastal development

INTRODUCTION

Mobile aeolian dunes are accumulations of medium to fine sands characterized by the absence of vegetation cover or cementation. They occur in coastal plains, continental desert areas, and in the vicinity of fluvial and lacustrine beaches and plains. The mobile aeolian dunes migrate when they are mobilized by winds and, therefore, are constantly changing form and position while the wind reorganizes their sand disposition.

In general, it is considered that the intensity of dune migration depends on the variations of the intensity and direction of annual, seasonal and daily winds, as well as of the turbulence patterns of winds (e.g. Tsoar et al., 1999), of the granulometry of the sediments (e.g. Kocurek and Lancaster, 1999; Livingstone et al., 2007; Potter and Weigand, 2016), of the topography of the surface (e.g. Bristow et al,, 2000; Necsoiu et al., 2009), of the intensity of atmospheric precipitation (e.g. Hunter et al, 1983; Maia et al., 2005; Forman et al,. 2009), of the moisture content of the sands (e.g. Sherman and Bauer, 1993; Tsoar and Arens, 2003; Potter and Weigand, 2016) and of the wind direction related to the shoreline orientation (Carvalho et al., 2016). It is considered that wind velocities of the order of 3 m/s are able to mobilize medium sands (Paula et al., 2016), and that if conditions are suitable – e.g. dry, open sand surface - the wind can transport even the coarse fraction of the sand (Györgyövics et al., 2014).

Small dunes migrate faster than larger ones (e.g. Jiminez et al., 1999; Carvalho et al., 2006), and displacements of 1 m/year can take place during the action of strong winds (e.g. Cooke et al., 1993). In the Sahara Desert, measurements indicate a migration rate of the order of 50 m/y for barchan dunes (Vermeesch and Leprince, 2012). In Antarctica, a study identified a rate of dune migration of 0.5 to 1.3 m/y (Bristow et al., 2010). A study about rates of dune migration of active subarctic dunefields indicates an annual migration varying from 0.5 m to 1.5 m (Necsoiu et al., 2009). In Great Britain, a research about the rate of migration of transgressive dunes gave an annual average of 1 m (Bailley and Bristow, 2004). In the Great Lakes area of United States, a study of the migration of continental dunes in a lake shoreline attained a maximum rate of 3.3 m/y (Kilibarda and Shillinglaw, 2014). At the Taklamakan Desert, China, measurements resulted in rates of dune migration of the order of 7.2 to 5.5 m/y (Zhibao et al., 2000). Dune migration in an estuary in New Zealand was identified at a rate of 5 m/y (Shepperd, 1987).

In the coastal area of Ceará State, in the northeast of Brazil (Fig. 1), large mobile dunefields formed by barchans, barchanoid dunes and sandsheets occur along its 573 km of length. The velocity of dune migration is high and has already been measured in some segments of its west coast. The resulting values appointed to a migration of the order of 17 m/y in Jericoacoara (Jiminez et al., 1999), of the maximum order of 12.5 m/y in

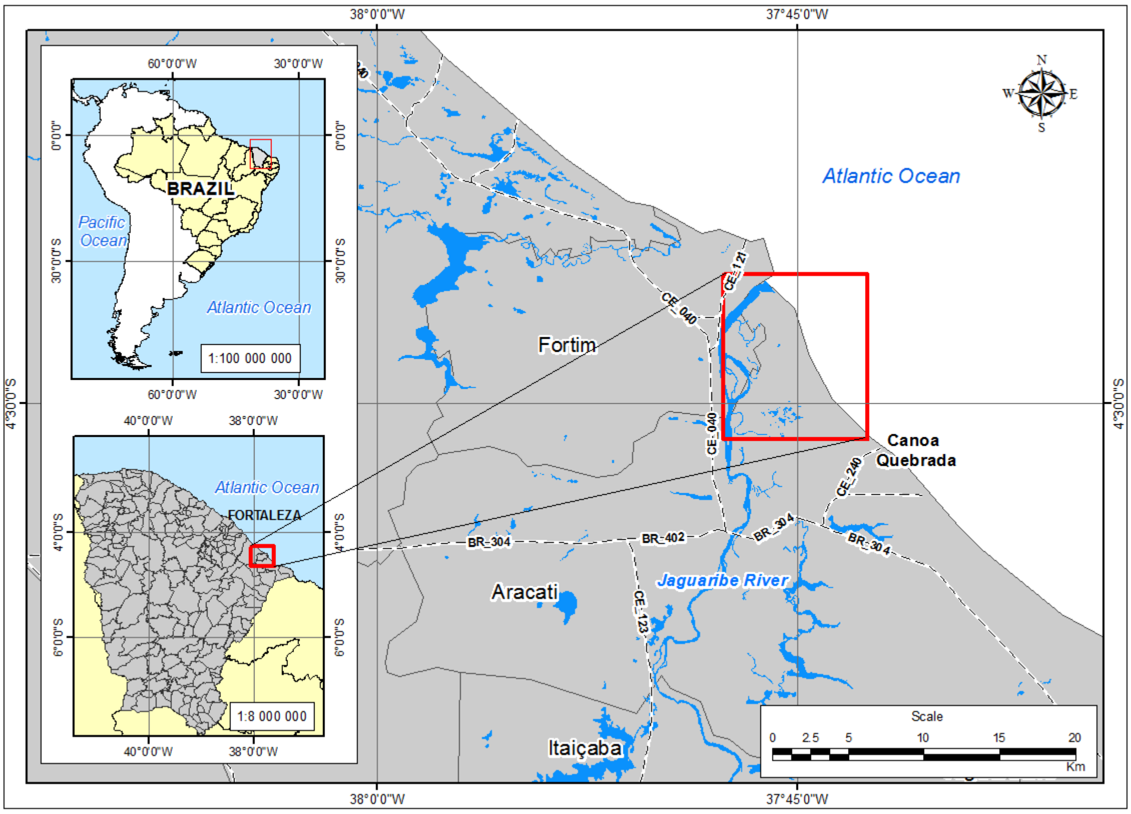

Fig 1 Location of the study area, the Canoa Quebrada Coastal plain, situated at the east segment of Ceará State coast

Paracuru (Castro, 2005), of 32 m/y for small barchans and of the order of 23 m/y for large barchanoid in the same area (Carvalho et al., 2006), and from 14 m/y to 19 m/y in Flecheira/Baleia beaches (Carvalho, 2003). Up to now, no measurements were made for the east coast of the state, a segment that is characterized by the presence of seacliffs extending for around 100 km and by less intensity of wind speed (Maia, 1998). It is important to mention that along this coast, wind-turbines have been installed in the last decade, which might affect the migration of the dunes. Nevertheless, no measurements have been made to evaluate the extent of the change.

