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Ecogeomorphic response of a coastal dune in southern Portugal regulated by extrinsic factors

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ABSTRACT

Coastal dunes are complex landforms whose morphology results from various interactions between biotic and abiotic factors. Here, we explore the longshore variability of the morphological features, plant community distribution and accumulation patterns of a dune segment (1.4 km-long) located at the downdrift end of a sandy peninsula in the Ria Formosa, Portugal. To understand the main drivers of the observed variability and the implications for dune morphological response, this information was combined with recent multidecadal shoreline evolution data. The integrated results document significant differences in dune morphology, sedimentation patterns and plant zonation, with two distinct dune configurations or states identified in close proximity. One (western sector) shows a narrower dune system, vegetation cover characterised by pioneer species with low densities, and squeezed plant zonation. Conversely, the other (eastern sector) presents a wider dune system with a new foredune, a more developed plant zonation and relatively high vegetation density. Both states could be partially explained by the recent shoreline trends and inlet shifts, with stable to retreating trends in the western sector and shoreline progradation in the eastern one. Plant zonation and accumulation patterns suggest that the dune along the retreating sector is in a cycle of inland migration, encouraged by the reduced accommodation space and the low retention capacity of the vegetation across the dune stoss. Alternatively, observations along the prograding sector suggest that the greater accommodation space and the stabilising feedback between vegetation and topography promoted the seaward progradation of the system and the development of an incipient foredune. Outcomes support the importance of biogeomorphic feedbacks for the dune configuration, but they also evidence that the role of vegetation within the feedback is primarily regulated by physical factors that ultimately promote or inhibit vegetation effects on dune topography.

1. Introduction

Coastal dunes are highly complex three-dimensional features that result from the combined effect and potential interactions of a number of key factors, among which the following are particularly relevant: frequency and magnitude of transporting winds, incident wind direction, beach fetch and sediment supply effects, dune scarping, vegetation type and density, and moisture content (Bauer and Davidson-Arnott, 2003; e.g. Buckley, 1987; Davidson-Arnott and Law, 1996; Hesp, 1989; Hesp et al., 2005; Namikas and Sherman, 1995). Thus, different combinations of these factors and the complex balance of their effects on the beach-dune system may occur alongshore, promoting and reinforcing longshore variability (e.g. Brantley et al., 2014).

Different hypotheses have been elaborated and tested to explain observed longshore variability in dune morphology, which is key in determining the level of storm impact in a beach-dune system (Itzkin et al., 2020; Sallenger, 2000). Houser et al. (2008) concluded that the main driver of the observed longshore variation in dune height and, thus, the response to storm impact along the studied barrier islands was the occurrence of inherited underwater morphologies, capable of modifying coastline wave exposure and surge levels. The authors found that the control on wave exposure determines dune height by modifying beach morphodynamics; higher dunes were backing beaches characterized by morphotypes halfway between intermediate and dissipative, where the volume of sediment in the backshore and in the foreshore bars were also at a maximum (Houser and Mathew, 2011). Alternatively, Durán Vinent et al. (2021) concluded that topographical variability results from a stochastic balance between erosional and accretional

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processes in barriers. According to the authors, the latter mainly depend on the average intensity of high-water events with respect to the maximum dune height and the frequency of high-water events relative to dune formation time. Regarding dune erosion, de Winter et al. (2015) found it primarily controlled by the morphology of the dune itself (dune steepness) while Keijsers et al. (2014) and Itzkin et al.(2020) pointed to the beach width as the main factor regulating dune erosion. Conversely, the capacity of these features to recover from the impact of storms depends on processes working at greater temporal scales such us the return of sediment to the beach following storms (e.g. Aagaard et al., 2004; Houser et al., 2015).

Brodie et al. (2019) found significant alongshore variability during events with aeolian sediment transport towards the dune, not only related to the dune topography, but also to the preferential sedimentation zone within the cross-shore dune profile. The authors suggested that the latter is modulated by the volume of sediment within the nearshore beach profile, controlling runup levels and sediment availability inland. In this regard, they concluded that aeolian sedimentation predominantly occurred inland of the crest, at areas showing erosive tendencies and lacking vegetation, while accumulation at prograding areas occurred within the densely vegetated foredune stoss. Ollerhead et al. (2013) suggested that a major factor influencing alongshore dune accretion variability was the actual morphology of the dune, namely the stoss slope, with dune ramps promoting the transference of sand from the beach to the dune crest and lee, and scarps preventing it. Alternatively, and depending on prevailing conditions, they found that dune accretion may occur as ephemeral embryo dunes seaward of the base of the stoss slope, preventing sand transference inland.

In summary, these works suggest that local conditions (i.e., nearshore bathymetry, beach width, foredune stoss slope) govern the long-term evolution and longshore variability of foredunes, determining their shape by controlling the supply of sediment to the foredunes and the magnitude of storm impact. In addition, if dunes display a range of shapes alongshore, the plant community holding those dunes in place is expected to change accordingly, introducing a higher level of complexity, linked to intrinsic biogeomorphic feedbacks. Stallins (2005) linked these feedbacks to two main barrier island resilient states. According to these observations, low dunes were typically dominated by burial-tolerant plant species, developing disturbance-reinforcing ecogeomorphic feedbacks, while high dunes were dominated by dune-building plant species, developing disturbance-resistant feedbacks. Thus, feedbacks result from distinct coupling of extrinsic overwash disturbance processes with intrinsic plant-mediated topographic modification. In this line, plants are considered as active agents in their response to changes in the environment (Odling-Smee et al., 2003), capable of adapting it to fit their growth strategies (Stallins, 2005). Plant distribution or community composition and zonation, widely recognised to be controlled by a number of abiotic factors (e.g. Hesp, 1991; Maun, 2009; Rozema et al., 1985), are often used as indicators of the dynamics of the coastal dune ecosystems. Yet, despite the importance given by the above and subsequent works to biogeomorphic feedbacks (Brantley et al., 2014; Durán and Moore, 2015, 2013; Stallins and Parker, 2003; Yousefi Lalimi et al., 2017; Zarnetske et al., 2015; Zinnert et al., 2017), they also recognise the challenging task of determining to which extent patterns attributed to domain dynamics can be explained by underlying variation in physical variables versus self-organization.

The main goal of this study is to investigate the alongshore variability in dune morphology, plant type distribution and short-term accumulation patterns of a coastal dune system and to understand the main drivers of the observed ecogeomorphic variability. For that, the present work aims to identify the possible links between the variation in the long-term (i.e. 65 years) evolution of the shoreline along the study site and the observed dune configurations, in terms of morphology, plant distribution and density, and sedimentation patterns. Such links can, in turn, inform about the possible strategies adopted by the dune system.

The area selected for this study is located in the Ria Formosa barrier island system, southern Portugal. Recent shoreline evolution in the area in terms of shoreline evolution appears dominated by the dynamics of the adjacent tidal inlet, however, the impacts on shoreline changes over the adjacent dune morphology and thus, dune morphological and ecological response have never been explored, much less, the associated links between temporal scales and ecogeomorphology. In addition, the case study arises as an example of the very high complexity that some regions may present, highlighting the importance of understanding the related controls on the longshore variability, especially if future management actions are going to be considered.

2. Study area

The study area is located at the eastern end of the Ancão Peninsula, within the Ria Formosa barrier island system (Fig. 1). It comprises a 1.4 km-long coastal barrier stretch, delimited to the west by the Praia de Faro settlement and to the east by a small migrating inlet (i.e., Ancão Inlet). The latter region has shown shoreline progradation over the last decades (Ferreira et al., 2016; Kombiadou et al., 2019), which was enhanced after the inlet relocation of 1997, with subsequent accumulation of sand within the updrift area (Ferreira, 2011).

The study area has undergone a series of changes in human activities and occupation over the recent past. Located within the Ria Formosa Natural Park, created in 1987, the area is regulated by conservation and protection measures that prevented its further occupation and urbanization, and even forced the partial removal of small houses occupied by the fishermen community, installed in the region after the 1950s. The oldest available aerial photographs, corresponding to the year 1947, show a rather sparcely vegetated dune ridge with rudimentary buildings in the lee side of the western sector, likely used to support fishing activities. These buildings were removed and replaced by small houses, somewhere between 1972 and 1976. Between 1976 and 1989 some of the houses were removed for safety and nature restoration purposes. Dune restoration further included sand fences to fix the dune (visible in the photographs of 1989). All installed fences were totally buried before 1996 and new stabilization measures were implemented between 2001 and 2002, fencing the frontal dune. These fences were again buried before 2014. The last measures implemented in the area include the additional removal of second residence houses during 2015, most of them within the lee of the dune ridge.

The shoreline in the area is shaped by waves approaching from W-SW (71%) and E-SE (23%) (Costa et al., 2001), by a mesotidal regime with a mean tide range of 2.2 m that reaches 3.5 m during spring tides, and by dominant winds approaching from W-SW (Fig. 1). Net longshore drift is considered the main sand supplier of this coastal system and is directed eastwards (Andrade, 1990). Estimates of longshore sediment supply vary from author to author, with the most recent, mean values on the order of 110,000 m^3/year (Santos et al., 2014). The supply of freshwater to the system is basically through precipitation (annual average 523 mm), which concentrates from October to April (Fig. 2). It is worth stating that, based on multidecadal data (Fig. 2), precipitation has been dropping below monthly averages over the last years.

The beach was classified as Low Tide Terrace Beach (Martins et al., 1997) and is often reflective during high tide and intermediate during low tide (Vousdoukas et al., 2012). The dune shows significant alongshore morphological variability, as well as changes in the patterns of sediment accumulation within the dune, resulting from a combination of local factors (Costas et al., 2020). Sediments within the dune-beach system of Ancão are classified as well to very well sorted medium to coarse quartz sands, with mean grain sizes varying from 0.35 mm to 0.80 mm at the beach (Achab et al., 2014; Costas et al., 2018) and around 0.50 mm at the dune (Costas et al., 2020).

