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Master of Science in Marine and Coastal Systems

Exploring the drivers of habitat and species distribution along the Ria Formosa dunes

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Declaração de autoria de trabalho / Declaration of the authorship

Declaro ser o autor deste trabalho, que é original e inédito. Autores e trabalhos consultados estão devidamente citados no texto e constam da lista de referências incluída.

Hereby I declare to be the author of this document, which is original and unpublished. Authors and works consulted are duly cited in the text and are included in the list of references.

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Felix Leonard Götzl

Faro, 27th of September 2023

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Abstract

Coastal dunes are complex landforms shaped by the interaction of various ecological and environmental factors. In this work, dune morphology and plant community distribution are studied in twelve different sites along the Ria Formosa. The study covers a distance of about 55 kilometres along the system. Current data on the evolution of shorelines over several decades are integrated to decipher the main determinants of the observed diversity and its impact on dune morphology.

The results show differences in dune structure and spatial plant distribution. There are two different dune configurations in the system. The western sector features higher dunes with a well-established plant zonation, influenced by comparatively robust energetic factors. In contrast, the eastern sector features dunes with lower heights and narrower widths, often characterized by steeper stoss slopes and less evolved plant zonation. The eastern dunes are more susceptible to change, reflecting a more dynamic environment. These differences can be partially attributed to current shoreline evolution trends and shifts in inlet dynamics. Also, they are more vulnerable due to their dimensions. There are different trends across the system, depending on the factors prevailing at the location. Plant zonation may indicate that increased space and the stabilizing synergy between vegetation and topography promote seaward dune growth, favouring the development of an incipient foredune. Conversely, observations with retreating tendencies indicate that the dune is in a phase of inland migration, driven by limited accommodation space and consequently reduced evolved vegetation zonation across the dune. The results highlight the importance of biogeomorphic interactions in dune configurations. Furthermore, they emphasize that the role of vegetation within these interactions is predominantly determined by physical factors that either facilitate or hinder the influence of vegetation on dune topography.

Resumo

As dunas costeiras são formas de relevo complexas moldadas pela interação de vários fatores ecológicos e ambientais. Neste trabalho, são estudadas a morfologia das dunas e a distribuição da comunidade vegetal em doze locais diferentes ao longo da Ria Formosa. O estudo cobre uma extensão de cerca de 55 quilômetros ao longo do sistema. Dados atuais sobre a evolução das linhas de costa ao longo de várias décadas são integrados para decifrar os principais determinantes da diversidade observada e seu impacto na morfologia das dunas.

Os resultados revelam diferenças na estrutura das dunas e na distribuição espacial da vegetação. Existem duas configurações diferentes de dunas no sistema. O setor ocidental apresenta dunas mais elevadas, com uma bem estabelecida zonagem da vegetação, influenciada por fatores energéticos comparativamente robustos. Por outro lado, o setor oriental apresenta dunas com altitudes menores e perfis mais estreitos, frequentemente caracterizados por encostas íngremes e uma zonagem da vegetação menos desenvolvida. As dunas orientais são mais suscetíveis a mudanças, refletindo um ambiente mais dinâmico. Essas diferenças podem ser parcialmente atribuídas às tendências atuais na evolução da linha de costa e às mudanças na dinâmica dos afluentes. Além disso, são mais vulneráveis devido às suas dimensões. Existem diferentes tendências em todo o sistema, dependendo dos fatores predominantes na localização. A zonagem da vegetação pode indicar que o aumento do espaço e a sinergia estabilizadora entre a vegetação e a topografia promovem o crescimento das dunas em direção ao mar, favorecendo o desenvolvimento de uma duna incipiente. Por outro lado, observações com tendências de recuo indicam que as dunas estão em uma fase de migração para o interior, impulsionada pela limitação do espaço de acomodação e, consequentemente, pela reduzida zonagem da vegetação evoluída ao longo das dunas. Os resultados destacam a importância das interações biogeomorfológicas nas configurações das dunas. Além disso, enfatizam que o papel da vegetação nessas interações é predominantemente determinado por fatores físicos que facilitam ou dificultam a influência da vegetação na topografia das dunas.

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1. MOTIVATION

A significant portion of the global human population resides in close proximity to coastlines (Cohen et al., 1997). These communities are constantly changing and expanding the environment they inhabit. This behaviour leads to severe degradation of coastal ecosystems due to various anthropogenic activities, such as residential, touristic, or industrial purposes (Martinez et al, 2013, 2004; Salman & Strating 1992). For this reason, it has always been important to study coastal dynamics, as anthropogenic influences lead to changes that in turn exert pressure on the environment and thus on humans.

The power of the ocean can be mitigated by the presence of dunes, which serve as the first line of defence. They can absorb the energy of storm-generated waves and flooding. Therefore, they are able to reduce the vulnerability of areas further inland (Costas et al., 2020). Apart from their protective function, coastal dunes offer various ecosystem services, such as regulating the sediment balance of sandy coasts and providing recreational areas for tourism. Additionally, coastal dunes are recognized as ecologically important habitats, as they offer suitable conditions for a wide range of plant and animal species (Van der Maarel, 2003). Coastal dunes, which are typically found in coastal areas, arise from the interaction of sediment transport with vegetation or other physical obstacles, whereby the transport is triggered by the wind. The accumulation of the sediment to form dunes is also influenced by the different plant species. If the beach sediment budget is positive, i.e. the beach is not eroding, plants may have an opportunity to grow and colonize the beach. This will contribute to the retention and accumulation of wind-blown sand. Thus, investigating this colonising process and the plant species able to grow at the beach is expected to contribute to understand how plants may affect the sediment transport and therefore influence the shape of the dune (Ciccarelli, 2014).

As aforementioned, for humans, these systems near sandy beaches offer an attractive environment as a recreational area. Because of that, they have been traditionally used for the development of holiday homes, campsites, or residences, contributing to irreversible impacts such as the levelling or complete degradation and even disappearance of dunes. Then, there are additional factors with lower impact such as pollution, careless behaviour towards flora and fauna or physical erosion caused by hikers that also contribute to the degradation of these systems (Acosta et al., 2013). The effects are fatal for dune ecosystems because they reduce or destroy the functions that dunes normally provide (Pye & Tsoar, 2004). The prevailing climate change is causing changes to the system of the Earth systems, including sea-level rise. This endangers dune systems and increases the risks of, for example, overwash and inundation. Another aspect of climate change is more frequent and stronger storms, which in turn may lead to more erosion of the dunes (Keijsers et al., 2016; Miller et al., 2010).

Given the great risks posed by climate change and human intervention it is questionable whether dune systems will be able to respond fast enough and adapt on their own in given circumstances or whether coastal protection efforts will be sufficient. Therefore, it is of utmost importance to gain further insights into the complexity of dune dynamics in particular to the interactions between the biotic and the abiotic components of the system. In this regard, this work will explore which are the main factors that influence the habitat and species distribution along different dune systems. And to find out how this distribution may or may not also control the shape of the dunes, giving the two-way relationship that exists between vegetation and morphology (Bonte et al., 2021). The study of these relationships, as well as external or internal factors of their mechanisms, is of great importance for understanding the adaptation of dunes to the effect of external forces and the associated changing morphology over time.

