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Aeolian mobility in the Middle São Francisco Dune Field, Northeast Brazil, as a response to Caatinga's droughts and land-use changes

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ABSTRACT

In the last decade, the semiarid northeast of Brazil (Caatinga biome) has experienced one of the most prolonged and most severe droughts ever recorded in regional history. The study of the landscape changes contributes to understanding the environmental, social, and economic consequences of extreme climate events in the region. Here, we investigate the marginal area of the Middle São Francisco dune field, where in recent years, aeolian landforms development and their migration have been observed. To map the migration line of the aeolian front, we used 2002–2019 high-resolution images, from which we estimate the migration rates and evaluate the monthly migration rates for several interannual intervals, particularly during the drought peaks. In the area of greatest migration, the dunes advanced 210 m in 18 years. In the first decade, under climatic conditions closer to the historical average, dunes migrated ~15 m/y, while in the second decade, they migrated 80 m at a rate of 9.4 m/y. Examining the ranges of intra-annual migrations, we estimate that the highest mobility rate was almost five times greater than the rate at the end of the decade. In addition, we calculated a dune mobility index and the dune's morphological patterns. We conclude that the morphodynamic processes of dune formation and migration were triggered mainly by vegetation removal from river banks. The more severe climatic conditions during the last drought (2012–2017) enabled the dunes to migrate relatively quickly. The last few years (2017–2019) were marked by a considerable reduction in aeolian mobility and stabilization of expansion margins, inducing the formation of barchan-parabolic dunes.

1. Introduction

The stabilized dunes of the Middle São Francisco River are the largest field of inland aeolian dunes in Brazil and one of the most relevant records of the expansion of aeolian activity in tropical South America during the late Quaternary (Sarnthein, 1978; Muniykwa, 2005; Lancaster, 2007; Tripaldi and Zaraté, 2016). The dunes are also a key landscape component of the semiarid region of Northeast Brazil (NEB) and a morpho-sedimentary archive of past and recent environmental changes caused by natural climatic changes and anthropogenically-induced environmental stress. The Middle São Francisco dune field (MSF-DF) is characterized by parabolic dunes of various types, ages, and dimensions. Thermoluminescence dating indicates that the aeolian dunes on the left banks of the Middle São Francisco River expanded mainly between the Middle Pleniglacial and the Late Holocene (Barreto et al., 1999; De Oliveira et al., 1999). The dunes must have become regionally stable ~900 years ago (Barreto et al., 1999).

The paleoclimatic evolution in NEB during the Holocene remains controversial when different proxies are interpreted. For example, results about the climatic pattern (wet/dry) in the mid-Holocene obtained from speleothems (Cruz et al., 2009) and paleovegetation (Pessenda et al., 2010) are uncorrelated. Pollen analysis in the Icatu valley in the MSF-DF (De Oliveira et al., 1999) indicates that after a wet interval at the end of the Middle Holocene (between 7.1 and 5.4 cal yr BP), a semiarid climate has predominated in NEB until the present (Nace et al., 2014). According to Novello et al. (2012), for the last 3000 years, wet intervals occurred abruptly every ~210 years, with the most significant one ~2800–2650 BP. Novello et al. (2012) also highlighted that the ^{18}O isotopic rates for the current dry climate correspond with those during dry intervals in the Medieval Climate Anomaly (MCA: ~890-1154 BCE) and the Little Ice Age (LIA: ~1538-1803 BCE).

Therefore, current knowledge suggests that the last aeolian mobility in the MSF-DF occurred during the MCA drought (Barreto et al., 1999). A period with similar climatic characteristics to the present day (Novello et al., 2012). Nevertheless, under the present conditions, aeolian erosion and deposition could be reactivated by minor natural or anthropogenic changes (e.g. increased evapotranspiration rate, higher wind speeds, vegetation removal). The NEB is one of the most susceptible regions of the country to climate change, with projections of reduced rainfall,

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increased temperatures, and, consequently, greater frequency and severity of droughts throughout the current century (IPCC, 2014; Marengo and Bernasconi, 2015; Vieira et al., 2015; Marengo et al., 2017). The droughts have been interpreted as a climatic response northern position of the Intertropical Convergence Zone (ITCZ) during El Nino events (Marengo et al., 2017). This climatic scenario already occurred over the last decade, particularly between 2012 and 2017, when the NEB experienced one of the longest and most extreme droughts in historical records (Cunha et al., 2019). Moreover, the higher frequency of droughts can exacerbate some morphodynamic aeolian processes, particularly in sensitive areas such as the currently inactive MSF-DF.

Drought events have been investigated using remote sensing and various indexes (e.g., Normalized Difference Vegetation Index-NDVI; Vegetation Health Index-VHI; Temperature-Vegetation Drought Index-TVDI; Vegetation Supply Water, and Drought Severity Index-DSI). While such indexes have significantly contributed to our understanding of the climates in regions with scarce coverage of meteorological data, the results derived from the various indexes also diverge (Cunha et al., 2015; Alvalá et al., 2017). Therefore, to validate these indexes, the largest amount of information needs to be integrated. One way is to incorporate geomorphologic information on the landscape response to extreme or recurrent climatic events to obtain qualitative information about a certain climatic condition.

In this context, we have identified from field surveys and high-resolution satellite images a recent aeolian reactivation and dune mobility on the south-eastern edge of the MSF-DF, in a place known as Dunes of Geleia. It is an aeolian front that extends laterally for ~1.5 km and has already advanced in some areas by more than 250 m towards the internal area of the MSF-DF, mainly in the period of the greatest aridity ever recorded in NEB.

Therefore, investigating the Dunes of Geleia provides an opportunity to correlate information on the migration rate of the dune front with the severe climatic conditions of recent years. Thus, the main objective of this study is to: (i) estimate the rate of aeolian mobility between 2002 and 2019; (ii) analyze and characterize the aeolian patterns that developed during the migration; (iii) estimate a Dune Mobility Index (Lancaster, 1988) based on meteorological data available in the region; and (iv) propose a progression model for the Dunes of Geleia by inserting the elements interpreted as determining factors for aeolian expansion in the area.