The vegetation of the study area is composed by herbaceous and shrubby dune species, developing different habitats across the dune profile. Three habitat types included in the Annex I of the European Habitat Directive 92/43/EEC (2013) are found in the study site (Martins

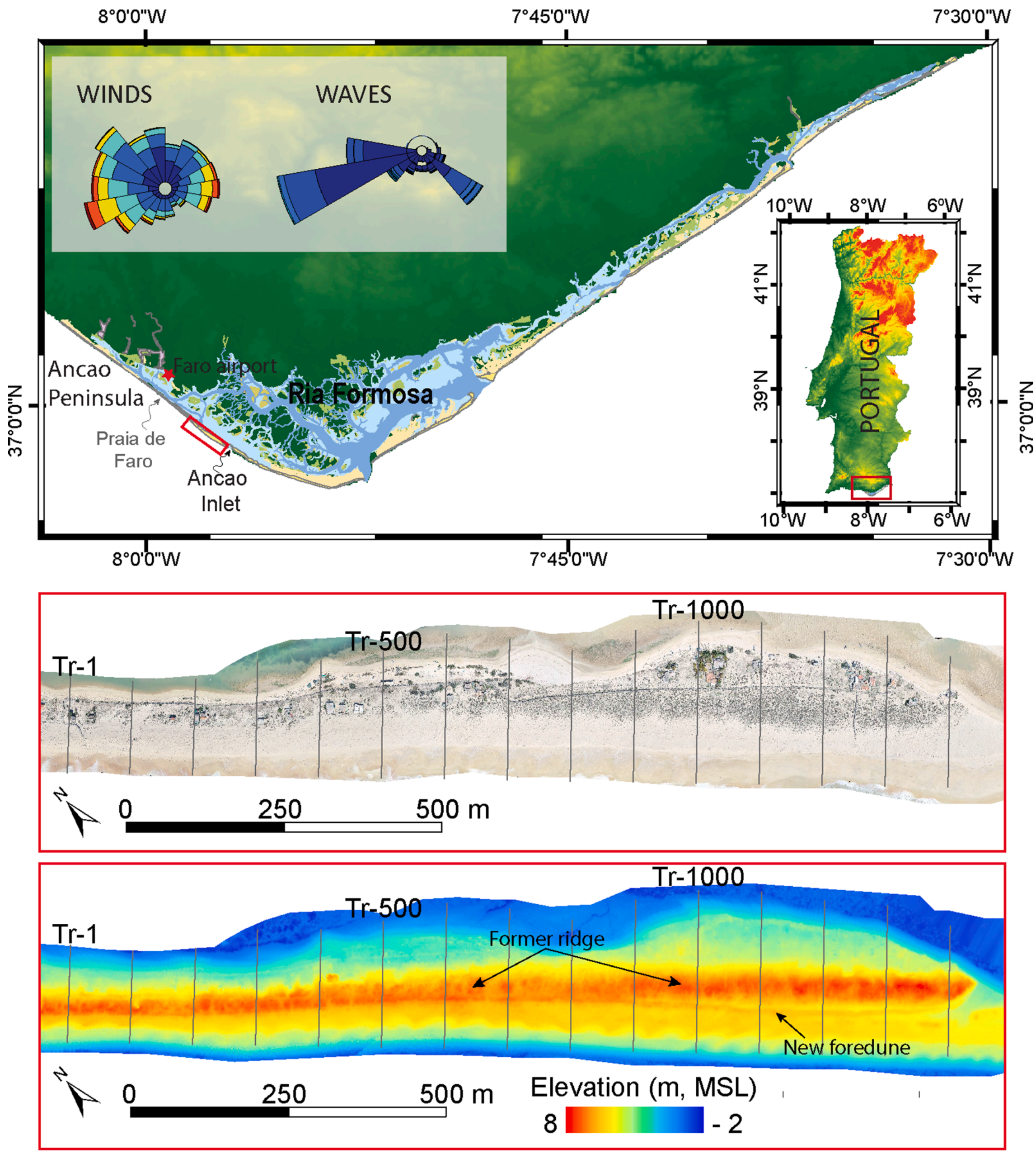


Fig. 1. Location of the study area (upper panel; red rectangle), orthophoto (middle panel) and altimetry (lower panel), showing the position of the transects each 100 m. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

et al., 2013): (1) Embryo dune, characterized by *Eryngium maritimum, Otanthus maritimus and Elymus farctus* (habitat type 2010), (2) foredune, characterized by the dominance of *Ammophila arenaria, Elymus farctus* and *Otanthus maritimus* (habitat type 2120), and (3) Fixed coastal dunes with herbaceous vegetation dominated by *Artemisia crithmifolia* and *Lotus creticus* (habitat type 2130).

3. Data and methods

3.1. Morphological data and methods

To identify the main factors controlling the recent ecogeomorphic evolution of the dunes in the area, we combined long-term shoreline trends (past 65 years) with high-resolution data on short-term morphological changes and data on the distribution of dune vegetation and morphological characterisation. Long-term shoreline trends along the coastal segment were analysed using the shorelines mapped from vertical aerial photographs by Kombiadou et al. (2019), which cover the period between 1952 and 2014 (all the details of the used aerial photographas are summarised in Table 3 from Kombiadou et al. (2019)). The latter period was extended within the present study up to 2017, using available high-resolution images from September 2017. Coastline uncertainty was estimated by Kombiadou et al. (2019) as the sum of squares of all measurement errors, following Morton et al. (2004), accounting for errors related to rectification and digitisation and varying between 0.6 and 2.1 m (Kombiadou et al., 2019). The long-term trend of the shoreline was evaluated using the seaward vegetation limit and the debris lines as indicators. The debris line, despite being considered as a less reliable indicator of long-term trends because of its high short-term variability in the short-term (Boak and Turner, 2005), has been also included in order to illustrate the direct link between the changes at the beach and the adjacent dune. Weighted Least Squares

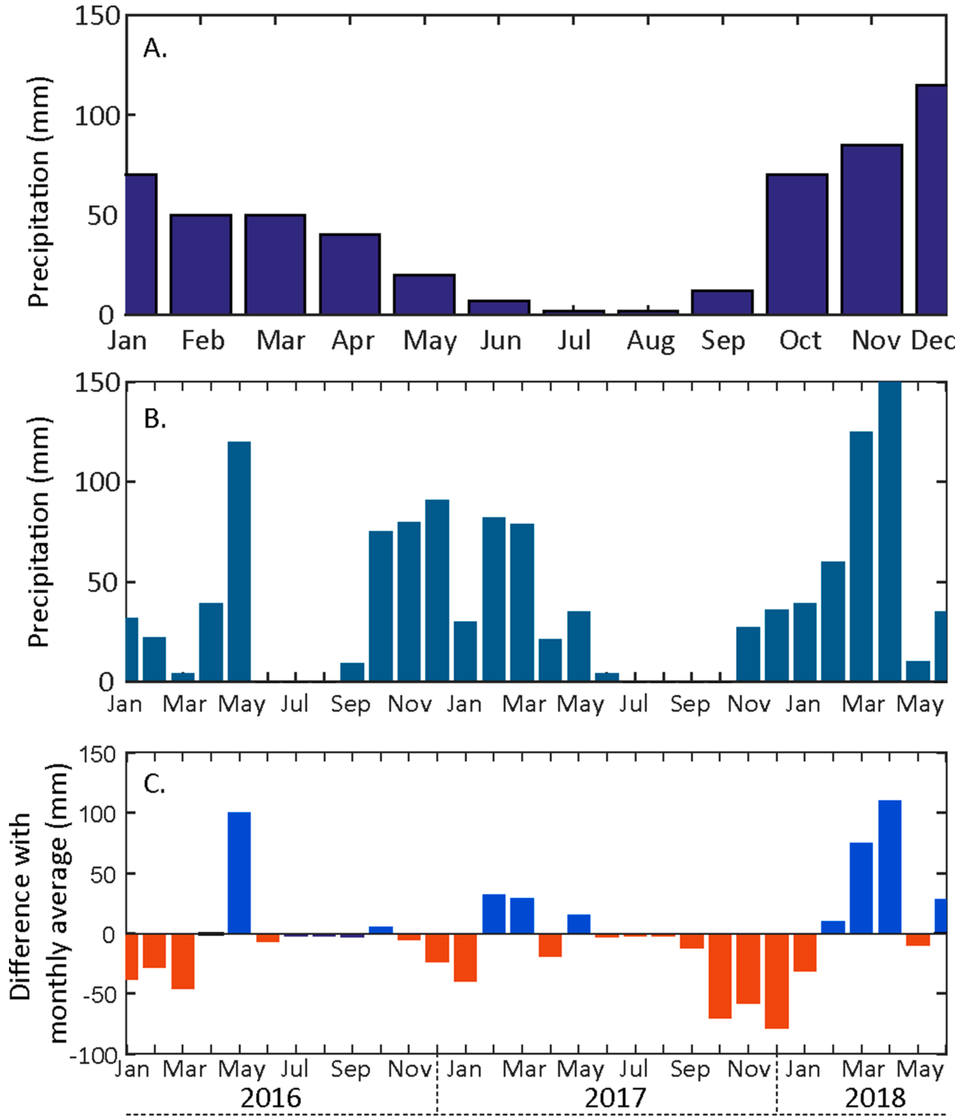


Fig. 2. Characterization of the precipitation showing: A. monthly averages (using the time period between 1971 and 2000), B. total precipitation per month since 2016 to June 2018, and C. the difference with the monthly average or normal.