In the other states that compose the Brazilian equatorial northeast, the intensity of dune migration defined by several studies present the same patterns of those identified in the coastal area of Ceará State: the rate of migration is in general higher than 10 meters per year. Illustrating this pattern, it is possible to highlight the migration in the coastal area of Piauí State - of the order of 21 m/y; in the state of Maranhão, where it can reach a maximum value of 25 m/y (Santos and Santos, 2015); and, finally, in the state of Rio Grande do Norte, where the dunes migrate with an intensity of at least 23 m/y (Carneiro et al., 2012).

The migration of dunes along the Ceará State coastal area is very important for the sedimentological budget of the area, considering that the region is semi-arid, with small production of fluvial sand. For this reason, an insignificant amount of sand is transported by rivers to the ocean, in order to nourish the beaches downdrift (Maia, 1998). The dunes, in doing the bypass across headlands and fluvial-marine plains, feed rivers with sediments, in such a way to contribute to the equilibrium of the coastal area (Maia, 1998; Claudino-Sales, 2002; Carvalho, 2003; Meireles, 2011; Claudino-Sales et al., 2018). In terms of environmental problems and dune mobilization, it is worth mentioning that in some places, there are conflicts between mobile dunes and urban structures, which have been installed in their path of migration.

In this paper, the migration of the dunes in the coastal area of Canoa Quebrada Beach, located in the east coast of Ceará State, is analyzed. The rate of dune migration at this area, identified here for the first time, has a current behavior completely different from the rate of migration identified for the other segments of the Brazilian northeast coast. The characteristics, as well as the reasons for the particularity of dune migration processes in Canoa Quebrada – such as natural driving forces, as well as those controlled by social activities, e.g. wind-turbine plants and tourism – are analyzed and discussed.

STUDY AREA

The coast of Ceará State, Northeastern Brazil (Fig. 1), consists mostly of long and wide quartz sand beaches, interrupted by small estuaries with mangrove formed by intermittent rivers, as well as by seacliffs, beach-rocks and headlands. The area is characterized by the presence of large transgressive coastal dune complexes distributed up to 6 km landward of the coastline. Small barrier-islands are present, especially in the west coast (Claudino Sales, 2002; Hesp et al., 2009).

Tertiary rocks, represented by the “Barreiras Formation,” is the most important type of deposition in terms of spatial distribution and control of regional coastal sedimentology. The Barreiras Formation displays a complex lithology ranging from conglomerates, sandstones and mudstones of terrestrial (Bigarella, 1975) and marine (Claudino-Sales, 2002) origins. It creates a low-lying tabular surface with less than 40 m in elevation that extends from the shoreline to 60 km inland. In the vicinity of the shoreline, the tabular surface is covered by aeolian sediments from both active and inactive dunes. In the east segment of the coast, Barreiras Formation outcrops as seacliffs 7 to 15 m high. In addition, it makes several headlands along the coast. (e.g. Claudino Sales and Carvalho, 2014).

Despite its tropical subequatorial location, Ceará state is dominated by an unusual semi-arid climate. The semi-arid characteristics are not directly reflected in the total annual rainfall value, which is relatively high compared to other semi-arid areas in the world (INPE, 2018). The semi-aridity is reflected in its great inter-annual variability, with more than 90% of the rain falling during the 3-month wet season, between mid-March and mid-June.

Temperature remains largely constant throughout the year, with monthly averages ranging between 25.5 °C and 27.5 °C in the coastal area (INPE, 2018). Due to this persistent high temperature and the resulting high potential evaporation, a severe water deficit of more than 1,000 mm occurs in the dry season in the coastal region (SEMACE, 1997). In addition, rivers with even drier catchment area are mostly periodic waterflows, not adding any important amount of sand to the seashore (Maia, 1998).

The climatic conditions of northeastern Brazil are mostly controlled by the Atlantic Ocean circulation system known as the "Intertropical Convergence Zone"- ITCZ (*e.g.* Wang et al., 2004). ITCZ is related to the sector of the globe where humid atmospheric masses coming from northern and southern hemispheres collide. During the first semester of the year (especially during March and April), the ITCZ is at its southernmost position over Ceará, resulting in the peak rainy season. After April, precipitation starts to decrease as the ITCZ shifts northward, reaching its northernmost position during the second semester of the year (September and October), leading to the peak of the dry season.

Another global scale control on the region's climate is the El Niño Southern Oscillation (ENSO) cycle. Maia et al. (2005) pointed out that ENSO tends to strengthen the dry season in the Equatorial segment of the northeastern Brazil, while Hastenrath and Heller (2006) suggested that it strengthens the wet season. In such a context, it is evident that, as compared to the ITCZ, the influence of ENSO on the regional climate regime is not yet well understood.

In the Ceará state coastal area, the wind conditions vary considerably from dry season to wet season, controlled by the seasonal migration of the ITCZ. It demonstrates a similar pattern as that of the precipitation variation, but with an opposite trend. Generally, as the precipitation rate decreases, the wind speed increases and reaches a peak speed during the peak dry season. Wind speed may exceed values of 15 m/s, but it goes from 4 m/s in the wet season to 8 m/s on average in the dry season, with annual averages of 5.5 m/s (e.g. Maia, 1998). The wind has a constant easterly direction, controlled by the trade winds. A unique aspect of this stretch of coastal area is that it is never influenced by severe storms.