2. Study area

The MSF-DF is located in the southern portion of NEB between 9°50′S and 11°S, covering an area of ~8000 km^2, specifically in the northwest of the State of Bahia. The examined area (Dunes of Geleia) is on the south-eastern edge of this active dune field (Fig. 1) and developed into a zone of direct interaction between the São Francisco River and the MSF-DF.

According to the Köppen classification, the semiarid tropical (BSh) climate prevails in NEB, and the average annual precipitation is less than 800 mm (Alvares et al., 2014). The current climate dynamics and variability in NEB is driven primarily by the positioning of the ITCZ, and also by anomalies in the Atlantic Multidecadal Oscillation (AMO) and El Niño-Southern Oscillation (ENSO) events (Marengo et al., 2017; Molion and Bernardo, 2002; Barbosa et al., 2019).

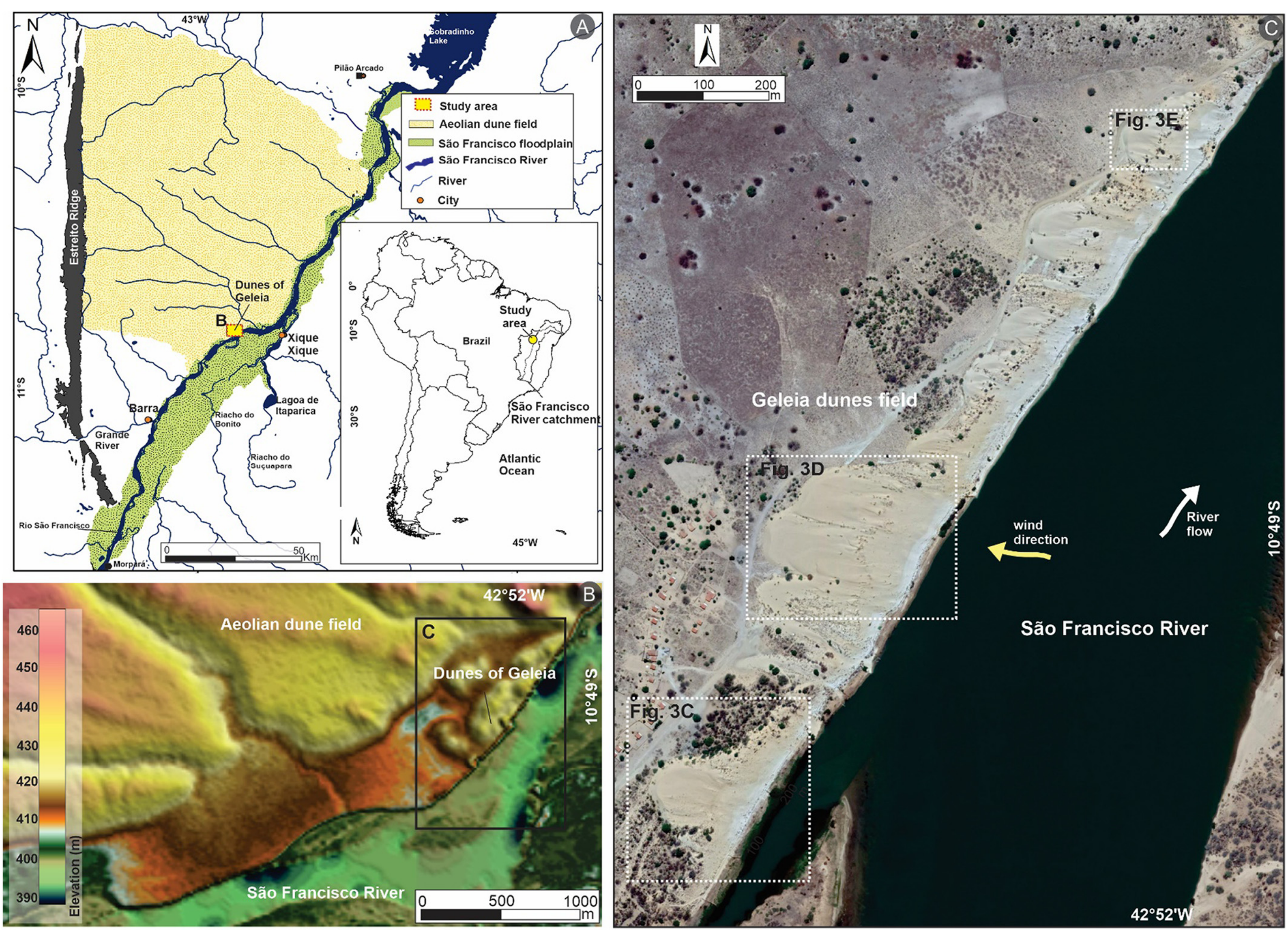

Fig. 1. Location of the investigated area. (A) A map highlighting the Middle São Francisco paleo-dunes field area and the São Francisco floodplain. (B) A DEM highlighting the local geomorphology in which the studied area is inserted. (C) An image from Google Earth (2018) showing the area of the active Dunes of Geleia.

The study area is characterized by a dry season that, on average, lasts five to eight months, with the driest period from May to September. The annual average temperature for the dry season is above 30 °C, and the mean rainfall is below 150 mm/yr (Fig. 2). According to data from Xique-Xique city, located ~15 km from the MSF-DF, the wind has a prevailing SE-NW direction and average annual speed of 4.6 m/s. The winds are strongest during the transition from winter to spring, mainly August and September when wind speeds are above the threshold for sand transport over a time range of ~8%–16% of the year.

The study area is in the Brazilian dry tropical forest called the Caatinga biome, (Leal et al., 2003; Santos et al., 2014). Typical Caatinga vegetation of sandy areas with some endemic species of the families *Leguminosae*, *Euphorbiaceae,* and *Cactaceae* predominates in the MSF-DF (Rocha et al., 2004). Half of all species sampled are trees or shrubs. Herbs and sub-shrubs represent almost 30% of the species. Among the most abundant species are *Eugenia* sp. and *Copaifera*, representing approximately 50% of the total (Rocha et al., 2004).