Regression was performed on the entire dataset using the Digital Shoreline Analysis Tool (Thieler et al., 2009) that calculates the shoreline changes along transects (spaced 10 m apart), cast perpendicular to a reference baseline. Weighted Linear Regression (WLR) rates were preferred as rate-of-change statistics, as they use coastline uncertainty values to weight towards more accurate coastline positions (Terrano et al., 2016). The position of the migrating Ancão inlet (downdrift edge of Ancão barrier) was also assessed with reference to the east-most transect of the region. These data were used to evaluate shoreline trends and trajectories over distinct temporal scales and to determine the extent of the influence of these trends on present-day morphology.

Present-day dune characterization in terms of morphology, morphological changes and vegetation coverage was based on orthophoto mosaics and digital elevation models (DEMs) obtained for April 2017 (0.02 and 0.03 m of horizontal and vertical accuracy, respectevely) and March 2018 (0.02 and 0.03 m of horizontal and vertical accuracy, respectevely) using an unmanned aerial vehicle. The DEMs were used to estimate the vertical changes between surveys, subtracting the elevations of the older from the newer DEM, on a cell-by-cell basis to obtain the DEM of Difference (DoD). The accumulated error of the obtained DoD was 0.04 m (see Costas et al. (2020) for more details).

The orthophoto mosaic of 2017 was used to map the seaward vegetation limit and the percentage of dune vegetation coverage, while the position of the maximum runup or beach scarp was mapped in both mosaics (i.e., 2017 and 2018) due to its greater short-term variability. Also, the weak condition of the vegetation by the end of the winter 2017–2018 and the significant burial within the frontal dune prevented the use of the 2018 mosaic for vegetation coverage estimates. The current morphology of the dune system was additionally characterized by identifying the number of foredunes alongshore and their elevation, the position and elevation of the ridge crest, the elevation of the seaward vegetation limit, and the dune stoss slope, from the 2017 DEM. The value of each parameter was retrieved at 1 m intervals alongshore, splitting the dune into 1 m long bins (Fig. 3). Additionally, the beach-dune profile was divided in different cross-shore compartments to facilitate the comparison of parameters across and along the system (Fig. 3). From the beach to the lee of the dune, the first compartment was the upper beach or backshore, comprising the area defined by the maximum runup or beach scarp and the toe of the dune or dune vegetation seaward limit. The second compartment, defined as the dune ridge stoss, comprised the area between the seaward limit of the dune vegetation and the ridge crest. The dune stoss compartment also integrated the incipient or new foredune, in transects where it was present (Fig. 3C). The third compartment represented the ridge crest, defined as

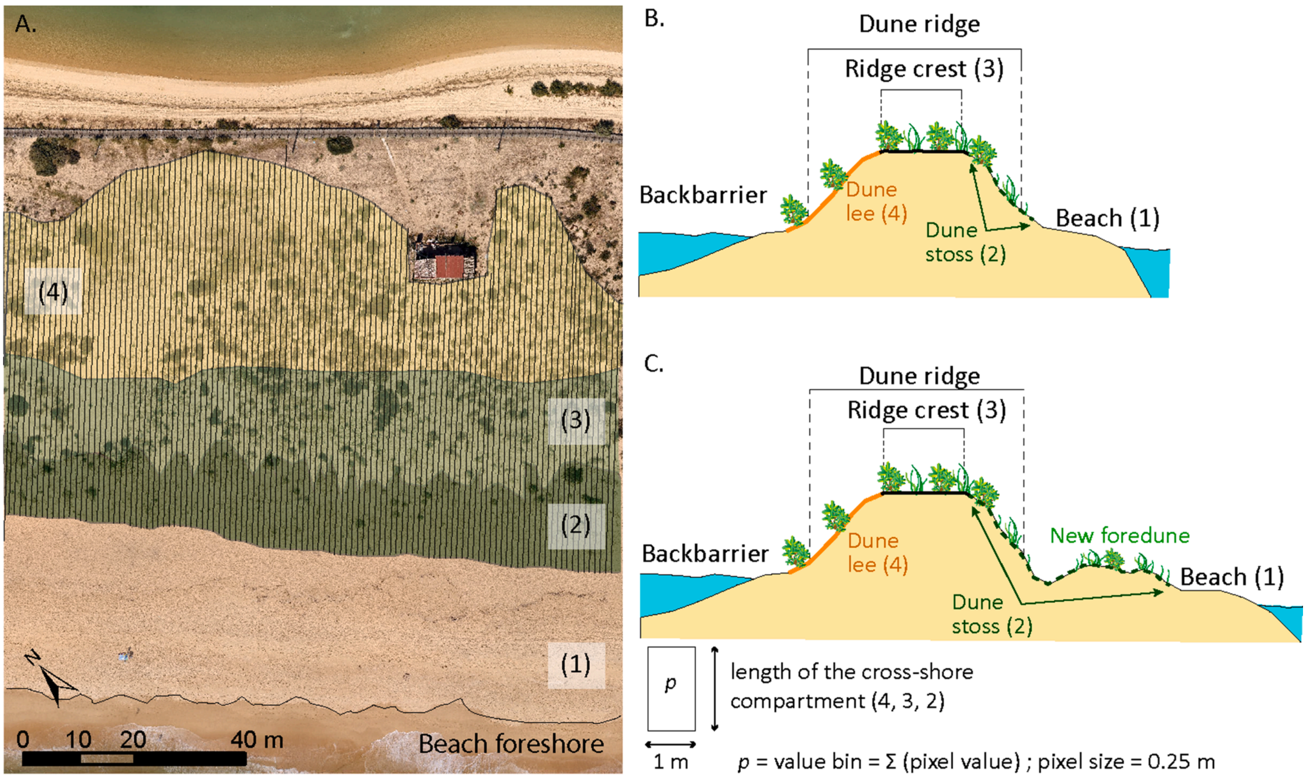


Fig. 3. A. plan view of the identified cross-shore compartments (1 to 4) that define the morphological zonation of the dune ridge and bins used to characterize the dune along and across-shore, splitting the compartments into 1 m segments. B. and C. represent the typical profiles that can be found along the study area, showing the morphological limits between the cross-shore compartments.

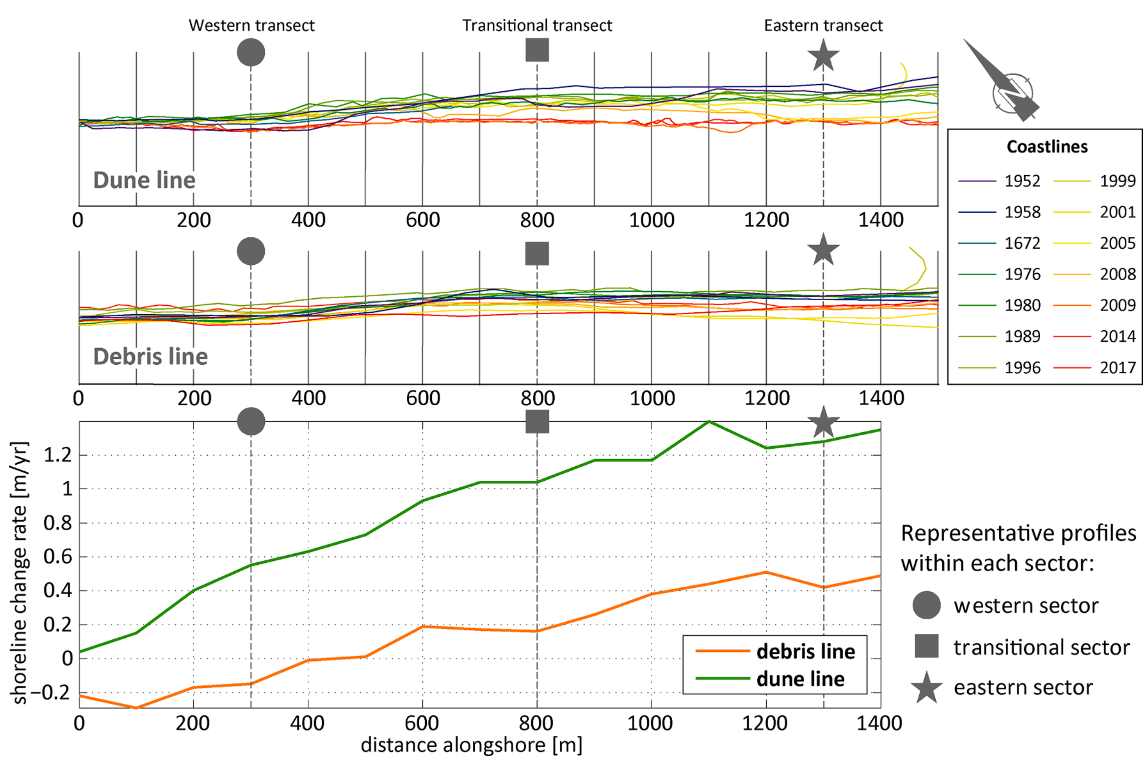


Fig. 4. Upper panel shows the mapped shorelines using both the dune vegetation line and the debris line over the period of analysis. The lower panel shows the resultant trends alongshore from 1952 to 2017 for both indicators. The position of the transects selected to characterise both the recent shoreline trends and the vegetation distribution at the identified sectors (i.e. western, transitional and eastern) are indicated with vertical lines and symbols.

the plateau zone that characterizes the top of the ridge. The fourth compartment represents the lee side of the ridge, extending inland from the landward limit of the crest to the maximum extent or penetration of aeolian transported sand observed (April 2017 to March 2018). Alternatively, if new sediment was not transferred inland from the ridge crest, the landward limit was defined by the change in the slope of the lee side of the dune ridge (Fig. 3).

3.2. Ecological data and methods

The vegetation coverage was assessed classifying the pixels from the mosaic within the dune into two categories: vegetation and sand. The classification of the image (three bands: red, green and blue) was carried out applying the unsupervised image classification from the ArcGIS Spatial Analyst extension. The classification process is based on the identification of clusters determined after grouping pixels with similar statistical properties. The two clusters obtained were then assigned a category, i.e., cluster 1 represented the vegetation while cluster 2 the bare sand. Vegetation densities over the dune stoss and ridge crest were calculated separately from the classified mosaic (Fig. 3).