Driven by the persistent and strong unidirectional winds especially during the dry season, as well as to the dominantly dissipative or intermediate type of meso-tidal beaches (Maia, 1998, Claudino-Sales, 2002; Carvalho and Claudino-Sales, 2016; Pinheiro et al., 2016), dunefields are very well developed along the Ceará coastal area.

The dunes occur as both stable vegetated older dunefields and modern transgressive dunefields (e.g. Claudino-Sales, 2002; Claudino-Sales and Peulvast, 2002). Luminescence dating of sand samples (~1 m below the surface) from vegetated dunes along the coasts of Ceará yielded ages ranging from 135 ky to 100 yr BP (Tsoar et al., 2009). Generally, the dunefields are composed of lunar-shaped/barchans and transverse dune ridges, with fixed parabolic "hairpin" dunes and aeolianites in the seaward segment of the coast (Maia, 1998; Claudino-Sales, 2002; Claudino-Sales and Peulvast, 2002; Carvalho, 2003; Carvalho et al., 2010). Mobile transverse dunes vary in height from less than 15 m to 55 m.

The vegetation in the dunefields is characterized by the presence of species of the halophile-psamophile community (especially *Ipomoea pes-caprae* and *Sporobolus virginicus*) in the mobile segment, and by species of the coastal tropical forest (especially *Anacardium occidentale* and *Byrsonima sericea*) in the vegetated dunefields (Moro et al., 2015).

The wave conditions in the Ceará State coast are also strongly influenced by the persistent and unidirectional trade winds. According to the National Institute of Navigation Research – INPH (1996), the predominant wave direction as measured at Pecém beach is 90°, *i.e.,* approaching from the east. The waves are mainly of the sea type, with occasional occurrence of NE swell originated in the northern Hemisphere from November to March (Maia, 1998). The most frequently occurring wave heights range from 1.0 to 1.5 m, with period of 5 s (Claudino-Sales et al., 2018; Maia, 1998). The Ceará State coastal area is characteristic of a semidiurnal mesotidal regime with a spring tidal range of approximately 3.1 m (DNH, 2018), and an average range of 2.64 m.

Canoa Quebrada Beach, as studied in this paper, is located in the east segment of Ceará State coast (Fig. 1). The studied coastal segment is 11 km long, occupying an area of 2,500 ha. The landscape, as see in the geomorphological map (Fig. 2), is characterized by the presence of long sandy beaches interrupted at the west by the mouth of the Jaguaribe River – where the fluvial-marine plain is colonized by mangrove. The strand is marked by the presence of active seacliffs shaped in the Barreiras Formation (Fig. 3A), which extend for around 30 km from SE to NW, as well as by littoral bars (see Figure 2). Coastal tablelands are also modelled in the Barreiras Formation in the inner coastal area, and are largely covered by mobile dunefields and interdune ponds (Figs 2 and 3B) (Pedrosa, 2016). The mobile dunefields of Canoa Quebrada are of the barchans type (lower number), barchanoids (abundant) and sandsheets (dominant) (Pedrosa, 2016). There are also semi-fixed dunes in contact with the mangroves (Figs. 2 and 3C). The vegetation of the mangrove is, in this case, the major factor in the fixation of the transgressive dunes that

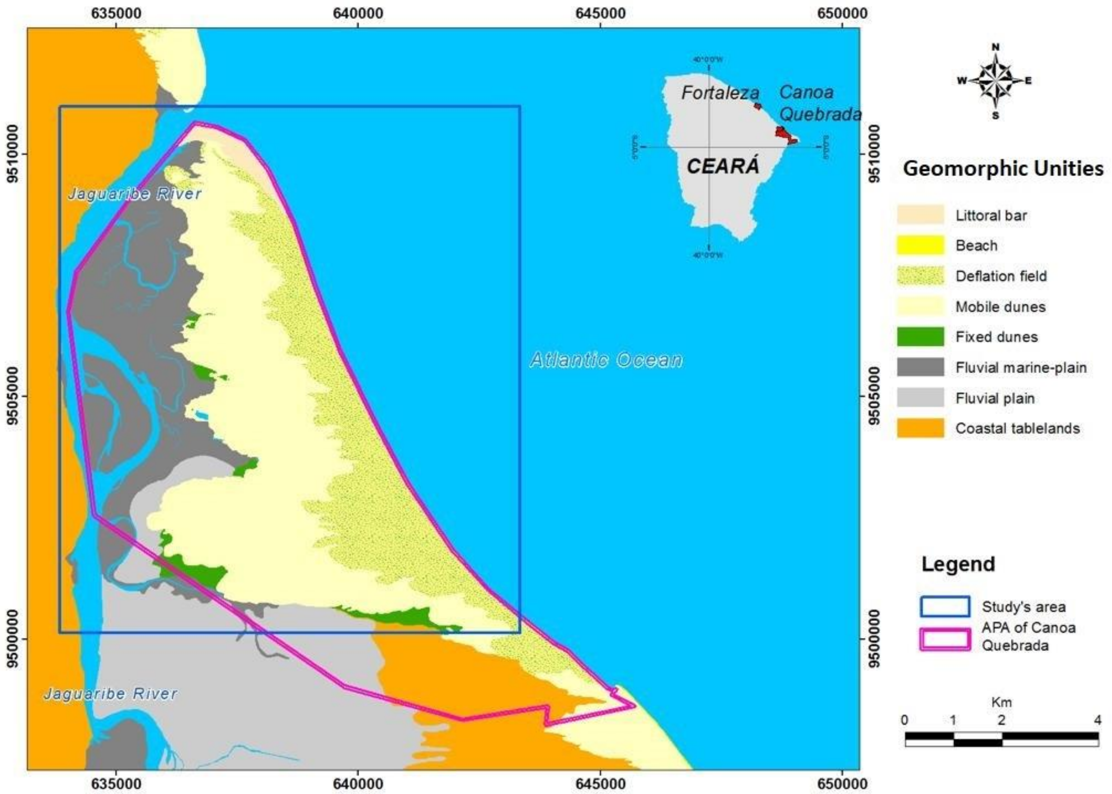

Fig 2 Geomorphology of Canoa Quebrada Beach, with indication of the presence of an Area of Permanent Preservation (APA) in the study area

migrate into the fluvial-marine plain direction. The dunes present maximum heights of 34 m (Fig. 3D) (Pedrosa, 2016). They are formed by medium and fine well-selected sands (Maia et al., 2006).