2. OBJECTIVES

The main objective of this work is to contribute to a better understanding of the evolution of dune systems, addressing several interrelated factors. Priority is given to establish the relationship between the composition of the vegetation cover and the morphological parameters. Another important factor is the evaluation of wind and wave data with their direction and strength. With the help of the data available on the evolution of shorelines in recent years, an attempt is made to determine the development trends along coastal dune habitats. However, to better understand these relationships, one needs to know how exactly components of the system function; in other words, what influence do the abiotic factors, such as marine and aeolian sediment transport as well as the prevailing morphology, and the biotic factors (i.e., vegetation cover) have on the evolution of coastal dune systems? For this purpose, the distribution of different plant species along and across the Ria Formosa barrier island system at twelve different sites is investigated.

Several questions arise from the literature review and the state of the art. From these, the following working hypothesis can be formulated, which will guide the objectives of the present work:

“The distribution of dune plant communities can reflect the state of a dune system in terms of morphology and recent development.”

1. Analyse the morphological variability, shoreline evolution trends as well as wind- and wave-data at the ria Formosa barrier island system.
2. Understand the distribution of plants across and along the system for the same sites,
3. Investigate possible links between all these factors.

3. STATE OF THE ART

3.1 COASTAL DUNES

Coastal dunes are unique ecosystems, characterized by a great diversity of geomorphological processes and environmental heterogeneity. They are aeolian land formations created by the accumulation of sandy sediments in coastal regions. (Martínez et al., 2004). They can form in almost any climate and shore form (Hesp, 2002). Not only do they protect areas further inland from erosion and storm effects, but they also provide a rich ecosystem for a variety of species (Duran & Moore, 2014). The formation of these dunes requires persistent topographic and climatic conditions that allow sand to accumulate over time, as well as a sufficient supply of sediment and strong onshore winds that can transport the sand. If these conditions persist, the sand gradually moves and accumulates to form the dunes (Pye, 1983). Certain pioneer plant communities provide sand fixation and deposition. Consequently, they play a substantial role in the formation and evolution of coastal dunes (Martins et al., 2013).

Especially in the case of barrier islands, the interaction between geomorphology, metocean conditions and vegetation is particularly relevant. The distinct zonation of species and communities here is a direct consequence of these processes (Ehrenfeld 1990). Looking at cross-shore profiles a series of dune types can be identified through the environmental gradient. The rearmost part of the dune in the profile is the so-called hind dune (Figure 1). The foremost part of these is the foredune (Figure 1), which can be defined as a shore parallel dune ridge located inland of the backshore. They have greater height, width, age and/or morphological complexity than the incipient foredune from which they arise. They are the more stable type of dune, as they are less affected by sand inundation and salt spray, leading to increases in nutrient content and vegetation cover. Sand is gradually deposited on the seaward slope, increasing the size of the foredune (Hesp, 1999, 2002). The incipient foredunes are located in front of the foredune (Figure 1) and they are formed by sand deposition within specific plant species or entire vegetation communities (Hesp, 2002). These pioneer species are thus largely responsible for sand accumulation and vertical growth of dunes. They are in interdependency with the transport of sediment, which in turn influences plant diversity and distribution (Martins et al., 2013).

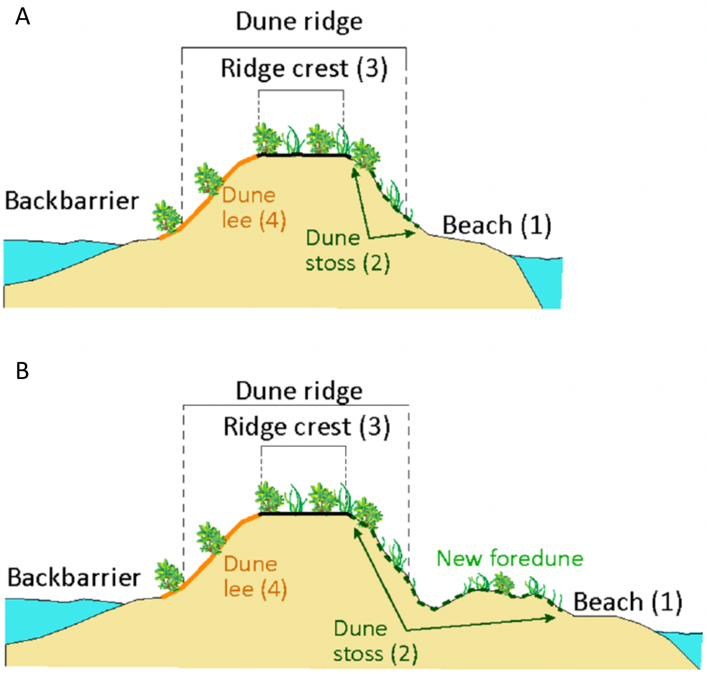


FIGURE 1 PROFILES A AND B EXEMPLIFY THE TYPICAL DUNE STRUCTURES OBSERVED THROUGHOUT THE STUDY AREA, CLEARLY ILLUSTRATING THE MORPHOLOGICAL BOUNDARIES BETWEEN THE CROSS-SHORE COMPARTMENTS (COSTAS ET AL., 2023)

Vegetation Zones

The harsh environment of dunes exposes plants to multiple stress factors, such as competition for nutrients and water, mechanical stress from wind-blown sand, and even potential burial by sand and water. Consequently, the dominant plant species have evolved unique adaptations to thrive under such conditions (Hesp, 1991). In temperate zones, just as with dunes, different types of habitats can be delineated for plants. We can distinguish these into the backshore, the dune stoss, ridge crest as well as the dune lee, which go hand in hand with the previously mentioned dune types.

The dune lee, which is most distant from the shoreline, is characterised by the tertiary vegetation zone. In this zone there is the most protection from wind and thus from the transport of sand and salt. The vegetation layer is comparatively thick, to protect vegetation further inland. The next compartment represented the ridge crest, defined as the plateau zone that embraces the top of the ridge. This part represents the second vegetation zone, which is the zone of foredunes. There are species tolerant to strong and salty winds. The zone of the dune stoss is defined as the area between the seaward limit of the dune vegetation and the ridge crest. It also includes the incipient foredunes as the primary vegetation zone, where plants colonize the upper part of the beach and intercept the abrasive sand particles blown by the wind (Kidd, 2001). These species are highly tolerant to sand burial and strong and salty winds, and some can even tolerate a certain degree of marine influence (i.e., overwash). The rooting depth of the plants is also somewhat deeper, which allows the plants to absorb water more easily and at the same time protects the dune from erosion (Grunewald

& Schubert, 2007). The last segment is the so-called backshore or upper beach, which is defined by the seaward boundary of the dune vegetation (Costas et al., 2023).