The state of the present-day dune was additionally characterized by mapping the spatial distribution of plant communities along and across the dune. For that, a survey was carried out during the spring season (May) of 2021. Since the ecological part of the study is mainly comparative, even if changes have been noted between the geo and eco surveys, the difference is expected to be smoothed, with no significant impact on the analysis. In order to identify the existing species, three pre-selected transects, representative of the longshore variability found in the study area (explained in section 4.1, Fig. 4), were surveyed. The plant communities within each cross-shore transect, running from the upper beach to the lee of the dune, were characterized by applying the standard line transect sampling. For that, 25 m-long lines parallel to the shoreline (cross-shore zonation lines, CZLs) and perpendicular to the pre-selected transects were surveyed by recording the presence (absence) of plants at intervals of 50 cm along the lines (i.e., 50 reading points within each CZL). The count at each point included the plants within a radius of 2.5 cm. The position of the lines within each transect was decided in the field, in order to characterize and capture the plant zonation across the dune. The number of lines across each transect was variable, depending on the local width of the dune. The identified plants were classified following the terminology proposed by García-Mora et al. (1999) into the three functional types: Type 1, representing mainly winter annuals of moderate size with soft leaves without indication of adaptations to the dune environment, Type 2, mostly represented by perennials with a below-ground spreading root network and leaves and adapted to coastal environmental stress, and Type 3, including perennial or summer annuals plants mostly capable of being dispersed by seawater and withstand sand burial.

3.3. Statistical methods

Species composition and abundance data of the obtained CZLs in each transect were grouped into incipient, stoss slope, crest and lee slope, in order to perform detrended correspondence analysis (DCA) using the PAST4 software. DCA is an ordination technique used to find a configuration of samples in the ordination space (Gauch, 1982), so that distances between samples within this space correspond to dissimilarities in their species composition. Rare species were not downweighted.

Finally, data on long-term shoreline trends, morphological parameters, vegetation coverage and short-term topographical changes were integrated in a multivariate statistical analysis in order to identify links between the different evaluated parameters and their impact in the alongshore observed variability. For that, Principal Component Analysis (PCA) was performed on the correlation matrix, to describe the eco-geomorphologic gradients, allowing also to reduce the dimensionality of variables. The PCA analysis was performed using PAST4 software. Only principal components with eigenvalues greater than one were considered significant (e.g. Cattell, 1978). Varimax rotation was performed to orthogonally transform the configuration of the resultant ordination diagram (Webster and Oliver, 1990). Kaiser-Meyer-Olkin (KMO) sampling adequacy test was applied to assess the suitability of the data for analysis (Hair et al., 1995).

4. Results

4.1. Long-term evolution

The position of the shoreline over the past 65 years, marked by both the debris and the vegetation limit lines (Fig. 4), suggests a relatively stable area with a major position shift after 1999, when both lines advanced seawards, to stabilise again shortly after. This shift was not homogenous alongshore (Fig. 4, Fig. 5A, B), defining different patterns in shoreline position change, that were used as the grounds for dividing the study area into three sectors. One transect within each sector was selected as representative (see Fig. 4 for transect location), both for the geomorphological evolution and for vegetation species mapping (see section 3.1, 3.2 and 4.4).

The first sector describes the response observed within the initial 450 m (western sector) and is dominated by relative shoreline stability, a low, though positive, trend (WLR rates) in the vegetation line and a low negative trend for the debris line (Fig. 4). This sector shows a significant retreat of the debris line by the end of the 1980 s and subsequent recovery and even progradation until 2001, with the greatest advance observed between 1999 and 2001 (Fig. 5). The dune vegetation line retreated slightly until 1976 and remained stable afterwards, until 1996, when it started to advance seawards, regaining its original position (i.e. 1952) by 2008.

The second sector (transitional sector) extends between 450 and 900 m and represents the transition between the western and the eastern sector. Shorelines marked by both vegetation and debris indicators in this sector show positive trends with increasing magnitudes eastwards (Fig. 4). Similar to the western one, the sector is characterized by retreat in the debris line until 1989, subsequent progradation until 2001 and shift to retreat once again afterwards (Fig. 5A). The vegetation line remained relatively stable until 1989 when it started to advance, accelerating between 2005 and 2008, before stabilising after 2008 (Fig. 5B).

The third sector (eastern sector) displays the highest shoreline progradation trends (Fig. 4) and the greatest short-term shifts in shoreline position (Fig. 5). The debris line mapped along this sector is relatively stable until 1999 when it advanced , showing a jump of around 43 m between 1999 and 2001 (Fig. 5A). After 2005 the line retreated, with higher rates between 2005 and 2008. The vegetation line shows a relatively stable position until 1996 when it starts to rapidly prograde until 2001 (Fig. 5), stabilising 45 m seawards from its original position in 1952 (Fig. 5B).

The above suggest that the main shoreline changes in the study area happened after 1999, when the inlet started its slow migration eastwards after its relocation in 1997 (Fig. 5C). This new position of the inlet, closer to the study area, is directly linked to the advance of the beach (debris line) and subsequent advance of the vegetation line, through the colonisation of the recently created beach by vegetation (we can note a lag of two years for the dune advance, compared to debris, based on the available dataset). This closer position of the inlet appears to have promoted the retention of sediment within the adjacent updrift shoreline while its migration eastwards after 2001 would explain the gradual retreat of the debris line, particularly along the more distant western sector (Fig. 5A). Therefore, the proximity of the inlet has likely contributed to the growth of the dune along the eastern and transitional sectors, with minimal influence along the western one.

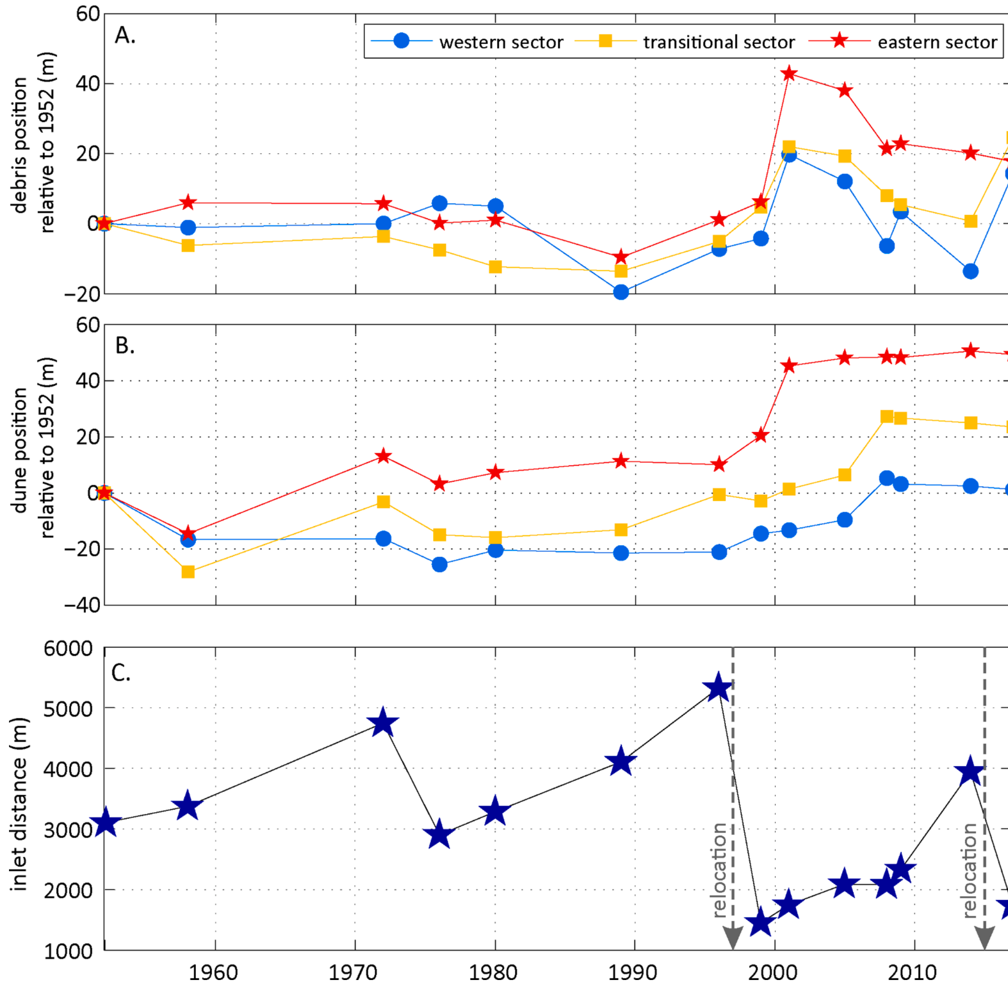


Fig. 5. Evolution of the position of the shoreline mapped using the debris (A) and vegetation line (B) over time for the selected transects (see Fig. 4), representing the western, transitional and eastern sectors and position of the inlet relative to the first western transect over time (C).

4.2. Geomorphological characterization

The study area is characterised by the occurrence of a continuous vegetated dune ridge (Fig. 1, Fig. 6A). The ridge bifurcates at the beginning of the eastern sector, where a new incipient (5.5 m above mean sea-level; MSL; Fig. 6B) foredune was formed after 2005 (see section 4.1), seawards of the former ridge. The second foredune occupies the space between the present-day straight shoreline and the former ridge (Fig. 1). The orientation of the dune ridge, and thus its distance relative to the shoreline, shifts inland towards the east, showing a gradual inflexion (transitional sector, Fig. 6A). This inflexion and the inland shift of the ridge alongshore were not reproduced by the seaward vegetation limit, which showed a rather straight plan shape, without longshore variability (Fig. 6A). The elevation of the former ridge crest and the mapped seaward limit of the dune vegetation are relatively constant alongshore (around 7 and 5 m above MSL, respectively) (Fig. 6B). The crest of the former ridge in the transitional and western sectors coincides with the crest of the active foredune, which moves seaward to the east because of the presence of the new incipient foredune (Fig. 6B).