3. Methods

3.1. Remote sensing and geomorphological mapping

The position of the Dunes of Geleia and their dune patterns during the aeolian expansion in the current century were obtained from 12 satellite images (RapidEye, PlanetScope, and images sourced by Google Earth) from different periods (Table 1). RapidEye and PlanetScope images were provided by Planet Team (2017). The area was also investigated during field surveys by car and boat in 2017. Thus, a morphosedimentary description in the field, combined with a Digital Elevation Model (DEM) of spatial resolution of the order of 12,5 m (ALOS-PALSAR images) and optical satellite images, allowed us to characterize the morphology of the dunes.

To better assess the aeolian progression (2002–2019), we used images available on Google Earth for 2002, 2010, and 2017. The 2009 and 2015 multitemporal analysis of the aeolian front-line migration was based on RapidEye images. Images of the Planet Scope constellation were used to obtain the position of the aeolian front between 2016 and 2019. Aeolian advances were mapped for all 12 images, and we selected six main annual aeolian advance lines (2002, 2009, 2010, 2012, 2015, 2019) to illustrate the annual and monthly migration rates for some representative periods (Fig. 3). The definition of the pattern of dunes at different stages of evolution of the Geleia of Dunes was based on a comparison with published results from similar types of dunes in other regions (Mckee, 1979; Tsoar and Blumberg, 2002; Wolfe and Hugenholtz, 2009; Durán and Herrmann, 2006; Hanoch et al., 2018).

We performed basic procedures for adjusting the RapidEye and Planet images' histograms and identifying dunes migration. The high-resolution images from Google Earth Pro software were exported and converted to TIF format and georeferenced in a GIS environment through control points.

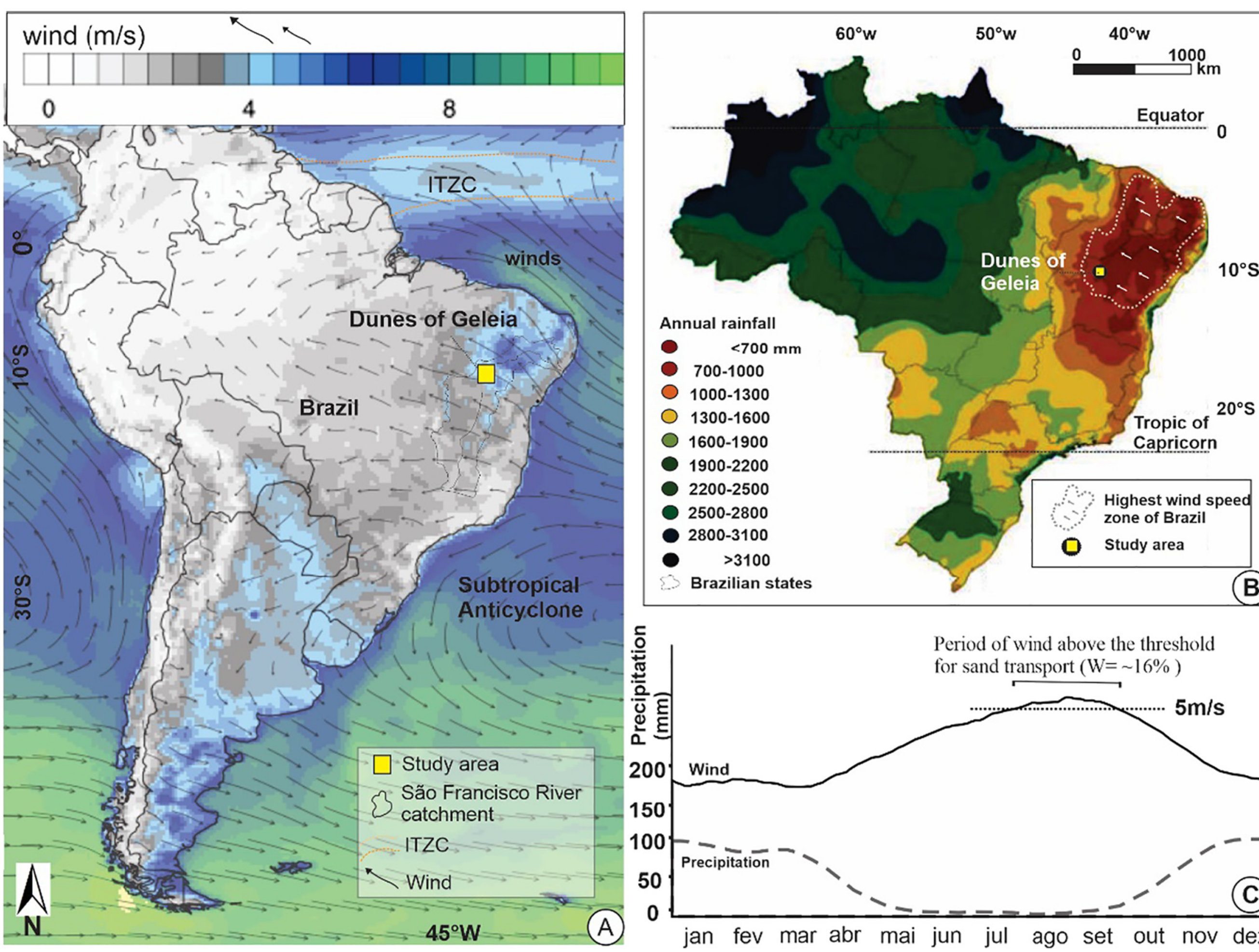

Fig. 2. Meteorological information of the studied region. (A) South American average wind speed in the months of July, August and September 2017 (modified ECMWF ERA 5) on a continental scale, provided by the Climate Change Institute (climatereanalyrzer.org). (B) Map of total annual rainfall in Brazil (modified from Alvares et al., 2014) and indication of the zone with the highest intensity of winds in the country. (C) Average precipitation and wind intensity for Xique-Xique city based on the MERRA-2 reanalysis model (Modern-Era Retrospective Analysis for Research and Applications), which consists of the mean of a historical series between 1980 and 2016, available from Weather Sparker (weathersparker.com).

Table 1
Data and resolution of satellite images used to map the aeolian front-line migration.

Satellite image	Date	Resolution (m)
Google Earth[a]	20 December 2002	0.5
RapidEye	14 June 2009	5.0
Google Earth[a]	21 August 2010	0.5
RapidEye	14 November 2011	5.0
RapidEye	08 December 2012	5.0
RapidEye	10 October 2013	5.0
RapidEye	17 September 2014	5.0
RapidEye	21 September 2015	5.0
PlanetScope	12 December 2016	3.0
Google Earth[a]	23 October 2017	0.5
PlanetScope	13 November 2018	3.0
PlanetScope	04 November 2019	3.0

[a] Image available in the archives of Google Earth.