Plant functional types

As described in the previous paragraph, the different plants are found in equally different plantation zones. It is important to understand that these are not randomly arranged. Rather, they are arranged in different, though often overlapping, zones that extend from the open water to the back of the dune. So, plants can be grouped into plant functional types (PFT), depending on the physiological characteristics of plants. The physiology of plants may be similar, e.g., in terms of growth and adaptive traits, i.e. to the extent that they share a common life strategy. Individual species may therefore have similarities in their response to prevailing environmental conditions. An analysis of plant functional types helps to interpret the function of communities and facilitates the comparison of communities in similar environments (García Novo et al., 2008). The study of plant functional types in coastal foredunes of the Gulf of Cadiz by García-Mora et al. (1999), suggests three categories in relation to environmental stress and disturbances: “Type I consist mainly of winter annuals of moderate size with soft leaves, showing no presumed adaptations to the dune environment.” It appears to be found more often in more stable soils in the foredune. “Plants of Type II are mostly perennials with a below-ground spreading root network and leaves with presumed adaptations to coastal environmental stress. Type III includes plants mostly capable of being dispersed by seawater and of withstanding sand burial." These types appear in more instable soils thus more in the incipient foredune. To be able to understand the dynamics of the foredunes one can adapt the ratio of the three types as an indicator (García-Mora et al., 1999).

3.2 DUNE MORPHOLOGY

Sediment Transport

Overall, the evolution of dunes is dependent on a number of intrinsic and extrinsic factors: “Frequency and magnitude of transporting winds, incident wind direction, beach fetch and sediment supply effects, dune scarping, vegetation type and density and moisture content” (Costas et al., 2023) to name a few examples. Above all, however, the aeolian transport of sediment is decisive for the existence of dunes. In 1941, Bagnold described sand transport as a function of the velocity of wind (Bagnold, 1941). Basically, there are three forces that determine whether and how a single grain of sediment is transported by the wind: Gravity, a drag component and the lift force created by the movement of the wind over the surface of a standing grain. When the velocity of wind increases slowly over a loose sand surface, high flow velocities on the top surface cause a stationary grain to vibrate and then move when the shear stress on the grain surface exceeds a certain critical value. This value is called the threshold velocity and describes the point at which vertical lift exceeds gravity and lifts the grain vertically into the air (Bagnold 1941, Pye 1983). The movement of sand in the bed load, which describes the sand layer that is closer to the bed, occurs with the help of various mechanisms. On the beach, the sand is usually moved by saltation. Saltation works by the grains moving forward through a series of jumps. Another form is called surface traction, in which grains slide or roll along the surface either by direct fluid drag or by impact of the saltation grains. Another mode of transport is the suspension. Here, smaller grains are directly caught by a gust of wind and transported over longer distances without touching the sand bed. The mass of the grain determines how it opposes the change in its velocity or position due to the action of the wind force. It is probably more important than the dimensions since the densities of the particles differ significantly depending on their compositions. However, these values can provide useful information. For example, by comparing grain size or the potential for sand transport, makes it possible to understand why some areas have larger dunes than others. (Pye & Tsoar, 2009).

For sand to be transported, a certain supply of sand must be available. Then the prevailing wind, as described earlier, must be sufficient to move the sediment with certain sediment texture and weight (Bagnold 1941). In order for the sand to accumulate on the dune, the wind must blow in the direction of the dune. Conditions such as surface moisture should also be low, as these make it difficult to transport the individual grains (Hesp, 2002). But transport also depends on the morphology of the dune itself. This is because depending on how steeply shaped a dune is, it will favour sand transport (Ollerhead et al., 2013). In this regard, transport rates decrease exponentially with height as well as with increasing distance from the base of the dune (Arens, 1996). The width of the beach also influences sediment transport: on a narrow beach with onshore winds, sediment transport across the dune line is slower than on a wide beach. This is because narrower beaches are constrained by the fetch distance, as the current needs a certain distance to become saturated for a given, equal velocity (Delgado-Fernandez & Davidson-Arnott 2011).

Vegetation and dune formation

If the interaction of all these factors is adequate to promote sediment transport based on what has been mentioned in the previous section, and the wind provides enough sediment in the direction of the dune, the question arises as to how exactly the accumulation takes place. In this context, it is important to note, as illustrated in Figure 2, that the majority of aeolian sediment transported towards the dune is trapped by the prevailing vegetation on the dune or by other obstacles (Luijendijk & van Oudenhoven, 2019).

Plants therefore have an influence on sediment transport. They accumulate sand by acting as a so-called friction element that slows down the wind, prevents saltation and thus promotes the accumulation of sand around them (Hesp, 2002). The wind speed is reduced by the plant cover, which promotes sand accumulation. Depending on the plant species, a certain morphology thus develops. This depends, for example, on the size of the species. Where tall, dune-forming plant species predominate, which are also more resistant to disturbance, higher foreshore dunes tend to form. On the other hand, low dunes are more likely to form at sites where a carpet of low spreading plant species predominates (Ruggiero et al., 2018).

The plants are actively adapting their growth strategy (Stallins, 2005). However, depending on the prevailing abiotic factors, plant distribution and composition may be limited (e.g. Hesp, 1991; Maun, 2009; Rozema et al., 1985). Nevertheless, they are often used as indicators of the dynamics of coastal dune ecosystems (Costas et al., 2023). Therefore, vegetation cover can be a good tool to understand the relative stability of a coastal dune: The higher and denser the vegetation, the more stable the site and also the geomorphological characteristics of the coast (Bush & Young, 2009).

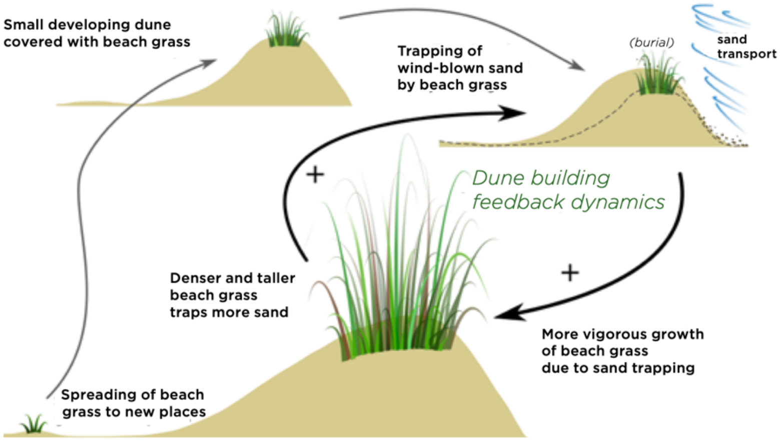


FIGURE 2 OVERVIEW OF HOW PLANT-SAND FEEDBACK DYNAMICS DRIVE COASTAL DUNE DEVELOPMENT (LUIJENDIJK & VAN OUDENHOVEN, 2019)

Dune Erosion

Coastal dunes are ecosystems exposed to constant environmental stress. The erosion that takes place is due to various natural and anthropogenic factors. Humans are primarily responsible for the destruction of dunes directly by building on and therefore levelling them (Pye & Tsoar, 2004). Natural events may also induce their erosion. In that case, storm events are the main cause of erosion of the dunes (Vellinga, 1982). The exact loss depends on several factors, but the most important factors for understanding the magnitude of dune erosion are the storm characteristics, such as wave height or wind speed and water level, and the beach condition, meaning the dry beach width and height (Garzon et al., 2021). Because of the wave attack at the base of the dune, the profile can become steeper or even create a notch or scarp and eventually lead to the collapse of the dune (Figure 3) (Erikson et al., 2007). The eroded sand is then transported downwards by the backwash and the seaward undercurrent. It is usually deposited on the lower beach as a bar but can also be transported into the open sea at sites with strong ebb currents (Masselink & van Heteren, 2014). Observations have shown that in the presence of a high foredune, the susceptibility to erosion decreases and with it the regression of the coastline (Pye & Tsoar, 2009).