The backshore width (dry beach in 2017) is also rather constant alongshore and remained stable until the impact of storms during the 2017–18 winter season and, in particular, by the erosion caused by the Emma storm (end of February 2018). The latter induced a greater inland penetration of the runup and the retreat of the shoreline (Fig. 6C), reaching the vegetation line along most of the area and the formation of a beach scarp (2 m high, see Fig. 7) that reached the toe of the eastern sector foredune and even slightly eroded it (see negative values of dry beach in 2018, Fig. 6C).

The slope of the dune stoss decreases eastwards as the distance between the former ridge crest and the shoreline increases (Fig. 6D). The greatest slopes were found within the western sector. The contact between the beach and the adjacent dune was characterized by a ramp, shaped by the combined effect of waves and winds.

4.3. Short-term topographical changes

The vertical changes along and across the study area (DoD) between 2017 and 2018 (Fig. 7) show that sand mostly accumulated in the western sector, namely within the interior part of the dune ridge, which can also be seen by the general inundation of aeolian sand across the dune in the orthophoto-mosaic (Fig. 7A). The accumulation of sand was lower towards the east, where it was concentrated in the lower parts of the incipient foredune, namely along its inland limit, which coincides with the toe of the former ridge (Fig. 7B). The inner part of the ridge along the eastern sector seems to register some erosion, however, groundtruthing of the collected data documented no elevation changes in this area, but did show changes in the vegetation cover, which appeared less vigorous in 2018 relative to 2017. This gave an erroneous result in vertical changes in the DoD, originated by the reduction of vegetation coverage after the dry winter of 2017–18 (Fig. 2).

The changes in the volume of sediment within the dune stoss were relatively homogeneous and low alongshore (Fig. 6E). Negative values along the western sector are related to the occurrence of narrow

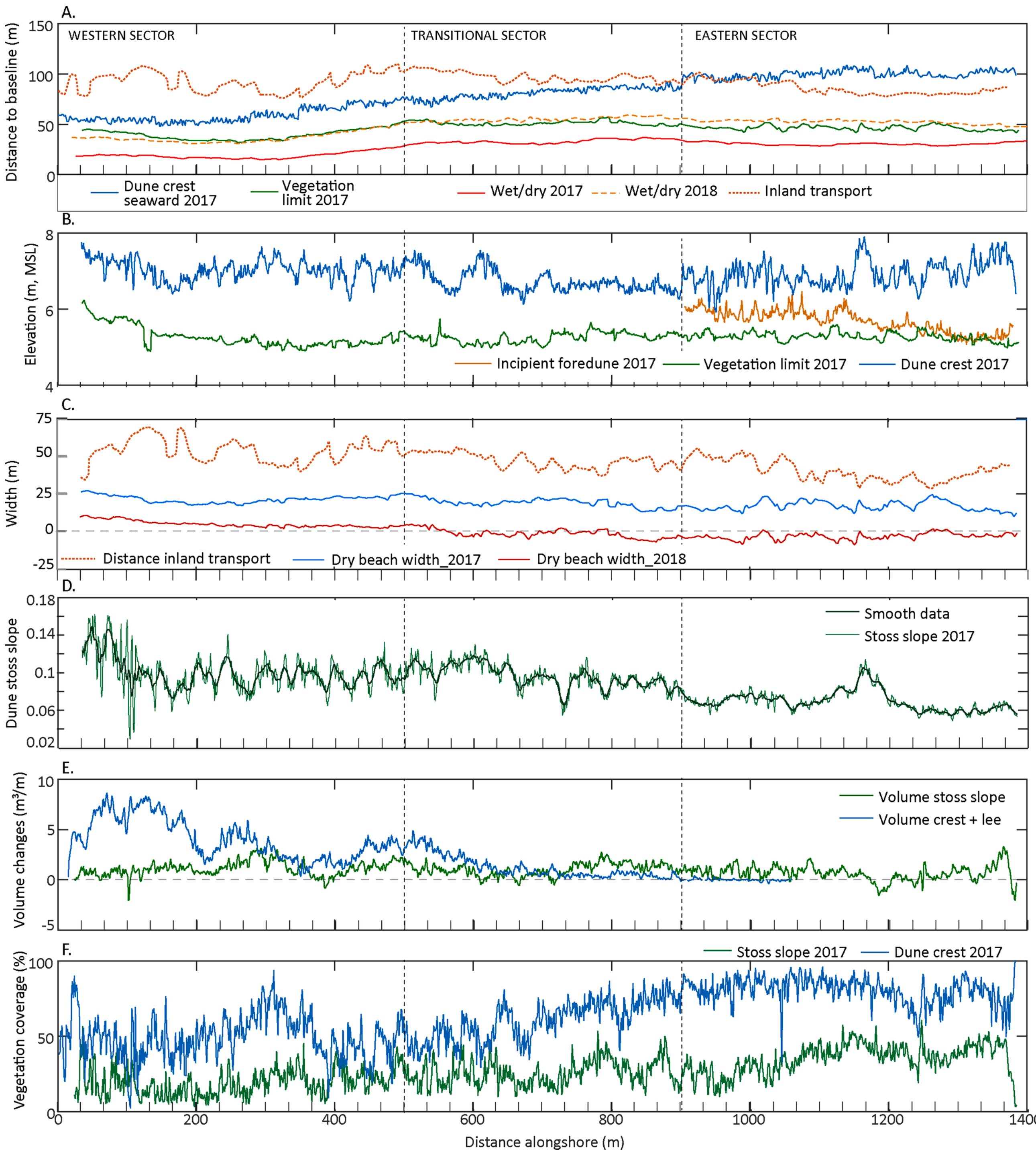


Fig. 6. A. to D.: Morphological characterization of the study area. data from April 2017 and March 2018. E. Changes in volume alongshore within the stoss slope of the dune and the sum of the accumulated sediment within the crest and the lee side of the dune ridge between April 2017 and March 2018. F. Vegetation density in percentage coverage alongshore within the stoss slope and the crest of the dune from April 2017.

depressions cutting through the dune, formed by human trampling and used as tracks to cross the ridge. The eastern sector shows low gains in volume that concentrated in the dune stoss and did not reach the former ridge (Fig. 6E and Fig. 7B). This explains the interruption in the data depicting the volume changes inland of the ridge crest in Fig. 6E. Low volumes are likely related to the decrease in beach width and the formation of a beach scarp after the impact of storms, which reduced the availability of sand from the beach (Costas et al., 2020), especially along the eastern sector where, as aforementioned, the retreat reached the previous vegetation line (Fig. 6C). Considering also that the sum of changes in the cross-shore sense within the frontal dune in the eastern area is close to null, it follows that the vertical changes observed (Fig. 7B) in the sector were related to the redistribution of sediment within the dune stoss compartment. The results also indicate active transference of sediment to the lee of the dune ridge along the western sector, where maximum accretion values, reaching 7.5 m^3/m (Fig. 6E). The stoss of the dune accumulated very low, almost null, sediment volumes, functioning as a bypass area. Overall, the inland penetration of sand, or transport distance across the dune, decreased eastwards (Fig. 6E).

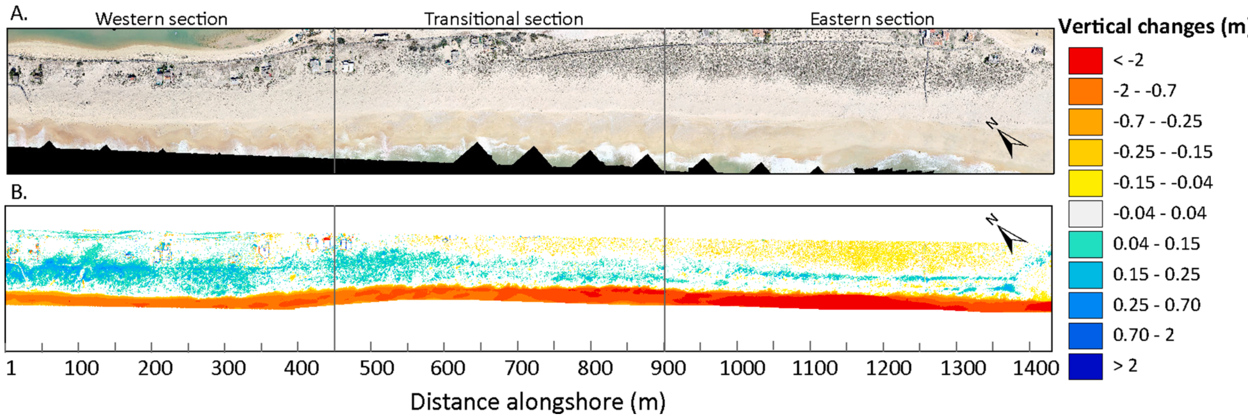


Fig. 7. A. 2018 orthophoto-mosaic. B. DEM of differences (DoD) showing the changes in elevation along the study site between 2017 and 2018.