3.2. Climatic data and aeolian mobility estimate

Characterizing the regional climate in the MSF-DF is difficult because of the scarcity of detailed meteorological information in the region. We incorporated available climatic data from nearby locations and precipitation and potential evapotranspiration data from the database of the National Institute of Meteorology (INMET) in Barra station, which is located approximately 40 km of the Dunes of Geleia. Historical rainfall series were available for the 2000–2019 studied period, but potential evapotranspiration data was incomplete with only four years of available data (2009–2012).

Wind regimes were assessed at Xique-Xique city, located in the lowlands and closer to the Dunes of Geleia (Fig. 1). Although Barra station is also relatively close to the MSF-DF we did not consider the wind regime at that location because it is influenced by the nearby high plateau (>1000 m a.s.l.), and wind intensities are slower than in Xique-Xique. Wind data were obtained from the MERRA-2 reanalysis model (Modern-Era Retrospective Analysis for Research and Applications), available from Weather Sparker (weathersparker.com), which consists of the mean of a historical series between 1980 and 2016.

It is considered that if wind velocities are above the sand transport limit for a certain period of time when the ratio between precipitation and the evapotranspiration potential is low, dunes can become mobile (Dune Mobility Index, Lancaster, 1988). The low ratio between precipitation and potential evapotranspiration also controls and interacts with soil humidity and vegetation, and that determines whether vegetation cover expands or shrinks and whether dunes will be inactive or mobile. Therefore, if the time duration of the threshold speed is maintained at average values when the precipitation ratio and potential for evapotranspiration in the MSF-DF are reduced, then the dune field can be subjected to reactivation by aeolian processes.

Based on the most reliable meteorological parameters available for the region, we calculated the Dune Mobility Index (Lancaster, 1988). The mobility index is based on the eq. $M = W / (P / ET)$, where P is the annual precipitation value, ET represents the potential evapotranspiration value estimated according to the Thornthwaite method (Thornthwaite and Mather, 1957), and W is the percentage of time when the wind is above the threshold for sand transport. As the wind estimates are based on anemometers with meters 10 m above the terrain's surface, we consider 5 m/s as a threshold wind speed for sand transportation (Tchakerian, 1999). The percentage of time when the wind is above the threshold for sand transport (W) was obtained from the available historical average (1980–2016).

4. Results

4.1. Morphosedimentary description

Dunas of Geleia is an active aeolian sandy system developed on the left bank of the São Francisco River (Fig. 3A). The sedimentary deposits that compose the fluvial bank and source sediment in the Geleia dunes field are three sedimentary units (Fig. 3B); (U1) 2.5 m of fine yellow sand, with sets 20–40 cm thick, overlaid by ~1.5 m of fluvial sandy mud; (U2) ~10 m fine to very fine white sand, well-sorted, interpreted as aeolian deposit (dunes and sand-sheet); (U3) ~16 m of fine, unconsolidated, well-sorted yellow aeolian sand.

The Geleia source-bordering field is characterized by parabolic dunes, and a barchan-parabolic transitional pattern (Fig. 3D). Parabolic dunes, ~40–100 m long, ~30–95 m in wide, and ~12–15 m high, predominate in the NE sector of the studied area. Small shadow (secondary) dunes are superimposed on the deflation slope of the main parabolic dunes (Fig. 3H). Field observations suggest that the secondary dunes are conditioned by shrubs and small blowouts (Fig. 3H). The low-velocity zone downwind the vegetation, obstacle conditions the elongated deposition of sand (Hesp, 1981).

In the southwest corner of the studied area, a ~125 m long, ~95 m wide, and ~16 m high U-shaped parabolic dune formed (Fig. 3C). The vertical development of the particular-shaped parabolic dunes is linked to denser vegetation around the slip-face.

The central section of the aeolian field is characterized by stronger aeolian activity, with a transitional barchan-parabolic pattern, trending towards a dominantly parabolic pattern, of laterally connected dunes (Fig. 3D). The dunes are between ~130–170 m long, ~85–90 m wide, and 11–13 m high. They are lower than in the other areas of the dune field. The dominant dune types in the Geleia aeolian field are shown in Fig. 3F.

4.2. Migration rate of the Dunes of Geleia

Fig. 4a shows the positions of the progressive front lines of the Dunes of Geleia. The dunes migrated more in the central and northern sectors of the studied area. The predominant migration towards NW is indicated by the orientation of the crest of the more well-defined dunes. Further south, aeolian progression was restricted to a few meters over the investigated period because of the stabilization effect of the vegetation (trees and shrubs), which was preserved mainly in that sector.

In the central zone of the Dunes of Geleia, aeolian deposits advanced the furthest in this century (~210 m), with an average migration rate of ~12.3 m/y between 2002 and 2019. The migration rate was faster between December 2002 and June 2010, ~15.6 m/y. Between June 2010 and December 2019, the migration rate decreased by ~32%, to a still considerable ~9.5 m/y (Fig. 4a).

Field observation indicates that the faster advancement (2002−2010) occurred in an area almost entirely without vegetation cover (Fig. 4b). The presence of houses in this area shows that human intervention has reduced vegetation cover. On the other hand, the area of slower advancement (2010–2019) is characterized by a vegetation cover of trees and shrubs, although not as dense as the arboreal vegetation found in the southern portion.

The annual migration rates for the two decades indicate higher values during the first decade when the rainfall average of the last decade is ~25% lower than the average of the previous decade. However, the interval of highest monthly migration of the dunes (2.3 m/month) occurred between December 2012 and October 2013 (Fig. 5A), coincidently with the drought's peak of 2012–2013 in the NEB (Fig. 5B). In 2015–2017 the aeolian migration was considerably smaller than in 2012–2013 (Fig. 5A) and even further reduced by ~70% in the last two years (2017–2019).

4.3. Aeolian mobility estimates

Based on the precipitation and evapotranspiration potential data, and the average monthly wind speed data, we considered scenarios with one or two months (August and September) of wind blowing out above the threshold for sand transport (Fig. 6).