The pluvial regime in Canoa Quebrada is mild tropical. The annual average precipitation rate reaches 1,024 mm (FUNCEME, 2015). September is the driest month, with only 5 mm of rain. The majority of the precipitation occurs in March, with a monthly average of 264 mm. The annual average temperature is 27.1°C (FUNCEME, 2015) (Fig.4).

Most of the studied area is part of the "Area of Permanent Preservation – APA" of Canoa Quebrada (for location of the APA, see Figure 2). The APA was defined by state law in 1998, and has the goal to preserve the biotic communities, fixed and mobile dunes, seacliffs, ponds,

Fig. 3 Coastal features in Canoa Quebrada Beach. A. Seacliffs modeled on Tertiary sediments in Canoa Quebrada Beach B. Mobile transgressive dunefields with interdune ponds. C. Transgressive dunes being fixed in contact with mangroves at the fluvial plain of Jaguaribe River. D. Thirty-four meters high barchan dune in Canoa Quebrada Beach coastal area

mangrove, reefs and soil. It also allows the development of the land, in the measure that the uses and occupations intended do not result in degradation of the natural attributes of the environment. The principal economic activity practiced in the APA is geotourism and ecotourism. In the last decade, wind-turbine plants were installed.

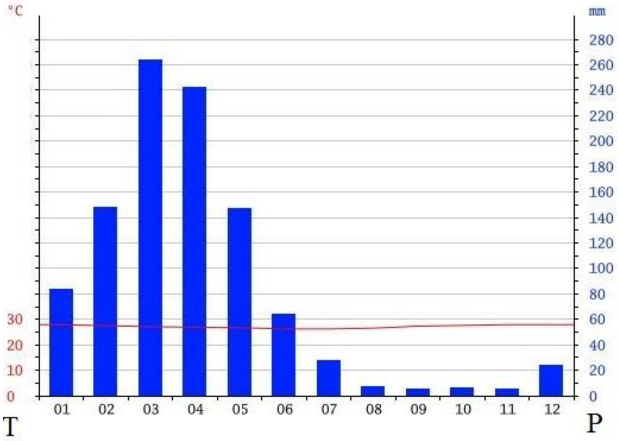

Fig. 4 Graphic of temperature (T) and precipitation (P) in Canoa Quebrada coastal area (meteorological station placed at Aracati, 30 km from the study area) for the year 2015

METHODS

The dune migration rate analysis along the Canoa Quebrada municipality covered the interval of 25 years, related to the period 1988 - 2013. Therefore, aerial photographs, scale 1: 25,000, of the year 1988, as well as satellite images "Quick bird" of the years 2004, 2010 and 2013 were used. Besides Google images, those were the only images found for the area in the Brazilian public and private sources. The location of the transects used in this research using the photographs and satellite images is indicated in Figure 5.

The determination of the migration rate of the dunes was obtained with the help of the tool "Digital Shoreline Analysis System – DSAS 3.2", applied to the ArcMapGIs 9 software. The DSAS is an extension that enhances the normal ArcGis software functionality. It allows the user to calculate change rates of a statistical series, considering the time and the multiple positions of successive lines drawn in the satellite images of the coastline (Oliveira, 2005; Thieler et al., 2005). The tool was used for this study, to allow measuring the lines of advancement of the dunes along the coastal plain.

The DSAS works by generating orthogonal transects at a spacing defined by the user, which in this case was 200 m. It calculates the change of rates between space and time, generating the statistics that are shown in an attribute table. The statistical method tool was the linear regression (LRR).

The DSAS tool was applied from the creation of lines in shapefile format in ArcMapGis 9 software. The boundary line of the dunefields, on the leeward side, was created for each year of observation, enabling the multi-temporal analysis. A baseline was acquired, also in shapelife format, set perpendicular to the direction of dune migration. The observation of the direction of migration was made using the satellite images, overlapping one and the other.

Finally, the tool that creates the transects was applied, also in shapefile format, for calculation of the migration rates. Each transect passing the lines calculates the rates, considering the space and the existing time between them.