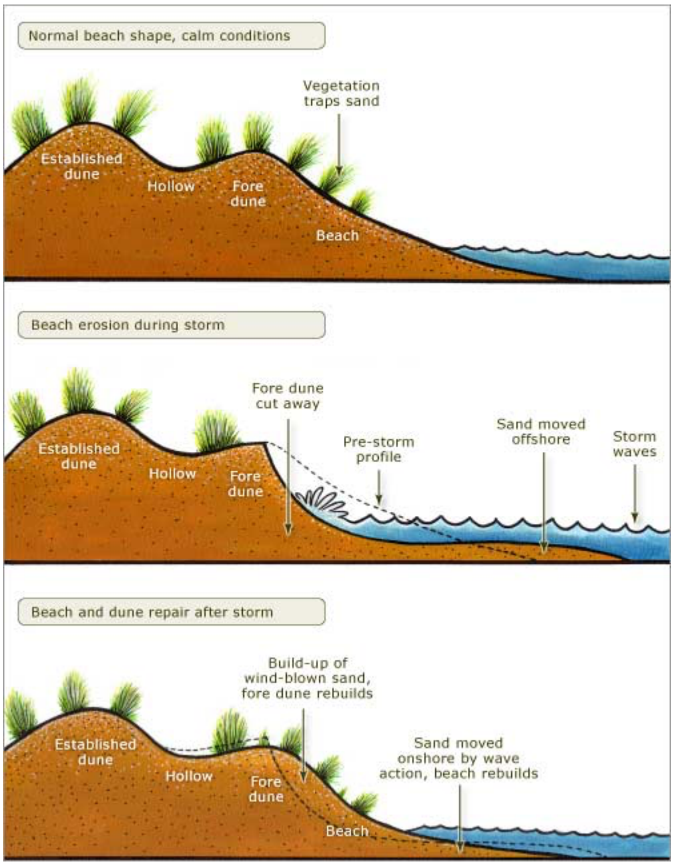


FIGURE 3 DEVELOPMENT OF A BEACH BEFORE AND AFTER A STORM EVENT (WASSILIEFF, 2006)

Dune systems with their foredunes change depending on waves and wind. The upper panel in Figure 3 shows how foreshore dunes develop and deposit the blown sand with the help of vegetation. In the second panel, the erosion of the dune can be seen when storm waves hit the dunes. The latter graph shows the dunes forming again when vegetation settles on an exposed site and begins accumulating sand again (Wassilieff, 2006). However, if the dune is already very low, there is a possibility that it will be overtopped during storm events (Sallenger, 2000). Overtopping of the dune by wave run-up is called “overwash regime” and will cause the eroded sand to move landwards (Wang & Roberts Briggs, 2015). In extreme cases, high water levels and wave run-up combined with the effects of storms can even lead to the inundation of low-lying coasts (Bauer et al., 2009). If at least one part of the dune survives the storm, it is possible that it will recover through the same processes that created the dune in the first place after it is transported back from the nearshore to the upper beach through the formation of a beach berm (see *Sediment Transport*). However, the recovery of the dune profile takes longer than the aforementioned storm erosion and also than the typical time for recovery at the adjacent beach. This means that the intervals between storms must be shorter than the recovery time in order not to cause lasting damage to the dune system (Karunarathna et al., 2014).

4. STUDY AREA

The study sites are located within the island barrier system of the Ria Formosa coastal lagoon, which is in the Algarve region in southern Portugal. The Ria Formosa extends over two peninsulas and five independent islands with a length of about 55 km starting from Ancão to the Cacela Peninsula. The system is estimated to be about 11 800 ha (Catalao Dionisio et al., 2000). Since 1987 it has been declared a reserve with higher levels of protection and has been under the observation and management of various institutions since then (Costas et al., 2015). The barrier islands serve as the first line of defence against the exposure of the Atlantic Ocean. They form a string of sand dunes cut by six inlets that also regulate the tidal flow. Which makes it essentially a tidal lagoon (Dronkers & Zimmermann, 1982).

The tidal inflows with their dynamics and the wave action determine the development of the Ria Formosa system. The resulting sediment transport is the main cause for the development of the coastline and the current patterns as well as the velocities in the lagoon (Ferreira et al., 2016). The inlets that have not been artificially fixed (i.e., Fuzeta, Armona and Ancão) migrate eastwards (Kombiadou et al., 2019). That is because of the net longshore drift in easterly direction with an estimated sediment sand-supply of about $6x10^3$ to $3x10^5$ m^3/year (Vila-Concejo et al., 2003). The uptake of freshwater in the system is largely due to precipitation from the months of October to April (Costas et al., 2023).

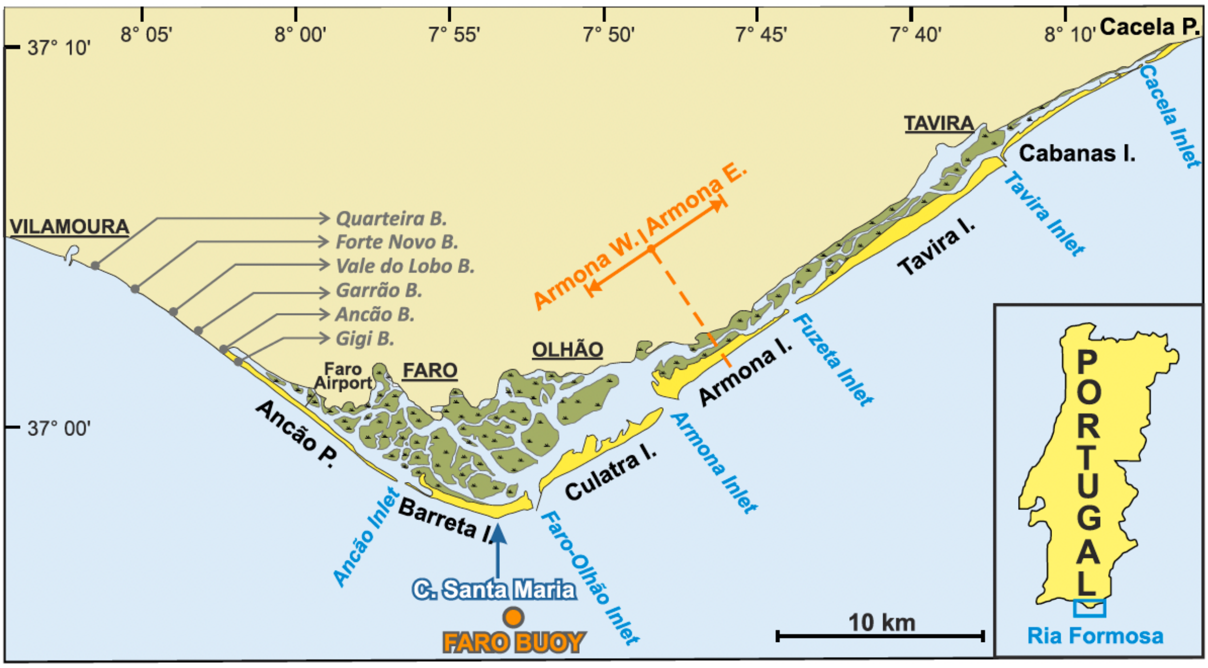


FIGURE 4 STUDY SITE - THE RIA FORMOSA MULTI-INLET BARRIER SYSTEM (BARRIER-INLET CONFIGURATION OF 2014). THE NAMES OF BARRIERS, INLETS, LOCAL TOPONYMS ('C.' STANDS FOR 'CAPE, 'P.' FOR PENINSULA, 'I.' FOR ISLAND) ARE NOTED (KOMBIADOU ET AL., 2019, P.130)