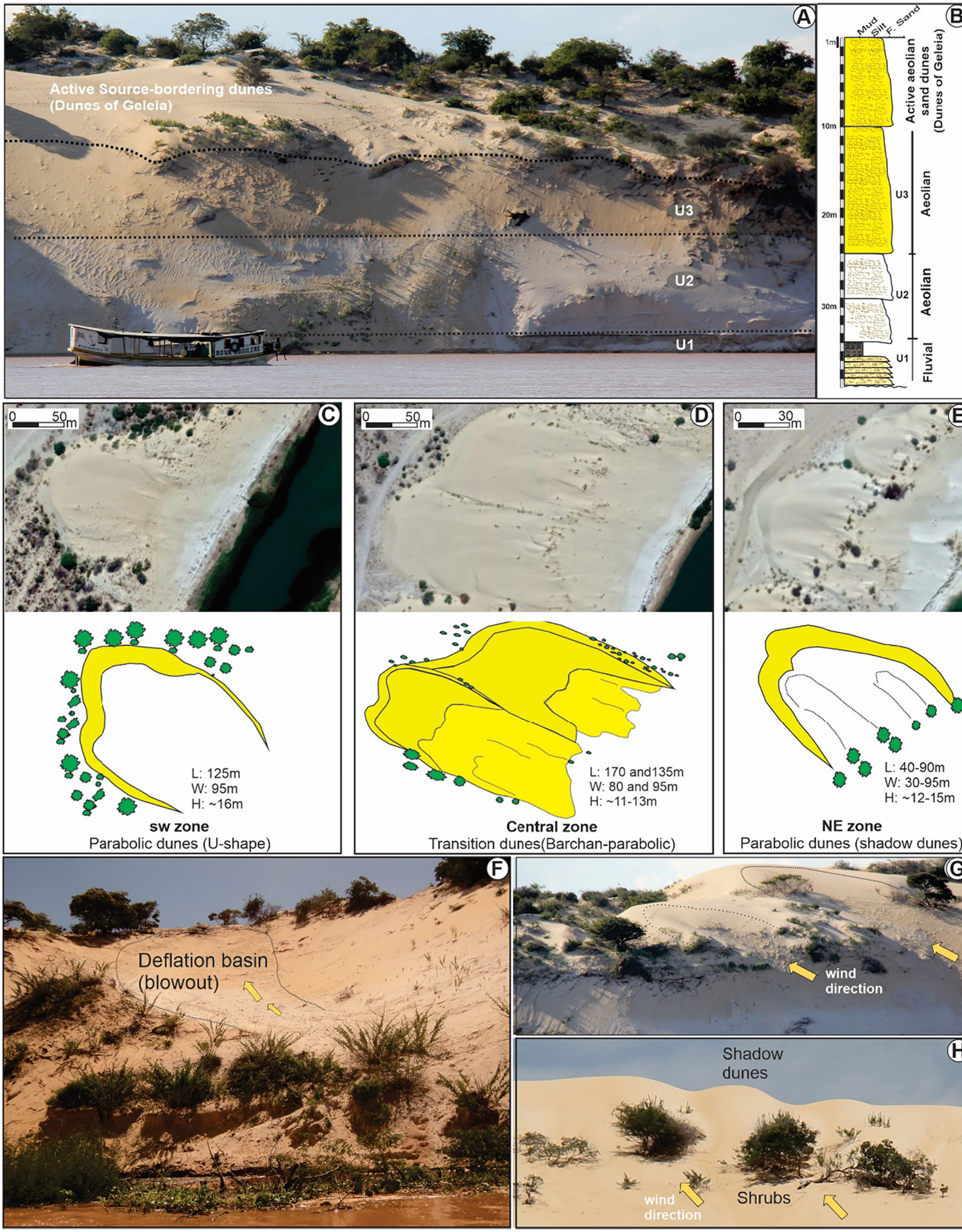

Fig. 3. Morphosedimentary characterization of the Geleia source-bordering dunes. (A, B) A sedimentary column of the Quaternary sediments cropping out on the right bank of the San Francisco River. (C-E) The main aeolian landforms. (F) A sketch of the dominant aeolian landforms and morphometric characteristics. (H: height, L: length, W: width). (G) Deflation zones. (E) Blowouts and small parabolic dunes. (I) Secondary dunes (shadow dunes) in the deflation basins of parabolic dunes, NE area of the Geleia field.