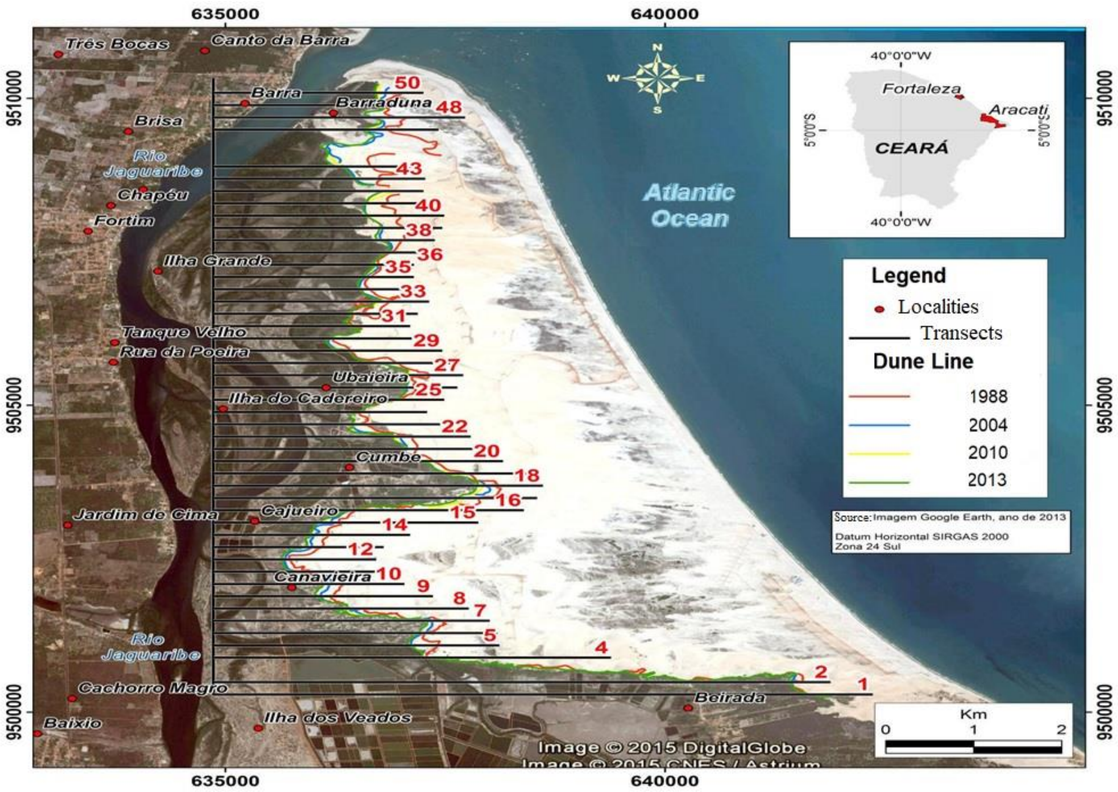

Fig. 5 Location of the transects made in the dunefields of Canoa Quebrada, in order to calculate the rates of migration of the dunes

The value that each transect calculates matches the given point of the dune. Therefore, the migration rate of a dunefield can be acquired by calculating the average of all transects.

The precipitation, temperature and wind speed data were collected in the Brazilian and Ceará State weather centers, at the meteorological station of Aracati City, 30 km from the study area. For the precipitation and temperature, monthly raw numbers were obtained at the Ceará State Meteorological and for Water Resources Foundation (FUNCEME), and statistics were made to give the annual averages for the time series analyzed. For the wind, raw monthly data was collected in the Forecast Weather and Climatic Studies Center of the National Institute of Spatial Research (CPTEC/INPE), and statistics were produced to attain the annual average numbers for the time series analyzed. There was no available wind data for the years 1988 and 2004.

For the physical recognition of the study area, as well as to evaluate the impact of tourism and turbine-wind plants in the natural dynamic, fieldworks were made in the dunefields, using a dune buggy. In addition, one day of navigation was done in a fishing boat in the channel of the Rio Jaguaribe, to identify the eventual impact of the migration of transgressive dunes toward the mangrove forest. The field trips took place in the years 2016 and 2017.

RESULTS AND DISCUSSION

The dune migration rate of the Canoa Quebrada dunefield obtained within 25 years is shown in Figure 6 This value was approximately 7.25 m/y. The greatest migration rate obtained was 18.4 m/y (transect 39, see Figure 6), while the lowest was 0.5 m/y (transect 2, see Figure 6). This migration rate appears to be much lower than those set for other sectors of the coastal zone of Ceará state and other states of Northeastern Brazil, as indicated by Maia (1993), Jimenez et al. (1999), Carvalho (2003), Castro (2005) and Carvalho et al (2006), Carneiro et al. (2012) and Santos and Santos (2015).

In the 1988-2004 period, the largest averages of migration rates showed values of the order of 9.3 m/y. In the spaces of time between 2005-2010 and 2011-2013, there was a decrease of the average rates of dune migration. In the period of 2005-2010, the average rate was approximately 3.5 m/y, and in the last interval, only 1.8 m/y.

The relationship between migration rates and the annual precipitation in the dunefields in the analyzed intervals is shown in Figure 7. The highest rainfall occurred in the period of 2005-2010, exceeding 1,000 mm/y. Much less rainfall occurred in the 2011-2013 period, reaching 600 mm/y. Comparing the intervals 1988-2004 and 2005-2010, there was a decrease in the average migration rate of the dunes while there was an increase of atmospheric precipitation. This confirms the normal behavior of dune mobilization, presenting a lower rate with the increasing rainfall. However, it appears that in the interval 2011-2013, even with decreased annual rainfall, there was not an increased migration rate of the dunes. Instead, the migration of the dunes for this time interval was also lower.