As to be seen in Figure 4, the morphology of Ria Formosa bears a striking resemblance to that of a triangle, which may be attributed to the shallow shelf accompanied by a steep slope towards the inner shelf (Dias & Gonzalez, 2000). The beach is referred to as low tide terrace morphotype, which is reflective at high and medium tide, and dissipative during low tide. Along the coast, there is considerable variation in the morphological variability of the dunes, which is related to different combinations of local factors (Costas et al., 2020). The sediments of the dune-beach system present different sizes. The finest sediments start at a size of less than 0.125 mm. In the eastern part of the barrier island system, the sediments are dominated by medium sand (approximately 0.3 mm). While coarser sediments, such as coarser sand of about 0.5-0.7mm are found on the western part of the barrier island system (Costas et al., 2018).

The vegetation cover along the barrier islands is characterised by a relatively high vegetation density on the dune crest, which is characterised by herbaceous and shrubby dune species. Costas et al. (2023) refer to three habitat types on the Ancão peninsula listed in Annex I of the European Habitats Directive 92/43/EEC (2013): (1) Embryo dune, characterised by *Cakile maritima* and *Polygonum maritimum* (habitat type 1210 and 2010), (2) Foredune, characterised by the dominance of *Ammophila arenaria*, *Elymus farctus* and *Otanthus maritimus* (habitat type 2120), (3) Fixed coastal dunes with herbaceous vegetation, dominated by *Artemisia crithmifolia* and *Lotus creticus* (habitat type 2130).

The study area has undergone several changes, particularly as a result of anthropogenic interventions in the recent past (Kombiadou et al., 2019). Since the 1950s, many small fishermen cottages have been built in some islands and peninsulas. There have been repeated actions to remove the houses for renaturation purposes or for safety reasons (Costas et al., 2015, 2020). There are still some settlements along the barrier islands, such as on Culatra or Armona. The municipality of Praia de Faro on the Ancão Peninsula is a particularly good example of intervention in the natural dune systems. Some parts of the built-up area have been artificially stabilised with measures carried out over the years, management plans were also implemented, which included, for example, the erection of sand fences to fortify the dunes (Ferreira, 2006, Costas et al., 2023).

5. DATA AND METHODS

5.1 DATA COLLECTION

The data collection phase plays an important role in providing an understanding of the coastal system under investigation. Through field measurements and data acquisition, critical parameters related to morphological variability, shoreline evolution, wind and wave characteristics, and plant distribution are collected. These collected datasets serve as the foundation for subsequent data processing and analysis, enabling the investigation of the drivers of habitat and species distribution along the Ria Formosa dunes. The initial step involved gaining an overview of the dune system, understanding its fundamental structure and sequence. Subsequently, it was crucial to determine the specific stations and their locations for investigation based on various factors. In the following sections, the individual study sites are listed, and the further procedures are explained based on these.

5.1.1. MORPHOLOGICAL VARIABILITY

To compile information about the morphology of the dunes and adjacent beaches, the study sites (Figure 5) were virtually integrated with the help of geographic information systems (GIS) using the software "QGIS". The needed data was retrieved using a LIDAR data set from 2011, which is interpolated with a raster resolution of one meter. The dataset is freely available and was provided by the Instituto Geográfico Português (IGP) - Direção Geral do Território (DGT).

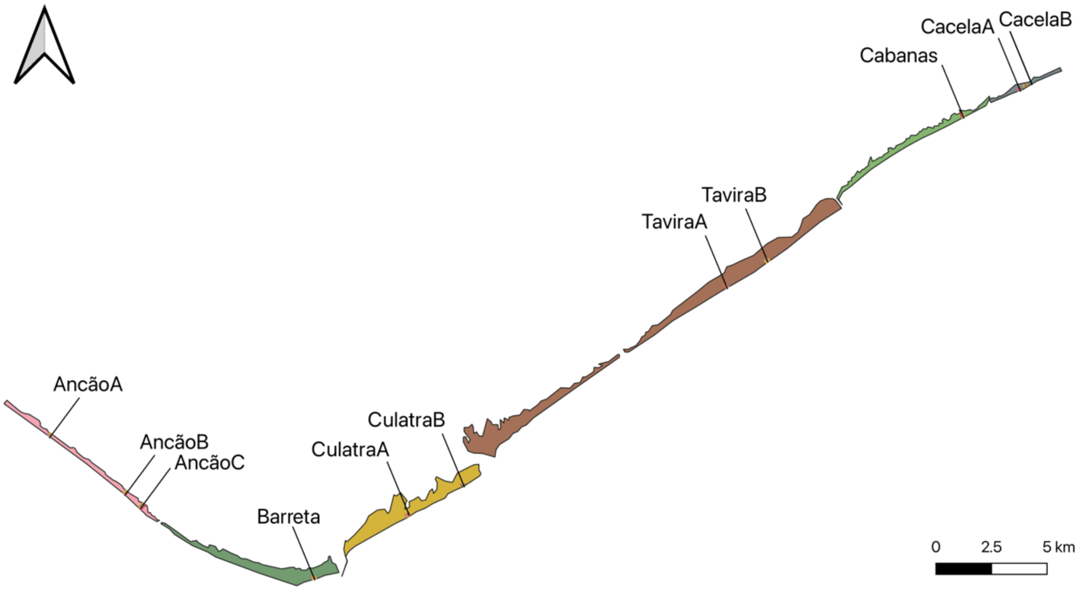


FIGURE 5 STUDY AREA - RIA FORMOSA LAGOON. THE BLACK BARS SIGNAL ALL TWELVE STUDY SITES. THE NAMES OF THESE ARE WRITTEN ABOVE THEM.