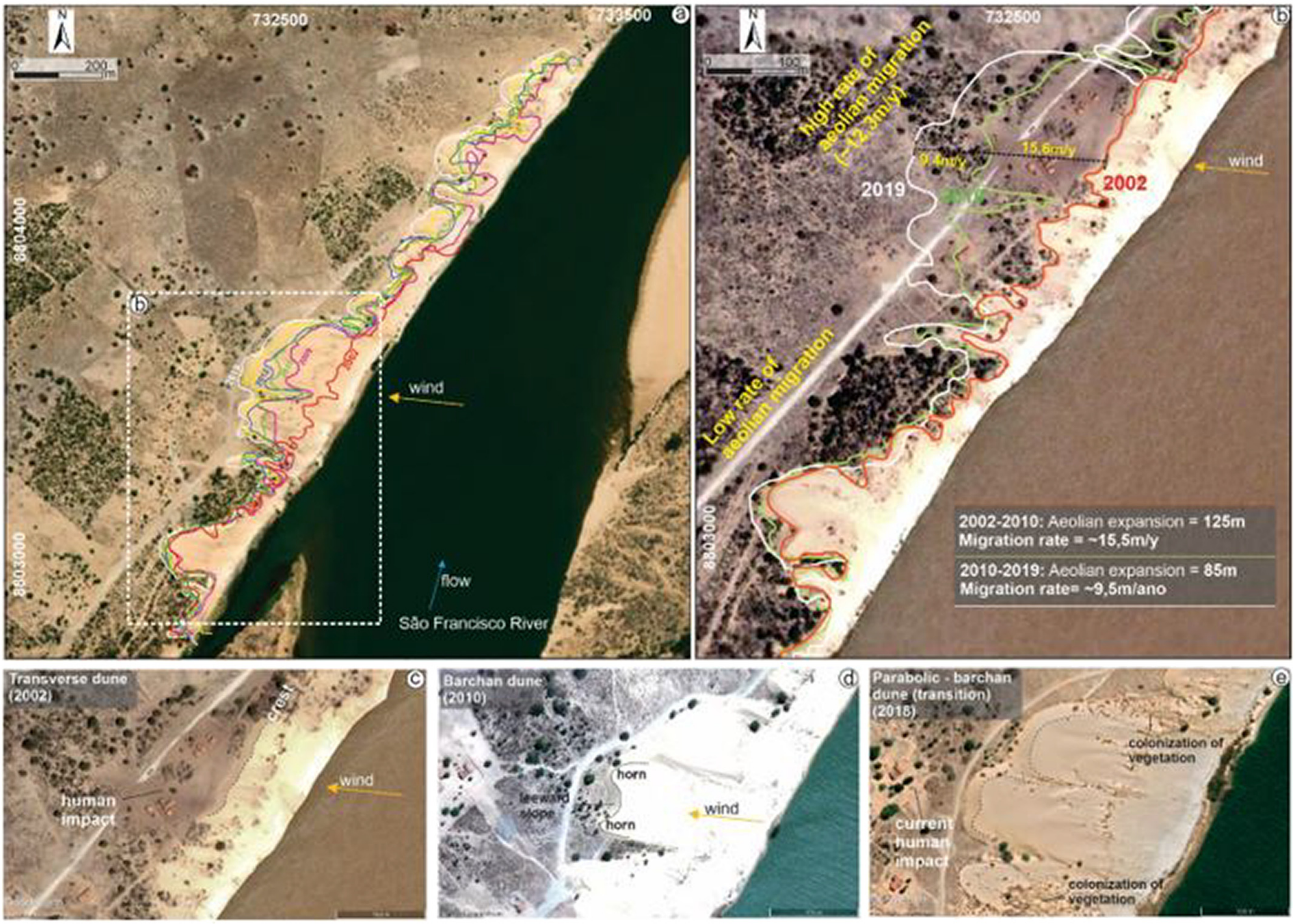

Fig. 4. (a) Lines of advance of the aeolian front in the last two decades (Google Earth Images). (b) The area of the greatest wind expansion between 2002 and 2019, highlighting the migration rate for each decade. (c) A transverse dune found in 2002. (d) A Google Earth image showing the characteristic features of a barchan dune in 2010. (e) A Google Earth image showing the advanced transition stage of the barchan to parabolic dune in 2018.

The two months scenario with an average wind speed above 5 m/s (W = 16.6% of the year) gives M values <50 in 2009 (M = 34.5), 2010 (M = 40.8) and 2011 (33.7). It means that, under current natural climatic conditions, the dunes would have been stable. However, for 2012, the index (M = 107.5) reveals that the area experienced a stronger seasonal aeolian capacity for erosion and transport. In the one month scenario (W = 8%), the threshold wind speed for sand transportation can also happen (Fig. 6) because the lowest rainfall (P = 288 mm) and the highest potential evapotranspiration (PE = 1871 mm) during the 21st century created favorable natural conditions for aeolian mobility.

Although Lancaster and Helm (2000) have argued the mobility index (Lancaster, 1988) results are more reliable on a decadal scale, our analyses show this index can be reasonably accurate even on an annual scale in regions with scarce meteorological data as the Dunes of Geleia. The calculated highest monthly migration rate (2.3 m/month) occurred between 2012 and 2013 (i.e., during extreme droughts).

5. A model of evolution and aeolian transformation of the Dunes of Geleia

The 2001–2004 period represents the first drought of the 21st century, and it triggered the first stage in the reactivation of aeolian processes and the development of the Dunes of Geleia sand field, which started with a significant localized sandy supply and the generation of transverse dunes (shown in the December 2002, Fig. 4c). In the first stage of developing the source-bordering Dunes of the Geleia sand field, transverse dunes formed From 2001 to 2004, rainfall was below average from March to May (Barbosa et al., 2019), the crucial months for the semiarid vegetation growing in NEB.

Based on the dune pattern transformation along the central strip, where the most remarkable aeolian migration occurred, the sand migrated in at least three stages (Fig. 7). In 2002, the sector with the most significant wind had the highest sand supply, and a transverse dune developed. Its crest over 130 m long was relatively perpendicular to the preferred wind direction (NW), and the elevation of the lee side ranged from ~10 to 15 m). The marginal erosion of the São Francisco River banks likely contributes to amplifying the erosion of sandy deposits and sourcing the proximal margin of the Dunes of Geleia.

The transverse dune pattern changed throughout the first decade, and a new well-established aeolian pattern formed in 2010. This second stage is marked by the aeolian migration of barchan dunes that destroyed a riverside village. The transition from transverse to barchan dunes was driven by wind mobility and favored by the degraded vegetation cover by deforestation and the intense droughts. The average rainfall between 2003 and 2010 was historically average, although with some more extreme arid years (2003 and 2007). The dune migrated and expanded by tens of meters in a relatively flat area on bare soil, favoring a somewhat faster migration. The bare and stable terrain characteristics favored the migration of barchan dunes without eroding and adding sediment from the substrate (Courech du Pont et al., 2014; Gao et al., 2015). Between the end of the first decade and the beginning