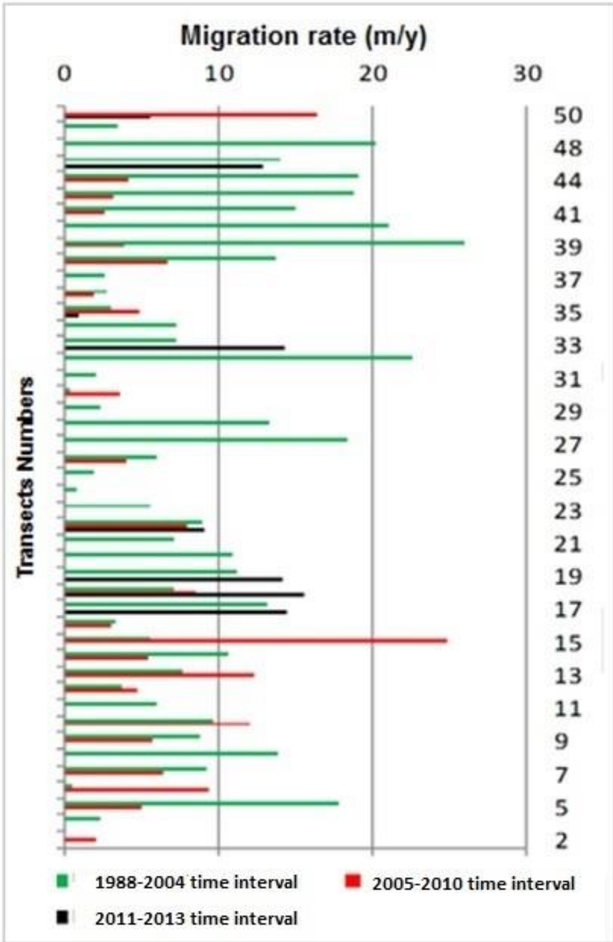

Fig. 6 Rates of dune migration in Canoa Quebrada for the studied time series

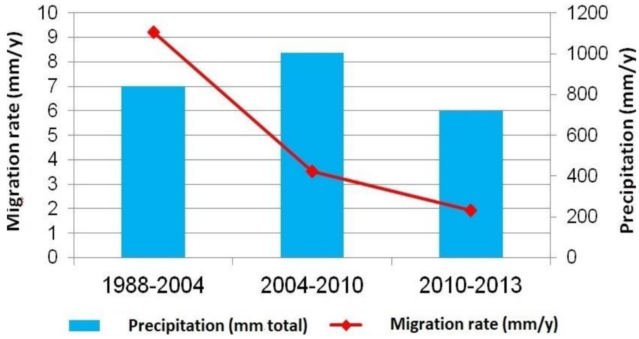

Fig. 7 Rates of migration and intensity of precipitation in Canoa Quebrada for the studied time series

Thus, the data in relation to the Canoa Quebrada Beach for the last time interval seem to contradict the relationship between the decrease of annual rainfall and increase in the average rate of dune migration, as seen in Figure 7. What is evident in the data of Canoa Quebrada is the occurrence of decreasing migration rates for the most recent time series.

The annual average wind speed obtained for Canoa Quebrada is below the speed measured in other parts of the Ceará State coast in previous decades: it was of the order of 1.45 m/s in 2010 and of 1.65 m/s in 2013 (CPTEC/INPE, 2015). The short interval of time of these data is not enough to affirm whether it is a systematic or just an eventual situation.

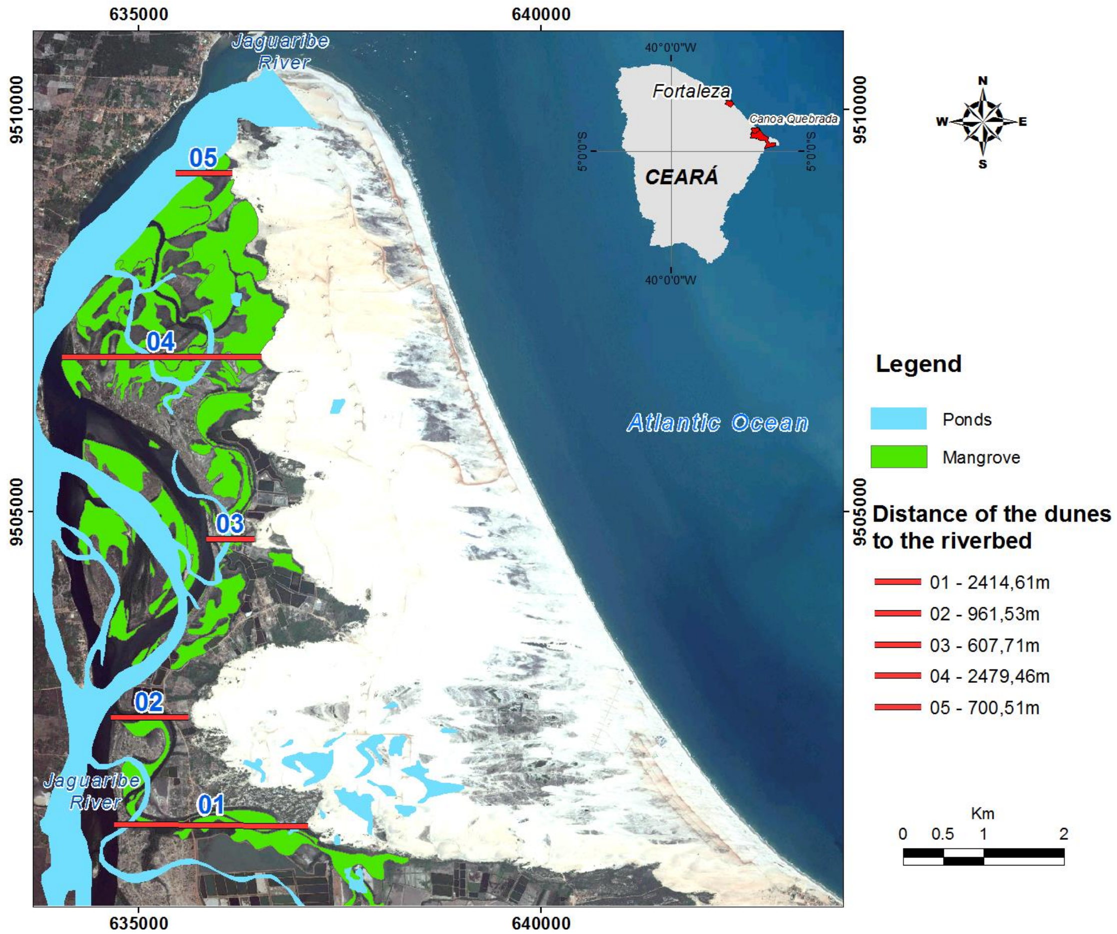

Fig. 8 Distances from the lee face of the mobile dunes to the Jaguaribe River estuary situated at the west segment of Canoa Quebrada coastal area

The mobile dunes of Canoa Quebrada migrated in the direction of the fluvial plain of the Jaguaribe River. Figure 8 shows the current average distance of the lee face of the dunes up to the riverbed. This distance is 1,432 m on average. The farthest point (04) measures 2,479 m, while the nearest (03) lies at 603 m.