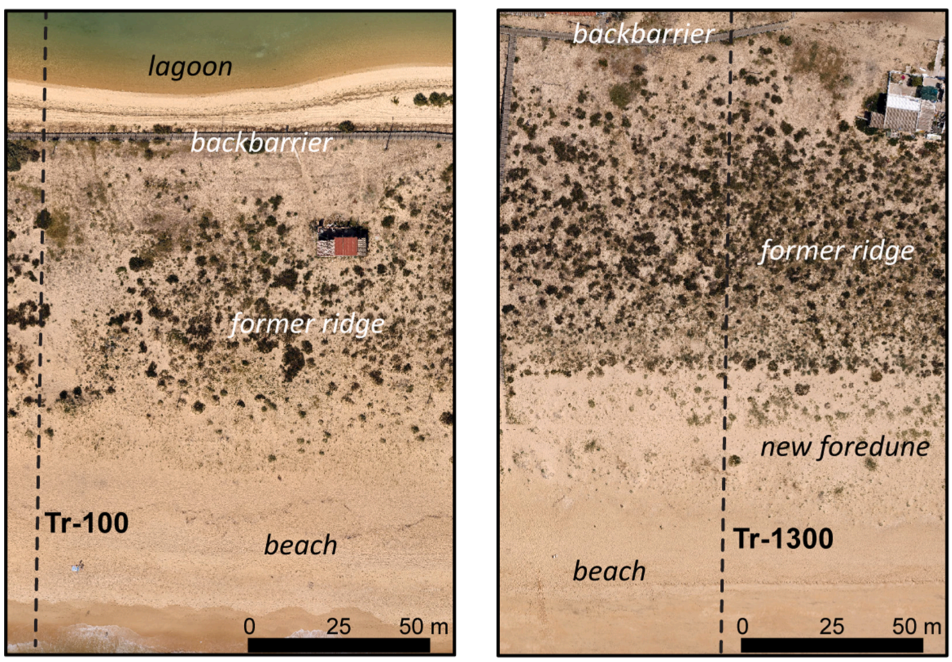


Fig. 8. Images showing the vegetation cover across the dune at the western (left image) and eastern (right image) sectors.

4.4. *Present-day vegetation cover and plant communities*

The spatial distribution of the vegetation density showed greater values along the crest of the ridge (Fig. 6F, Fig. 8), with high alongshore variability and the highest values (around 85%) along the eastern sector. Reduced vegetation coverages (circa 50%) were found between transects 400 and 600, around the transition between the western and the transitional sectors, increasing to the east. The western sector was also characterized by low values (around 50%) and the greatest variability, ranging between 0 and 70%. Vegetation coverage generally increases eastwards, with the lowest values (around 10%) along the first 200 m of the stretch, high spatial variability in the transitional sector, and greater coverages (around 40%) in the eastern sector.

The analysis of the spatial distribution of species, carried out across the transects selected as typical of the long-term behaviour of each sector (Fig. 4), points towards important spatial variability along and across the system. As aforementioned, the number of CZLs within each representative transect depended on the width of the dune at each sector, with 6 CZLs within the western sector, 8 CZLs within the transitional sector and 13 CZLs surveyed across the transect representative of the eastern sector. In total, 27 species were identified (Table 1), of which 7 are Type 3 species, i.e. species adapted to the high levels of stress and disturbance that characterize the foredune, with *Elymus farctus* as the most abundant one. 12 species are classified as Type 2, among which *Artemisia crithmifolia*, *Medicago marina* and *Lotus creticus* were dominant, while the remaining 8 species are classified as Type 1 herbaceous annual species with *Paronychia argentea* as the most common one. The number of species identified in each sector was similar, despite the different number of surveyed CLZs, with 24 species in the eastern sector, 23 in the transitional and 20 in the western one. The three sectors displayed similar patterns of spatial vegetation distribution (Table 1, Fig. 9). The number of species increased from 4 to 6 in the incipient dune and/or stoss slope to 9–14 in the lee slope. The composition and the abundance also changed in the same direction, with the seaward-most zone dominated by Type 3 species, such as *Elymus farctus*, and the remaining zones dominated by Type 2 species, such as *Artemisia crithmifolia* and *Medicago marina*. Type 1 species, which are not adapted to sand burial, were very rare in the incipient dunes and progressively increased their abundances inland.

The results from the performed DCA illustrate the cross-shore (explained by axis 1) and longshore (explained by axis 2) gradients in species composition and abundance (Fig. 10). Greater distances between

Table 1
Species composition (% mean cover) in studied sectors in transects of incipient (I), stoss slope (S), crest (C) and lee slope (L). Functional types (FT) and species burial tolerance (BT) according to García-Mora et al. (1999). THB = high burial rates tolerant, TLB = low burial rates tolerant, NT = not tolerant to sand burial.

Species	FT	BT	Eastern sector				Transitional sector				Western sector			
			I	S	C	L	I	S	C	L	I	S	C	L
Ammophila arenaria	3	THB	3									1		
Anthemis maritima	2	NT	0						1	2				4
Artemisia crithmifolia	2	TLB	**15**	**19**	**26**	**18**	3	**22**	**23**	**25**		6	**18**	**25**
Calystegia soldanella	3	TLB	8	1			6					3	4	
Carpobrotus acinaciformis	2	TLB				1								2
Crucianella maritima	2	TLB	5	2	1	1		4	1	2		6	3	3
Elymus farctus	3	THB	**14**	9	5	5	**17**	**22**	6	**10**		**23**	**15**	**13**
Erodium cicutarium	1	NT		6	1	2			3	4				
Eryngium maritimum	3	TLB	6				**12**					6		1
Helichrysum picardii	2	NT								1				
Linaria lamarkii	2	NT						1				1		
Linaria pedunculata	2	NT	1		1		7		1	1		7	2	1
Lotus creticus	2	TLB	2	8	**11**	0.4			7	9		4	**35**	**24**
Malcolmia littorea	2	NT		3	1	3			3			1	**6**	4
Medicago littoralis	1	NT		9	4	3				1				
Medicago marina	2	TLB	**21**	**10**	5	2	**17**	**21**	7	1		5	2	
Otanthus maritimus	3	THB	1				1	1				1	1	1
Pancratium maritimum	3	TLB	2	1	2	2	1	**10**	2			6	4	6
Paronychia argentea	1	NT		**15**	**24**	**42**			**16**	**19**				1
Polycarpon alsinifolium	1	NT	0.2	6	1				**15**	4		1	6	6
Polygonum maritimum	3	TLB					1	1						
Pseudorlaya pumila	1	NT	0.2											
Reichardia gaditana	2	NT		1	3	0.4				2			1	
Senecio lividus	1	NT						1						
Silene nicaeensis	2	NT	6	5	5	**10**	2	4	8	9		1		2
Sonchus asper	1	NT				1								
Vulpia sp.	1	NT		5	4	5		5	1	5		1	3	2

morphological zones indicate a greater difference in terms of composition. In this line, the incipient (if present) and stoss zones across the western and transitional sectors show a very different community from the one found at the crest. However, the crest and lee are similar in terms of composition. Cross-shore zonation in the eastern zone appears to show a more gradual change clearly defining each zone. In terms of longshore variability, the three analysed transects show clear differences with the transitional transect showing greater similarity to the eastern one. The ordination provided by the DCA clearly shows the cross-zone zonation in the eastern sector and the squeeze of this gradient within the stoss zone across the western and transitional sectors (Fig. 10).

4.5. Integration of the results

The PCA was performed using only variables with some alongshore variability, namely long-term shoreline change trends, dune stoss width, foredune (i.e. active dune) elevation, percentage of vegetation within the stoss, total volume of change, accumulation pattern (position of maximum inland sediment transference relative to the crest), and backshore beach width in 2018. One principal component produced by the PCA (PC1) explained 82.03% of the total variance of the seven evaluated parameters that define the variability of the dune system in terms of morphology, vegetation coverage, shoreline trends and recent topographical changes. The Kaiser-Meyer-Olkin test of sampling adequacy performed, resulted in a value of 0.89, which classifies as excellent. In principle, variables within a principal component (PC) a represent similar effects on the system and can help to illustrate the alongshore variance of the dune and discriminate among the sectors previously identified. PC1 was correlated positively with the width of the stoss, the long-term shoreline trends, the vegetation cover and the accumulation pattern dominated by stoss retention, and negatively with elevation of the foredune (crest of the active dune), the width of the dry beach, the total volume of change (Fig. 11). This ordination of the variables further suggests that PC1 separates the temporal scale that controlled each variable, with the positively correlated variables ruled by the long-term response of the dune system to the evolution of the shoreline and the negatively correlated variables, with the exception of the foredune elevation, related to the short-term response of the beach. The foredune elevation variable (Fig. 10), correlating negatively with PC1, is clearly dominated by the evolution of the shoreline, which in turn allowed its formation. However, the temporal scale of vertical dune growth is inversely related to shoreline progradation, meaning that the greater the progradation of the coast, the lower the elevation of the incipient dune. This pattern has been previously observed and conceptualised (Herrero et al., 2020; Moore et al., 2016; Psuty, 2004).

In terms of spatial expression, PC1 successfully separates the different sectors along the dune system (Fig. 11), with positive and larger scores at the eastern sector, low scores along the transitional sector, and high but negative values at the western sector. This ordination implies that the eastern sector is separated by its greater vegetation coverages and a wider stoss where the incipient dune developed, facilitated by the progradation of the shoreline in the long-term. In addition, present aeolian sedimentation patterns reinforce this morphology, retaining sediment within the stoss and further promoting the eventual growth of the incipient dune. These characteristics can be integrated to define a dune state, which for the case of the eastern sector would be termed the prograding dune state. Parallelly, the ordination of the western sector, at the opposite end of the component axis (Fig. 11), is associated with lower vegetation coverages, a narrow stoss lacking incipient dunes, the transference of aeolian sand to the lee of the dune, and retreating shoreline trends, which all together define the inland migrating state.