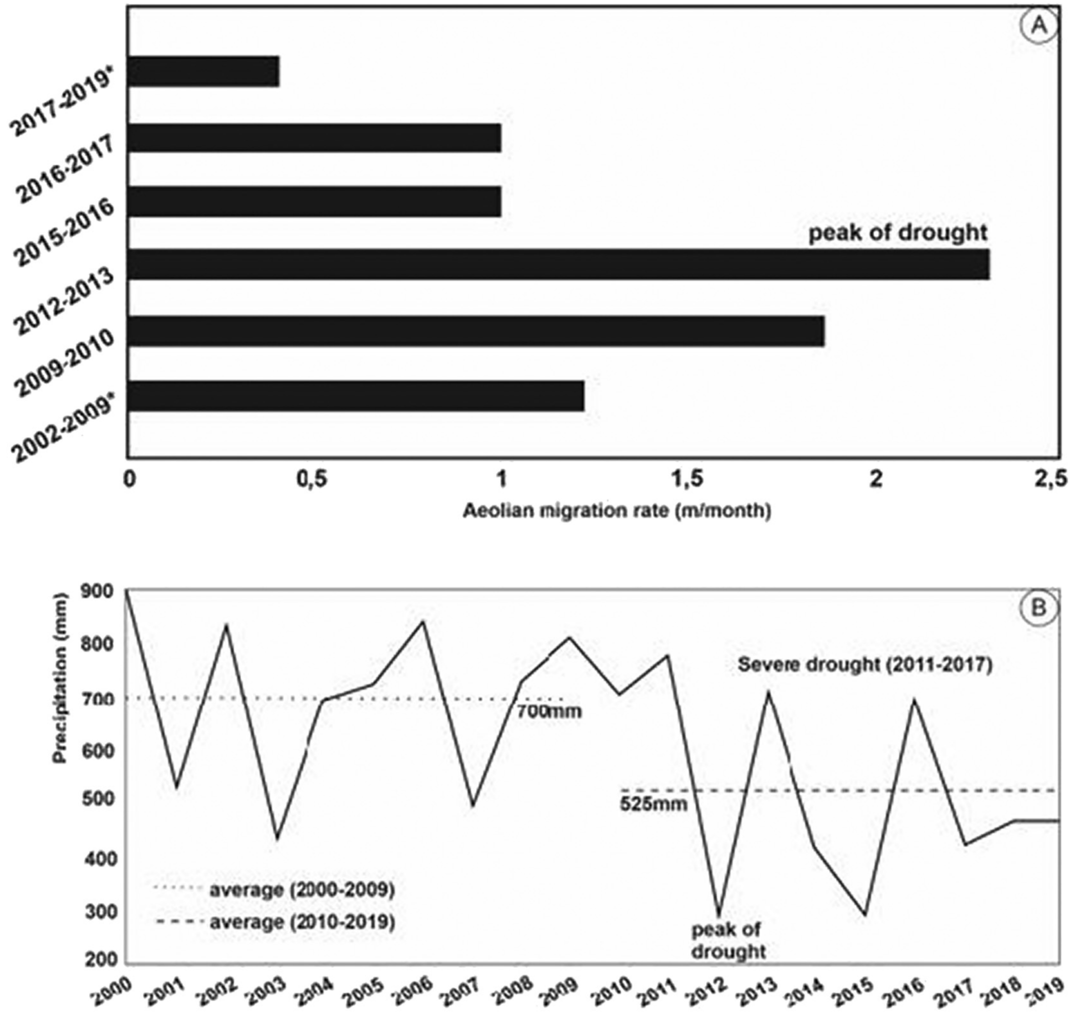

Fig. 5. (A) An estimated monthly aeolian migration rate for interannual intervals. (B) The total annual rainfall for the current century in the region (data provided by INMET for Barra weather station).

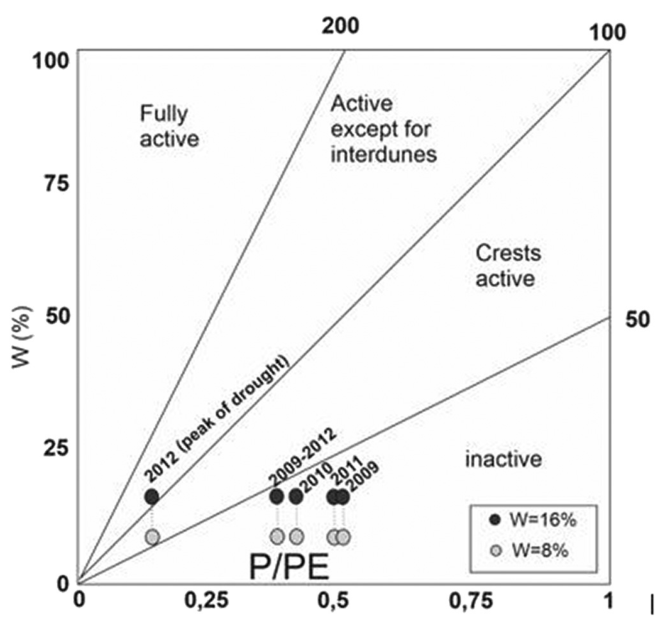

Fig. 6. A diagram showing the dune mobility index estimates (Lancaster, 1988) for the studied region.

of the second (2009–2014), two barchan dunes were well developed to respond to an inland decreasing sand supply, as the dunes were shifting farther from the source area. By 2012–2013, during the extreme drought pulse, the expansion of Dunas da Geleia occurred, and barchan dunes migrated 23 m in 10 months. This velocity rate exceeds the average migration (~15 m/y) estimated for barchan dunes in Lençóis Maranhenses (Gonçalves et al., 2003), the largest barchan dunefield in South America.

The third stage lasted from 2015 until the end of the decade. The dunes were still prograding inland but started to transition from a barchan to a parabolic type. The migration rate decreased considerably, and the transitional barchan-parabolic dune morphologies were established. After the end of the multiannual drought (2011–2017) in NEB (Cunha et al., 2019) until the end of 2019, sand transport was significantly reduced (~ 0.5 m/month), which favored colonization of the dunes' margins by vegetation. Thus, as previously identified in the literature, the decrease of sediment supply, the increasing roughness by vegetation, and the flat, stable terrain controlled the autogenic adjustment of the landforms transforming the shifting of barchan dunes to low mobility parabolic dunes (Hesp and Walker, 2013; Yan and Baas, 2015).