During parts of the Holocene, the mobile dunes of Canoa Quebrada fed the Jaguaribe River with sediment. The river, in turn, probably deposited the sands in the ocean through its near mouth. Thus, the coastal sedimentary budget should have some sort of balance: the sediments would be transported by the action of winds from the beaches to the coastal zone’s interior. Part of this stock would go back to the ocean through the bypass of dunes in headlands and by the supply of rivers. The sediments returned to the ocean by rivers would feed new beaches downstream, creating a retro-feeding mechanism capable of ensuring the balance of the shoreline and the control of coastal erosion.

With decreasing migration intensity of the dunes toward the river in the Canoa Quebrada coastal area, the amount of aeolian sand that fed the river flow became smaller. According to the average distance of the sliding face of the dunes to the river, and if the current aeolian regime continues, the dunes would take about 198 years to reach the riverbed, or 84 years, considering the nearest point. Thus, the sediment yield to the ocean by the Jaguaribe River is certainly decreasing, which may be contributing to the growth of the coastal erosion that occurs in the beaches downstream of the river mouth. This erosion has been detected by Morais and Pinheiro (2011), who also considered the role of damming of the river in the last decades, as well as other occupation of the fluvial-marine plain by social activity, such as shrimp farms.

The considerable decrease in the migration rate of the dunes in Canoa Quebrada in the last decade, as measured, can also result in part from the forms of land use and occupation. Indeed, since mid-2009 wind turbines are being installed by private investors in the dunefields of the study area, as allowed by government, aimed to produce wind energy for regional consumption (Fig. 9).

For the installation and maintenance of the wind power plants, the installation of a network road for access was necessary, as well as the adoption of measures to protect the base of the structures from burial by sand and wind erosion. Therefore, a process of artificial fixation of sand began, using straw (Figs 10 and 11). The migration speed of the dunes was certainly altered to lower values with the implementation of containment techniques for mobile sands. Indeed, from 2010, the dunes presented little annual migratory movement, as identified by the analysis of satellite images. Nevertheless, the wind

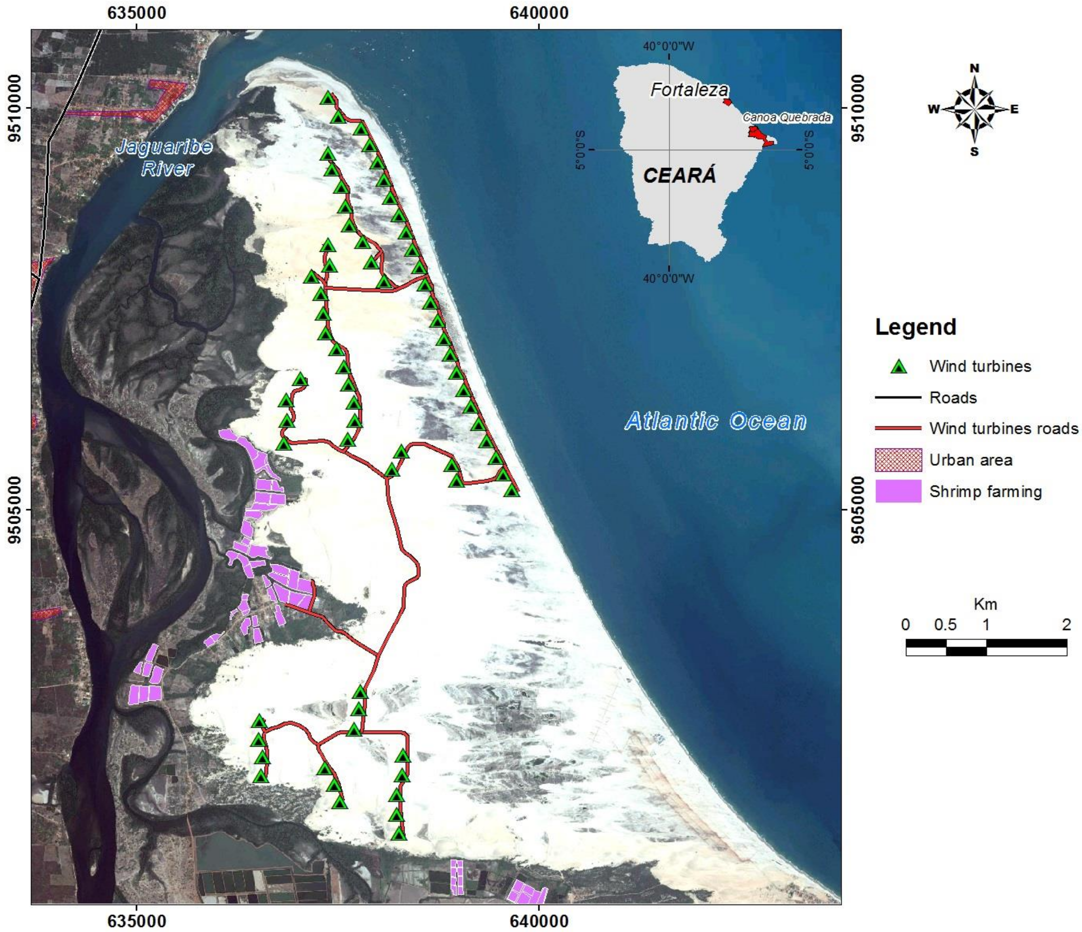

Fig. 9 Map of use and occupation of the study area, showing the location of wind-turbine plants