5. Discussion

The integration of the spatial variability of geomorphological parameters, plant communities and coverage, together with long-term shoreline trends and short-term volumetric changes across a dune system, allowed exploring the possible links between variables and changes on different timescales. The obtained correlations can be interpreted as the statistical representation of morphologic and biologic feedbacks and can help to define different dune states. These express the dynamic

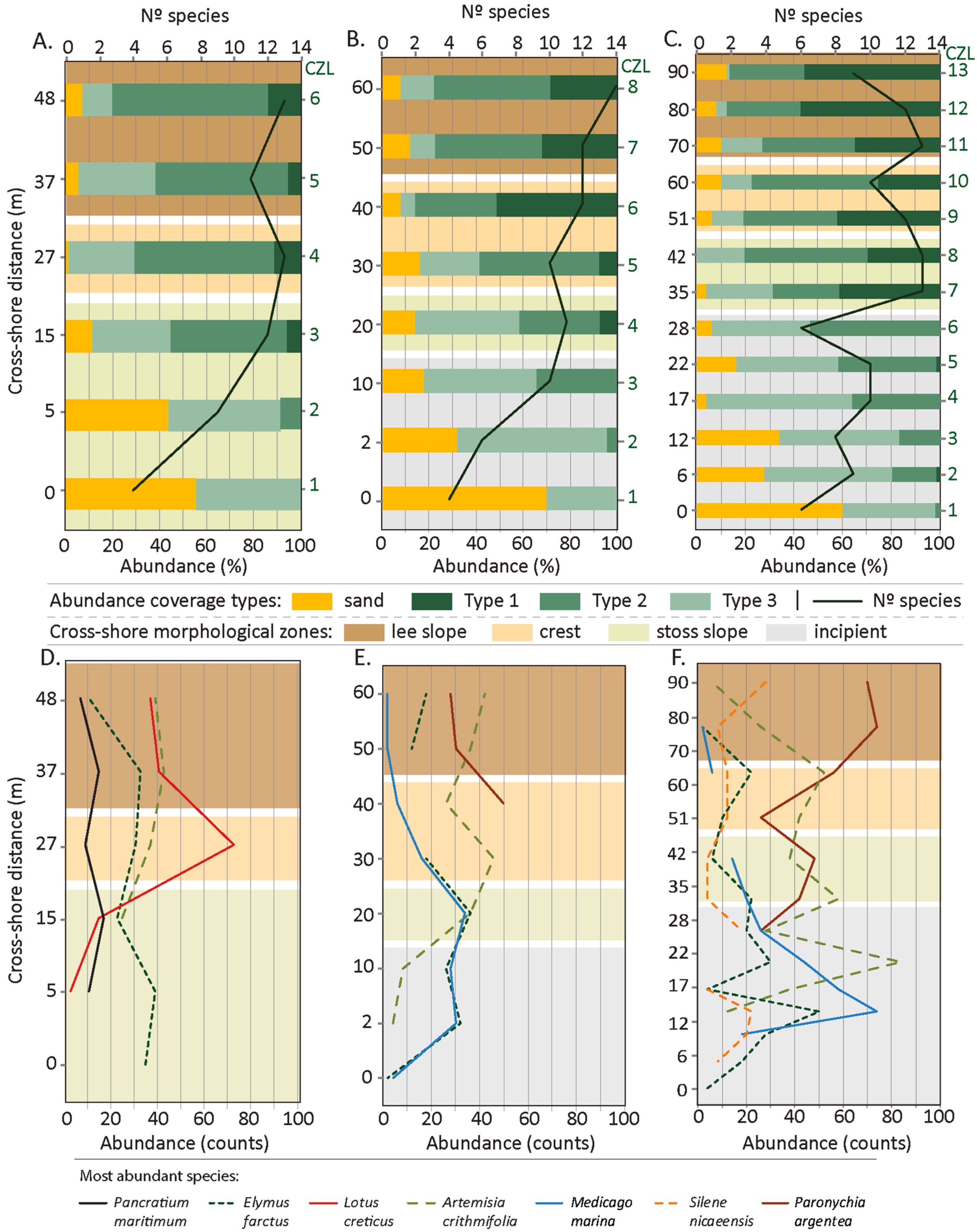


Fig. 9. A. to C. Show the cross-shore distribution within each sector (west to east) of the three type of species identified within each cross-shore zonation line (CLZ) and the number of species. D. to F. Show the dominant plants across the dune.

adaptation of the biogeomorphic dune system to external long-term drivers of change (shoreline trends) and highlight the influence of internal cross-scale interactions on morphological changes over shorter timescales. Overall, the main driver controlling the high variability of dune states over this narrow barrier stretch appears to be the long-term evolution of the shoreline. The link between barrier or dune morphology and shoreline changes was also documented by Houser et al. (2018), who linked decadal shoreline changes along barrier islands to mesoscale

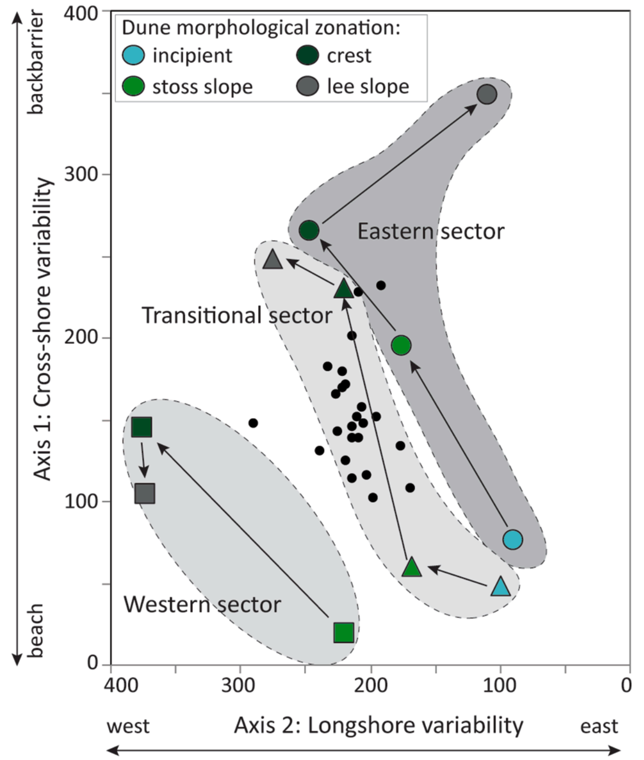


Fig. 10. Detrended correspondence analysis (DCA) ordination of present-day vegetation, based on the plant composition and abundance, surveyed along and across the dune. Eigenvalues of axis 1 and axis 2 were 0.117 and 0.044, respectively. Arrows indicate the changes in species composition and abundance between morphological zones across de dune at each of three transects representing each sector along the study area (western sector-square, transitional sector-triangle and eastern sector-circle symbols). Species are represented by black dots.

(~1000 m) dune morphology variability, and by Gutierrez et al. (2015) at the barrier island scale.

5.1. Long-term ecogeomorphic dune response

The development of two very distinct states (i.e. prograding and inland migrating) at such close proximity was triggered by the relocation of the adjacent Ancão Inlet in 1997 (Fig. 12). This promoted the shift from a relatively stable state to a prograding state at the eastern sector due to the provision of additional accommodation space seawards. Conversely, the western sector remained in an inland migrating state due to limiting conditions in terms of seaward accommodation space. As a result, the prograding dune system expanded over the beach through the growth of an incipient foredune and the full development of a cross-shore plant zonation, with a well-defined transition between the three identified functional types. Plant zonation across the inland migrating dune was characterized by reduced cross-shore variability,

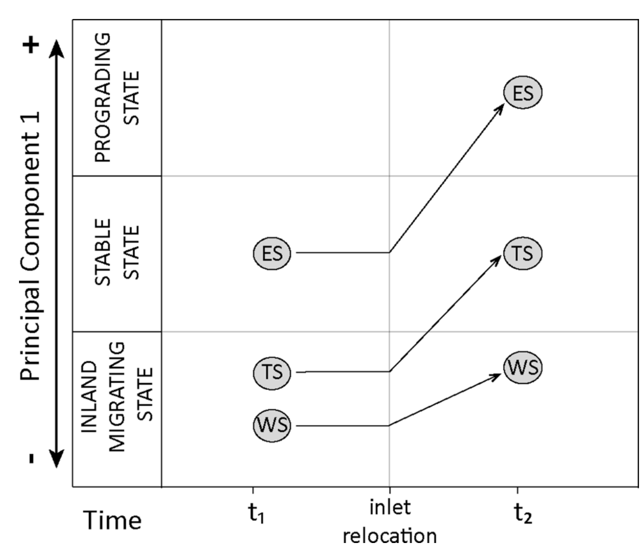
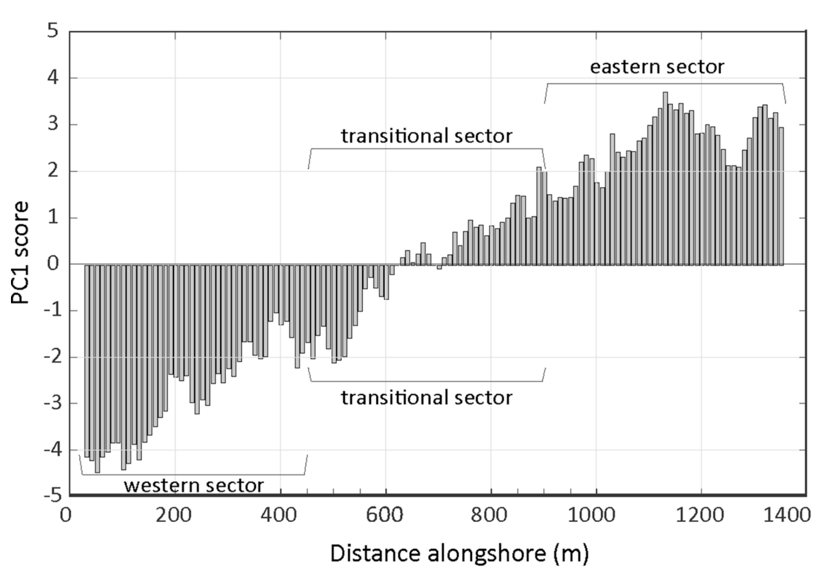


Fig. 12. Graphical representation of the shifts between states defined by the Principal Component 1, following inlet relocation in 1997. ES, TS and WS stand for eastern sector, transitional sector and western sector, respectively.