To analyze the morphological variability across different sites, a standardized procedure was employed for all profiles. A distance of 200m was deemed suitable to encompass significant variability in the dune landscape, allowing for the characterization of specific areas within the dune system. Initially, a line shapefile spanning a width of 200 meters was delineated parallel to the coastline. New profiles were then drawn at 20-meter intervals from the waterline to the landward boundary of the foredune, comprising cross-shore profiles oriented perpendicularly to the existing ones (Figure 6). They covered lengths ranging from approximately 100 to 200 meters, depending on the prevailing conditions. A total of 10 cross-sections were obtained within the 200-meter width. These additional shapefiles were used to extract individual cross-sections of the dunes from the LIDAR-data, enabling the identification of various characteristics at each study site. By systematically capturing data along the coastline at regular intervals, this approach provided comprehensive information for assessing the morphological variability of the dunes, which included: the points on the transects for the foreshore (in case it was surveyed by the LIDAR), the backshore, the dune stoss, the dune crest, and the dune lee, as well as the heights (m, above mean sea level) of the crest and dune toe.

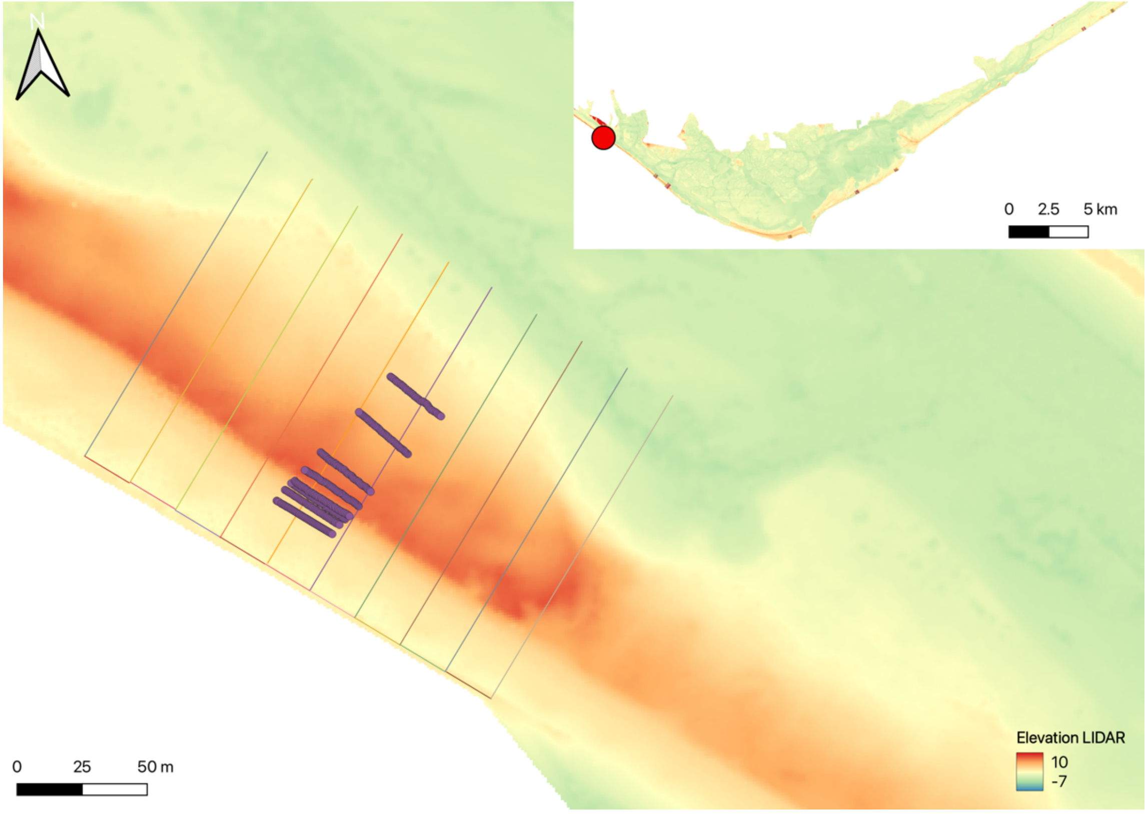


FIGURE 6 AERIAL VIEW CAPTURING THE 200-METER WIDE LINE SHAPEFILE PLUS PROFILES AT 20-METER INTERVALS, FACILITATING THE ANALYSIS OF DUNE MORPHOLOGY AND ADJACENT BEACHES USING GIS SOFTWARE "QGIS" WITH LIDAR DATA FROM 2011. THIS STUDY SITE IS THE FIRST ON THE ANCÃO PENINSULA AT THE WESTERNMOST POINT OF THE RIA FORMOSA (LOCATION MARKED AS RED DOT).

5.1.2. SHORELINE EVOLUTION

The investigation of shoreline evolution along the Ria Formosa island barrier system builds upon the work conducted by Kombiadou et al. (2019). Their study primarily examined long-term changes in shorelines across individual islands. Aerial photographs spanning from 1952 to 2014 were utilized for their analysis. However, to enhance the temporal scope and incorporate more recent data, the dataset has been expanded in this current study to include information up to 2018, extending the timeline to over 65. The orthophotographs used from 2018 were provided by the Direção Geral do Território (DGT). In order to maintain consistency and ensure the utilization of standardized methods throughout the dataset, the entire process underwent retracing. This encompassed digitization, mapping, and analysis procedures, which were applied anew to the 2018 dataset. For this purpose, two types of coastal indicators must be determined along the entire system. First, the debris line which marks the landward boundary of the debris deposits resulting from the upper reaches of the wave action. And the seaward vegetation limit which represents the first line of vegetation along the shoreline. By adhering to the same methodology for the entire dataset, the study ensures a seamless and coherent approach to examining shoreline evolution over time.

5.1.3. WIND AND WAVE DATA

Wind and wave data along the Iberian Peninsula can be accessed from the Spanish government website, Puertos del Estado. Navigating through the menu, you can find the oceanography tab, which provides access to historical data. To specifically examine the Ria Formosa, SIMAR points 5018021 and 5023022 were selected on the map (see Figure 7). These points capture data from the western starting side and the eastern end side of the area.

The historical data of the wave recordings were extracted. The data set contains hourly recordings over the period from January 1958 to July 2023. It contains data such as the significant wave height and mean and peak period as well as wind data on velocity and direction. The main objective of utilizing wind and wave data is to compare the magnitudes and directions of waves and winds along each flank of the Ria Formosa. This comparative analysis offers valuable insights into the spatial distribution of wave and wind patterns, enabling a comprehensive understanding of the coastal processes at play. By examining the wave and wind data from both the western starting side and the eastern end side of the area, it is possible to identify variations in wave and wind intensity, directionality, and potential impacts on the coastal landscape.

FIGURE 7 WIND AND WAVE DATA ACCESS POINTS ALONG THE IBERIAN PENINSULA AND THE RIA FORMOSA AREA WERE CHOSEN. SPECIFICALLY, SIMAR POINTS 5018021 (WESTERN) AND 5023022 (EASTERN) WERE SELECTED ON THE MAP, WITH 5018021 REPRESENTING THE WESTERN STARTING SIDE AND 5023022 REPRESENTING THE EASTERN END SIDE OF THE AREA (PUERTOS, 2023).