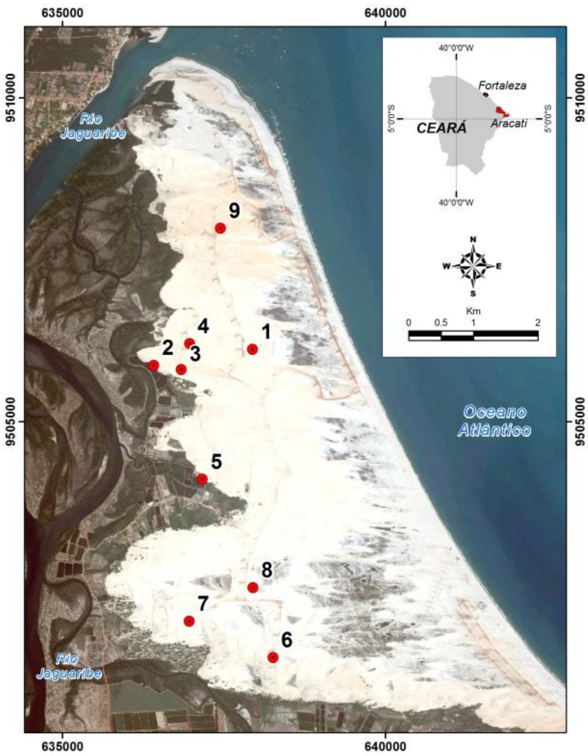

Fig. 10 Location of the introduction of straw to promote the fixation of the mobile dunefield of Canoa Quebrada, in order to protect the aeroturbines from burial by the sands and from aeolian erosion

speed was a little higher for the years 2011-2013, as shown in Figure 6.

The fixation of the mobile dunefields of Canoa Quebrada for the purpose of protection of the plants for aeolian energy is not the only threat to the dunefields and to the APA there. The opening of circulation routes to facilitate the traffic of buggy type vehicles, which carry tourists on the dunes, has to be mentioned (Figure 12). The village of Canoa Quebrada is one of the most important tourist destinations of the state, and is national and world renowned. The tourism flux is intense, and the traffic of buggies is considerable. This can also be a factor in the compaction of sand and of the reduction of the dune migration rates.

Dwindling sediments already present in the riverbed due to the construction of dams (around 30,000 tons of sediment annually retained: Morais and Pinheiro, 2011), particularly the large dam "Castanhão" at the end of the 1990s, the additional decrease of intake sediment caused by decreased dune migration in Canoa Quebrada on the riverbed possibly will result in non contribution of sediments from the Jaguaribe River to the ocean. It is considered here that without sediments, and taking into account the littoral dynamics of the study area, the river runs the risk of having its mouth barred by the construction of sand barriers formed by sand coming from the ocean, deposited by the action of waves and longshore drift.

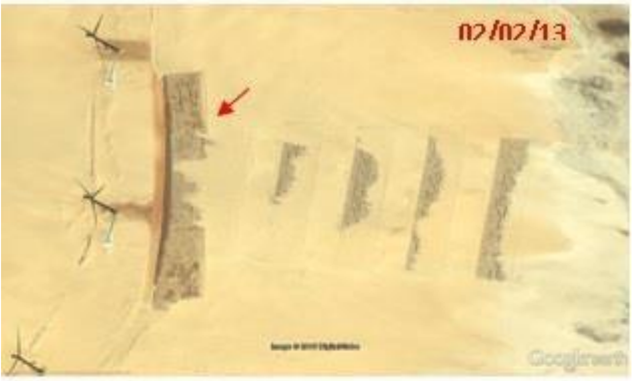

Fig. 11 Dunes fixed by straw in the coastal plain of Canoa Quebrada. (Source: Google Earth)

Fig. 12 Unpaved road (arrow) built on the mobile dunefields to allow the use of dune buggy vehicles, in order to answer tourist demands

CONCLUSIONS

The research synthesized here indicates the occurrence of a low annual average migration rate of the mobile dunes along the coastal plain of Canoa Quebrada Beach within 25 years, between 1988 and 2013. In addition, it appears that this reduction was increasing at the end of 2013. The migration rates (with minimal of 1.45 m/y) are considered lower when compared to the other sectors of the northern Brazilian area, as indicated by Maia (1998), Jiminez et al. (1999), Carvalho (2003), Castro (2005), Carvalho et al. (2006), Meireles (2011), Carneiro et al. (2012) and Santos and Santos (2015).

The data also showed a low annual wind speed, despite the decrease in precipitation in the last five years, which is the normal trend in the Brazilian northeast. The decrease in precipitation illustrates the great drought embracing the northeast region in recent years, through the action of El Niño. Such a situation seems to disprove the idea that the El Niño action increases the migration of dunes in the coastal zone of Ceará State, as indicated by Maia et al. (2005).

On the other hand, the low average migration rate of the dunes along the coastal plain of Canoa Quebrada, as identified in the data presented here, is clearly due to the low intensity of the wind in the area. Indeed, even with the decrease in precipitation, the migration rate did not increase between the observed time intervals. This seems to indicate that the main element responsible for dunes migration is wind speed. The installation of straw in some segments of the dunefield also contributed to a lesser rate of dune migration. The moisture content present in the sands resulting from precipitation and other elements of the natural environment such as the topography of the land and the geometry of the dunes seem to be secondary factors.

Despite the existence of an area of environmental preservation - APA - in the dunefields of Canoa Quebrada, it is clear that some activities permitted by public agencies are degrading the dune ecosystem. This is the case of the measures taken to ensure the maintenance of the turbines for wind energy installed in the dunefields, and the resulting compaction from traffic by tourist passenger cars. These activities, approved or known by the state and local public agencies responsible for monitoring and ensuring the local environmental preservation, clearly work against the integrity of the dunefields. They are also possibly responsible for the lower rate of dune migration in the last analyzed interval of time.

Together, the natural dynamics and the dynamics induced by social activities in the coastal area of Canoa Quebrada have pointed to a virtual stabilization of the local dunefields, because of the increasing decline of the migration rates of the dunes. This may have regional implications, such as the lower contribution of aeolian sand to the sedimentary budget along the east coast of Ceara State. This stabilization can result in alterations in hydraulic and sedimentary dynamics of water resources coupled to the dune system, which can produce a magnification of the coastal erosion underway downdrift of Canoa Quebrada Beach. These findings should be incorporated into integrated coastal zone management strategies for the area, especially those associated with coastal erosion and preservation of the environment

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