PCA results	PC1
Eigenvalue	5.74
% variance	82.03
Variables	**Loadings**
Stoss width (m)	0.97
Foredune elevation (m)	-0.87
Vegetation coverage stoss (%)	0.80
Shoreline trends (m/yr)	0.97
Beach width 2018 (m)	-0.90
Accumulation pattern (distance relative to crest, m)	0.92
Total volume change (m^3/m)	-0.91

Fig. 11. Summary of the principal component analysis (PCA) results, showing the graphical representation of the scores on PC1 and the loads on each variable (positive and negative loadings highlighted with light and dark grey, respectively).

being dominated by high burial tolerant Type 3 species (stoss slope) and low burial tolerant Type 2 species (crest and lee). The lack of the transition to not tolerant Type 1 species suggests a breakdown of the plant community successional process, resulting from the impact of squeeze in the sand dune plant habitat between the land and the sea (Feagin et al., 2005). Still, the slow retreat of the shoreline in this sector could be interpreted as a long-term disturbance agent (press/ramp disturbance). These permanent stressors are often associated with regime shifts, when the system response to the disturbance overpasses a certain threshold, after which a large and potentially irreversible shift takes place in the system (Piégay et al., 2020).

5.2. Short-term geomorphologic dune response

In the short-term (1 year), the area was strongly dominated by the relocation of the inlet in 2015, which induced short-term shoreline retreat. This retreat explains the lower volumetric changes towards the east, but it did not affect sand distribution within the system, which was also in agreement with the long-term behaviour, showing that the short-term dune response is dominated by a long-term trend. Works based on monthly surveys show that maximum sand deposition, in general, occurs near the seaward edge of the vegetation, decreasing with distance upslope (e.g, Arens, 1996; Brodie et al., 2019; Christiansen and Davidson-Arnott, 2004; Schwarz et al., 2021). This pattern fits the observations within the prograding eastern sector, where sediment retention occurred within the area with more scarce vegetation and dropped landwards. The latter is indicated by the presence of a band of *Artemisia crithmifolia*, which appears to mark the inland limit of the active sedimentation zone. Conversely, the western sector showed transference of sand up to the lee of the ridge, despite the inland increase in vegetation cover.

Deviations from the aforementioned general pattern of accumulation across the dune profile may be induced by the occurrence of scarps at the seaward edge of the dune (Ollerhead et al., 2013). Dune scarps usually evolve into ramps through a mix of aeolian, marine and avalanching processes. While these ramps remain bare, they may facilitate the transfer of sediment from the beach onto the upper portion of the stoss slope (Christiansen and Davidson-Arnott, 2004; Ollerhead et al., 2013) or just leeward of the vegetated dune crest (Brodie et al., 2019). This type of dune response has been previously described and conceptualized by Ollerhead et al. (2013) as the cliffed lower stoss slope type. Despite the absence of a scarp along the western sector, the scarce vegetation cover and the gentle (resembling a ramp) slope fit this type of profile behaviour, that has been associated with dune retreat and growth during transgression of erosive coasts (Walker et al., 2017 and references therein). Conversely, the eastern sector (prograding sector) is comparable to the stoss slope with embryo dunes profile type from Ollerhead et al. (2013), characterized by a vegetated stoss slope and the presence of a vegetated embryo dune at the back of the beach, capable of trapping the sand transported from the beach.

5.3. Critical factors controlling dune ecogeomorphology

In principle, the type of community found within the frontal dune ridge includes functional types that promote the vertical growth of the foredune, i.e. dune builder plants with high tolerance to burial (García-Mora et al., 1999; Godfrey, 1977; Hesp, 2002; Stallins and Parker, 2003). However, regional (e.g., precipitation and wind intensity regimes) and local (e.g. sediment supply) conditions likely constrain the vegetation growth in the area. The broader scale of the former is expected to have a similar effect along the area, however local variations in sediment supply can be important even within reduced spatial scales (~1000 m), as suggested by the significant changes in beach width at long and short-term scales (Costas et al., 2020; Kombiadou et al., 2019). The latter has been proven to largely control the amount of sediment transferred from the beach to the dunes in the area (Costas et al., 2020) and it is, in turn, controlled by the inlet dynamics and its proximity to the evaluated area. Thus, local variations in sediment supply will translate into spatial variation in plant burial, which is a strong selective force that alters the density, composition and growth of plant species that colonise dunes (Maun, 1998). If burial is not active, the plant community will be preferentially dominated by less tolerant species (Type 2) or species that are not sand dependent, in order to maintain vigorous populations (Maun, 2009, 1998). This explains observations from the western sector (inland migrating state) and implies that existent sand dependent plants may lack the conditions to actively retain sand and promote the vertical growth of the dune. Instead, this can facilitate the inland migration or roll-over of the dune. In fact, vegetation within the dune stoss and crest of the inland migrating sector appear to maintain relatively low abundances and vigour. Therefore, based on the plant community (low burial tolerance plants across the dune) and the observed short-term volumetric changes, the negative (stabilising) feedback between dune vegetation and topography, expected to reinforce dune topography, did not fully materialise within the inland migrating state stretch. Contrastingly, in the eastern sector (prograding state) long-term conditions appear to promote sand retention and growth of the incipient dune, while overall the sector is also characterized by more vigorous and dense vegetation.

Dune or barrier states have been recently explored through bistable domains or bistability models that attempt to integrate the two-way relationship between dune vegetation and morphology (Hayden et al., 1991; Stallins, 2005; Zinnert et al., 2017). The resulting configurations (disturbance-resisting state or high dune and disturbance-reinforcing state or low dune) interact with physical or ecological processes shaping the dune or barrier landscape (Zinnert et al., 2017). In this line, a barrier state is reinforced or perpetuated by the colonising species, as "plants attenuate geomorphic processes and landforms to promote the development of habitat conditions for which they are adapted" (Stallins, 2005). This view places the control of the stability state to the biological component. Durán Vinent and Moore (2015) and Goldstein and Moore (2016) identified these stability domains from model results that included one species of plants and physical processes associated with storm events (high water events). These works suggest that the role of the biological component is ultimately controlled by physical processes. This implies that if the effects of storm erosion dominate, dunes may become trapped in a perpetual state of low elevation and maximum vulnerability to storms, while, if these conditions revert, biophysical processes gain relevance, contributing to the vertical growth of the dune.

Part of the coastal segment evaluated here, namely the western sector (inland migrating state), seems to have limited capacity for vertical growth, behaviour that could partially be accentuated by a positive (destabilising) ecogeomorphic feedback. However, we also find that the role of vegetation on dune growth is rather passive and mainly controlled by regional (low precipitation and sediment transport potentials) and local conditions, e.g., variations in the sediment supply alongshore. Therefore, despite the undeniable role of vegetation in reinforcing dune topography, it is worth highlighting that local external forces may dominate dune response, inhibiting, allowing or reinforcing ecogeomorphic interactions in the long-term.

6. Conclusions

The present work investigated the main drivers of the ecogeomorphic variability of a coastal dune segment (1.4 km-long), located in the Ria Formosa barrier island system, southern Portugal, by exploring the differences in dune morphology, plant type distribution, short-term accumulation patterns and long-term shoreline rates, and identifying the dominant links between them. The results suggest that shoreline evolution over the past 65 years, mostly linked to the relocations of the adjacent inlet, explains not only the observed dune morphology, but also the gradients of plant zonation and the patterns of sedimentation along and across the system. In this regard, two different dune configurations, or states, have been identified, located at the western and eastern sectors, while a transitional one occupies the area between both.

The western sector is characterised by a single dune ridge, lacking the full gradient in plant zonation and showing spatial contraction of the plant communities with lower vegetation densities, by the transference of sand towards the lee of the dune, and by a slightly negative to stable shoreline change rate. These define the inland migration state linked to this sector. Conversely, the eastern sector is characterised by the occurrence of a new incipient foredune seawards of the former dune ridge, with a well-defined plant zonation and higher vegetation coverages, by the retention of sediment within the dune stoss, and by a significant progradation of the shoreline after the relocation of the adjacent inlet. The latter induced the growth of the beach, allowing its subsequent colonization by vegetation and promoting the formation of the incipient foredune. These characteristics summarise the state of this sector, termed as prograding state.

The analysis of the short-term temporal scale, including the estimate of the volumetric changes along and across the dune, highlights the importance of the beach width in this temporal scale by controlling the amount of sediment available within the beach to be delivered to the adjacent dune. In fact, it illustrates how the sector showing greater growth (eastern sector) over the long-term, can show the lowest accumulation under limiting beach width conditions.

The results from the present work also contributed to understanding the links between the long-term shoreline changes and the plant zonation. In this line, the high abundance of Type 2 and 3 plants (low burial tolerant and high burial tolerant plants, respectively) across the inland migrating dune profile, suggests a breakdown of the successional process, resulting from the dune plant habitat squeeze between the land and the sea. It also documents the impact of the ongoing cycle of inland dune migration through the transference of sand landwards, whose feedback with vegetation explains the high abundance of burial tolerant plants.

In addition, the results suggest that plants have a rather passive role within the feedback between topography and vegetation, which seems mostly regulated by external agents, namely sediment supply, in turn controlled by local (beach width) or regional conditions (wind intensity). Observations suggest that the vertical growth of the inland migrating dune is limited in part due to the very weak negative (stabilising) feedback between vegetation and dune topography, consequence of the incapacity of the system (i.e., low sediment supply) to maintain vigorous burial tolerant populations or dune builders. Therefore, despite the undeniable role of vegetation in reinforcing dune topography, it is important to highlight that local external forces may dominate dune response, inhibiting, allowing or reinforcing ecogeomorphic interactions.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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