5.1.4. PLANT DISTRIBUTION

Field visits were carried out for plant mapping along most of the islands and peninsulas of the Ria Formosa. These took place in the April and May of 2023 (i.e., spring season). It is advisable to work with the classification of plants in the springtime, as the flowering of the plants makes the differentiation doable. The identification of vegetation was carried out during field visits and was supported by literature about the vegetation in the Ria Formosa lagoon (Costa et al., 1996), a smartphone application named "PlantNet", which makes it possible to distinguish between different plant species and the information available in the website Flora-on. Surveying each line involved utilizing GPS technology to obtain precise elevation and positioning data. To achieve this, a GPS/GNSS RTK system was employed, accessing information from the National Network of GNSS Permanent Stations (ReNEP). This public geo-positioning service is administered by DGT and served as a reliable data source.

The goal was to cover each island as comprehensively as possible. The selection of precise locations on the islands took into account estimates of representativeness of the geomorphological variability of the foredunes in the area of the Ria Formosa, as well as practical considerations for easy accessibility by foot or other means. Additionally, the presence of flora and fauna on the islands was carefully considered, ensuring minimal disturbance to breeding birds during data collection. Their final location was selected after carefully evaluating the dune morphology through field visits and aerial photographs.

To characterize the plants along the profiles, the standard line transect sampling method is employed using Cross-Shore Zonation Lines (CZLs). The number and positions of these lines are selected on-site to meaningfully characterize dune plant zonation. As illustrated in Figure 8, they extend approximately 25 m parallel to the shoreline and perpendicular to the profiles, with plant types counted every 50 cm within a 2.5 cm radius.

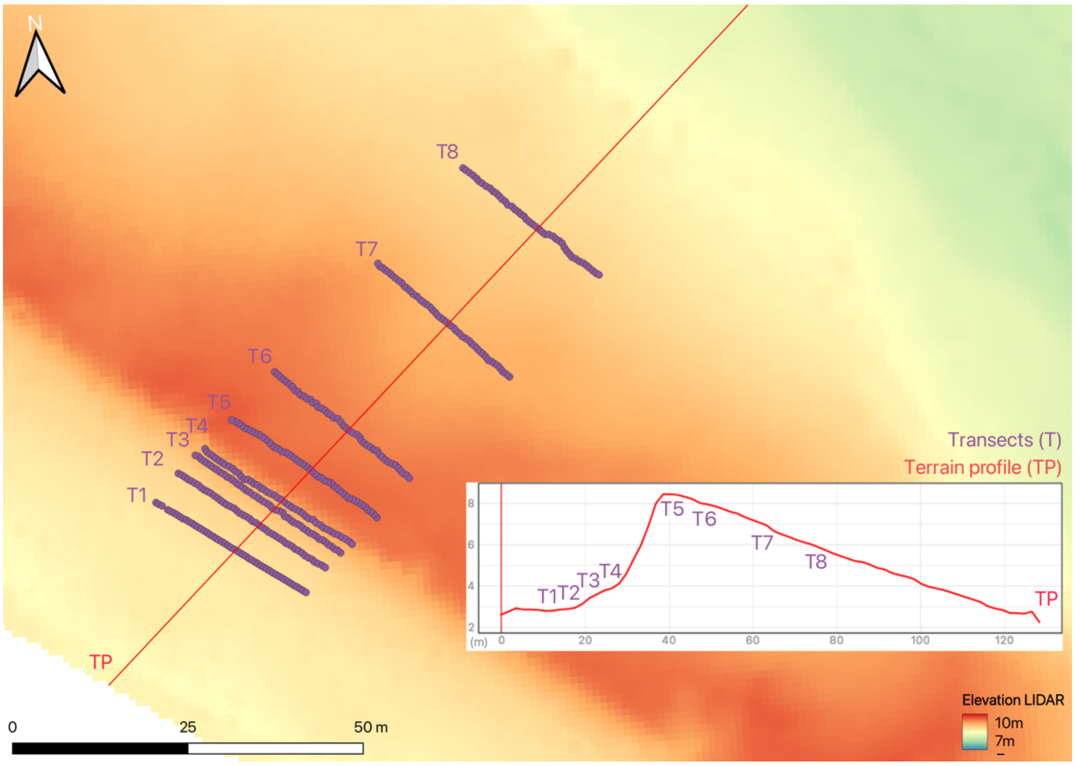


FIGURE 8 EXAMPLE FOR RECORDING OF THE CROSS-SHORE ZONATION LINES (CZLS) PERPENDICULAR TO THE FIRST PROFILE ON THE ANCÃO PENINSULA (SEE FIGURE 5), ALLOWING PLANT CHARACTERIZATION AT 50CM SPACES. THE REPRESENTATION IS MADE WITH THE GIS SOFTWARE "QGIS" AND LIDAR DATA FROM THE YEAR 2011.

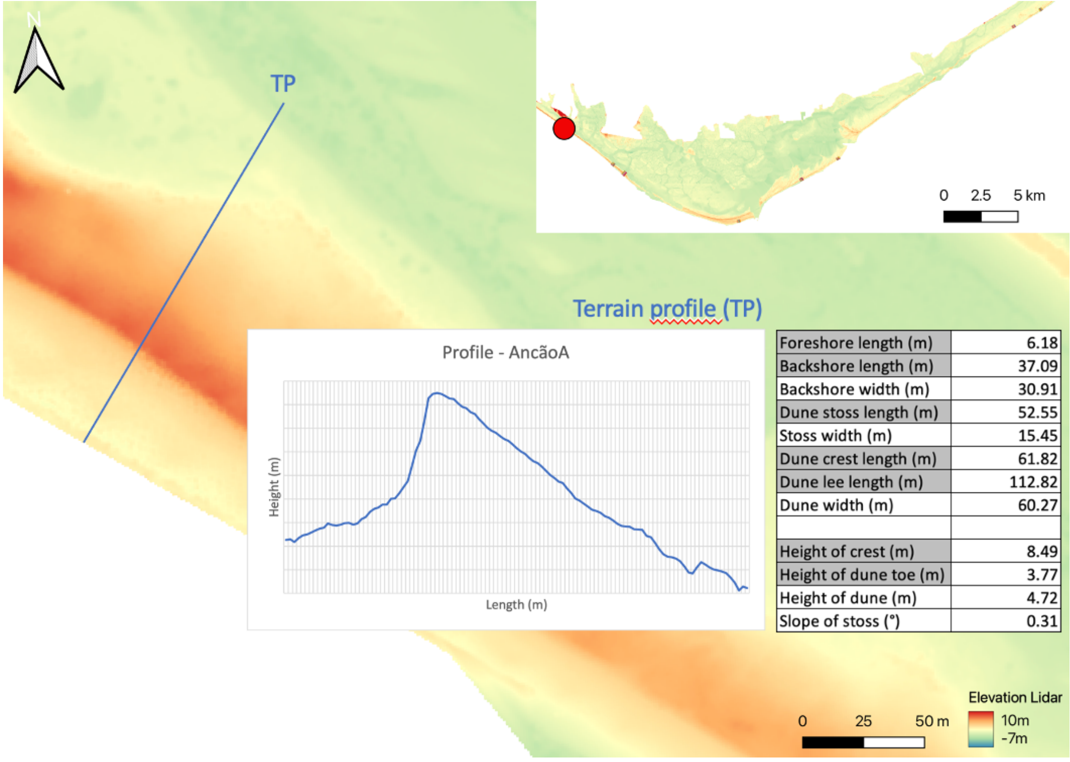
5.2 DATA PROCESSING

Data processing constitutes a vital step in uncovering the underlying patterns and relationships within the collected datasets. By applying analytical techniques and statistical methods, the processed data allows for the extraction of valuable insights and the identification of significant trends. The analysis encompasses various aspects, including morphological variability, alongshore variability, shoreline evolution, wind and wave conditions, and plant distribution, both cross-shore and alongshore. Through systematic data processing, the research aims to solve the dynamics and interdependencies among these factors, contributing to the understanding of the final configuration and plant distribution within the coastal system under study.