Since November 2018, the margin of the main aeolian migration zone presented a considerable increase in the colonization of vegetation in the windward erosion area expanded and the dunes have lower monthly migration rates, indicating that in recent years the winding

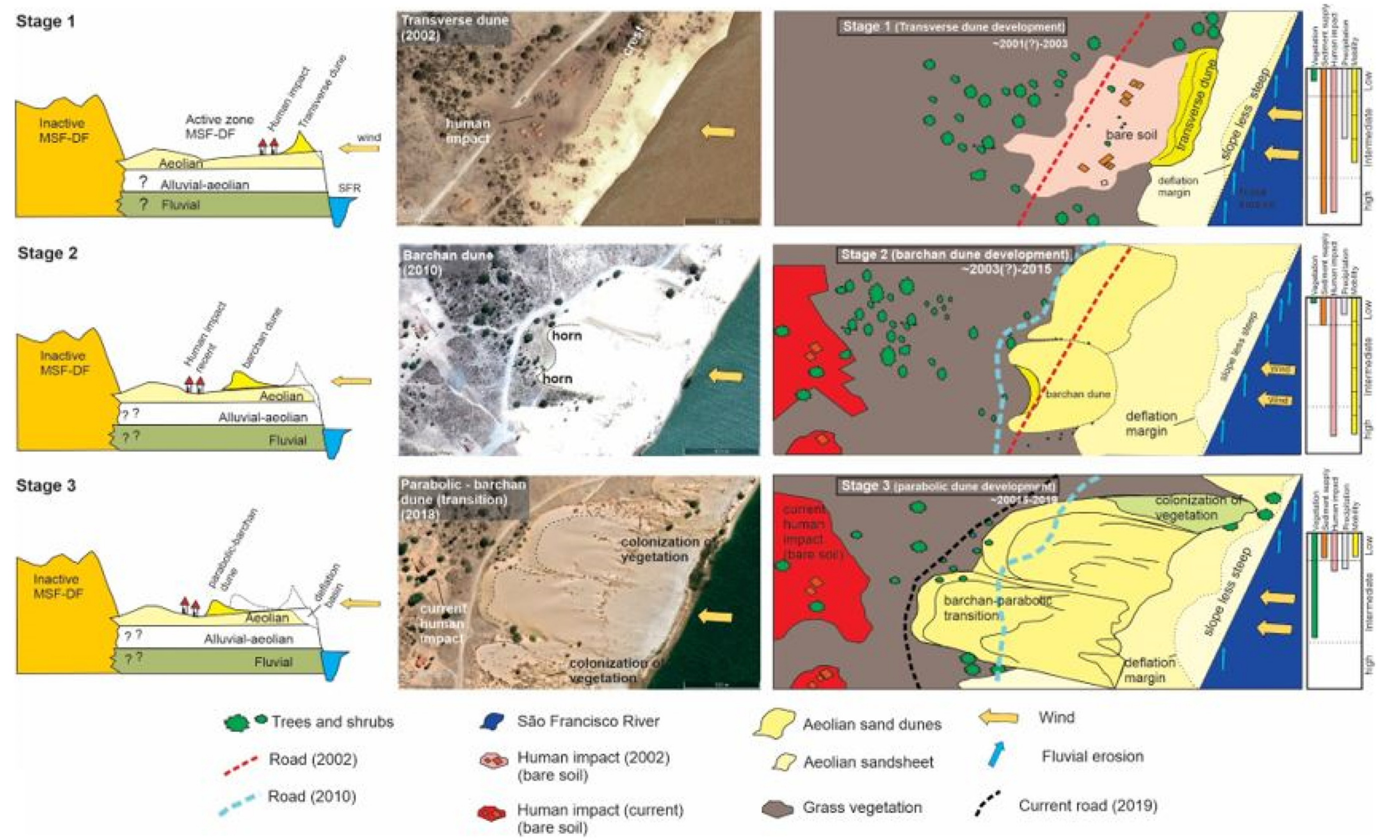

Fig. 7. A conceptual model of the development and evolution of the Dunes of Geleia in the 21st century.

mechanism must have changed in response to less severe climatic conditions than during the drought. Thus, the transition from a barchan to a parabolic dune was almost complete by December 2019.

Although droughts were the primary factor in aeolian remobilization, vegetation removal from an area stretching from the houses of the riverside community to the São Francisco River contributed to and/or intensified the morphodynamic processes responsible for the beginning of the aeolian remobilization and expansion. Vegetation removal seasonal water level variation intensified erosion of the sandy banks of the São Francisco River. Once the banks collapsed, sandy deposits formed a natural ramp that facilitated wind erosion and transverse transport of the abundant sediments inland, mainly in August and September. At the same time, sediment transport exposed aeolian deposits of the older and inactive MSF-DFs. Thus, the Dunes of Geleia can be described as a consequence of landscape imbalance created by the combination of climate changes (droughts) and human activities.

6. Discussion and final remarks

The vulnerability of the semiarid NE Brazil to Anthropocene impacts and a predicted increase of desertification/aridization of the region relate to two main factors: land use/land use cover changes and climate change. The most recent literature has concentrated on the analysis of climate change, and there is a general agreement that NE Brazil is the most vulnerable region of the country to droughts (Santos et al., 2014; Vieira et al., 2015; Tomasella et al., 2018; Vieira et al., 2021). However, studies on the geomorphological consequences of climate change on the landscape were not yet conducted. It is relevant to highlight that the Holocene record of the MSF-DF indicates that aeolian mobilizations widespread even during different periods of the Holocene (Barreto et al., 1999; Santos, 2020). Those widespread aeolian reactivations responded to climate change because humans in the early Holocene could not significantly impact the landscape and vegetation cover on this area (Araujo et al., 2005).

Regarding land use-land cover changes (LULCC), Ab' Saber (2006)'s pioneering work highlighted the need for geomorphology to understand the landscape response and the potential negative consequences of land use on ecosystem vulnerability aeolian remobilization of the MSF-DF. Our study demonstrates that geomorphology is an essential tool to assess the vulnerability of the NEB to climate change and LULCC. The aeolian mobility in a sector of the margin of the MSF-DF since the beginning of the current century is a pertinent example of how inland tropical landscapes, susceptible to aeolian morphogenesis, can quickly respond to short episodes of droughts and human pressure.

Studies of climate change attempted to categorize droughts in NEB based on estimates of meteorological, agricultural, hydrological, and socioeconomic indices. Here, we demonstrate how vulnerable to aeolian erosion and remobilization large areas of Brazil with inactive sand fields are without the need for significant climate change. We call the attention to scientists and decision-makers by pointing to the relevance of incorporating geomorphology to vulnerability assessment, climate change scenarios, and territorial planning in the semiarid Brazilian Northeast.

Declaration of competing interest

The authors (Landerlei Santos and Edgardo Latrubesse) declare no known conflicts of interest associated with this publication (Aeolian mobility in the Middle São Francisco Dune Field, northeast Brazil, as a response to Caatinga's droughts and land-use changes).

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