5.2.1. MORPHOLOGICAL VARIABILITY

Cross-shore variability

Calculations were conducted to measure the distances between specific points with a morphological meaning by simply subtracting one length measurement from another. For instance, to determine the backshore width, the foreshore length was subtracted from the backshore length. Similarly, the widths of the stoss and dune were calculated by applying the same principle of subtraction. Additionally, to ascertain the height of the dune, the height of the dune toe was subtracted from the height of the crest. Furthermore, the slope of the stoss was derived by dividing the stoss width by the height of the dune. These computations allowed for assessments of the various dimensions and characteristics of the dune system. Applying the same approach, data for the other nine cross-shore profiles per study site were determined and subsequently combined by calculating the averages for each specific parameter (Figure 9). This process ensured a comprehensive and representative overview of the studied parameters across the entire dataset.



Foreshore length (m)	6.18
Backshore length (m)	37.09
Backshore width (m)	30.91
Dune stoss length (m)	52.55
Stoss width (m)	15.45
Dune crest length (m)	61.82
Dune lee length (m)	112.82
Dune width (m)	60.27
Height of crest (m)	8.49
Height of dune toe (m)	3.77
Height of dune (m)	4.72
Slope of stoss (°)	0.31

FIGURE 9 PRESENTATION OF THE WORKING METHODOLOGY FOR CALCULATING THE CROSS-SHORE VARIABILITY. SHOWN IS THE AERIAL VIEW OF THE FIRST PROFILE ON THE ANCÃO PENINSULA AND THE CORRESPONIDNG TERRAIN PROFILE, USING GIS SOFTWARE "QGIS" AND LIDAR DATA FROM 2011. THE TABLE CONTAINS THE DECLARED LENGTH AND HEIGHT POINTS AS WELL AS ALL THE OTHER CALCULATED PARAMETERS.

Alongshore variability

Alongshore variability, within the context of coastal landscapes, refers to the fluctuations and distinctions observed in specific characteristics or features, such as dunes or vegetation, along the coastline. It encompasses the analysis of how these attributes change or vary in parallel or along to the shoreline. For this purpose, the distance from the starting point of the entire system to the end point of each individual island is plotted to show its variability along the system. By plotting the crest height against the corresponding distance values, one can effectively illustrate the alongshore variability of dune crest elevation. Similarly, the same procedure is applied to assess the alongshore variability of other parameters: the height of the dune and dune toe, the width of the backshore, stoss, and dune, as well as the slope of the stoss.

In this context, it is crucial to outline the process of aligning the longshore variability of each parameter with a linear trend line to explore potential associations with the alongshore distance. Furthermore, a regression analysis was undertaken to investigate the patterns of longshore variability and their correlation with the alongshore distance. These actions were instigated by noticeable trends in certain parameters with respect to the longshore distance. To assess the statistical significance of these correlations, the p-value was computed using the data analysis tool, providing precise insights into the statistical significance of the observed relationships. For the majority of the relationships, with p-values below 5%, there is compelling evidence to suggest statistically significant associations or trends between the variables.

5.2.2. SHORELINE EVOLUTION

To analyze and assess shoreline evolution trends, the "ArcGIS" software, incorporating the digital shoreline analysis system (DSAS) extension tool (Himmelstoss et al., 2018), was utilized. The seaward vegetation limit was mapped and saved as shapefiles for each individual island along the entire system in order to add this new line to the temporal dataset provided by Kombiadou et al. (2019). Similarly, debris lines, as described by Boak & Turner (2005), were also mapped as indicator of the position of the shoreline depicted by the higher water lines. After generating the necessary shapefiles for the year 2018, they were consolidated into a single geodatabase, integrating them with shapefiles from other years. This merging process was conducted separately for the debris line and the seaward vegetation limit. A baseline was established using the DSAS to create transects along the coast with an internal spacing of 25 meters. Subsequently, the DSAS, was employed to calculate the evolution trends of the coastline between 1942 and 2018. This application works by comparing the distances of the respective year to a baseline and allows later calculations to determine the changes in the coastline in the next step of the analysis. In order to assess the evolution of the coastline, a systematic approach was employed. At each study site, corresponding to the coordinates of the already selected study sites (Figure 5), three neighbouring profiles were selected and the corresponding data sets extracted. Three transects were selected to cover as wide a range of evolutions as possible. They are spaced 25 meters apart and a 200-meter coastal transect is observed. The datasets contain the distances of the individual shorelines to the baseline. To be able to precisely describe the evolution of the individual profiles, the individual distances are subtracted from the first year of their recording. By plotting these distance values and years against each other, significant patterns in the evolution of the shoreline were revealed, providing insights into its dynamic changes over time. To ensure the accuracy of the Data, consideration was given to minimize the potential impact of outliers. To achieve this, an average of the evolution values was computed from the three selected profiles, resulting in a more reliable representation of the overall shoreline development. For the profile in CacelaB the same methodology was used as in Google Earth Pro, as it was located outside the limits of the data provided by DGT.

Digitization errors in this study could pertain to inaccuracies introduced when converting analog maps and photographs into digital format. They can result from issues like low resolution, georeferencing mistakes, human errors during manual tracing, and precision limitations in digitization software (Kombiadou et al., 2018).

5.2.3. WIND AND WAVE DATA

The wind and wave data analysis aims to investigate and compare the general wind-wave conditions along the eastern and western flank of the Ria Formosa. The main objective is to identify potential differences in wind and wave patterns between the two sides. To begin, the prevailing wind and wave direction at each location were determined. The data sets were processed using Excel, and the directions were subdivided into north, east, south, west, northeast, southeast, southwest, and northwest based on their degrees: North (N): 337.5° to 22.5°; Northeast (NE): 22.5° to 67.5°; East (E): 67.5° to 112.5°; Southeast (SE): 112.5° to 157.5°; South (S): 157.5° to 202.5°; Southwest (SW): 202.5° to 247.5°; West (W): 247.5° to 292.5°; Northwest (NW): 292.5° to 337.5°.

The pivot table is a tool in Excel to summarise large amounts of data. Herewith it was possible to identify the individual counts of occurrences, enabling a comprehensive understanding and comparison of the percentage distribution of the respective wind and wave directions. In order to illustrate the values in a suitable form, a detailed analysis of the significant wave heights and wind speeds on both flanks was carried out. A wave rose and wind rose diagram was chosen for the presentation. The website of the Spanish state enterprise "Puertos del

Estado" provides an "Interactive Analysis" tool under the tab "Access to data", with which one can evaluate the respective data sets. The tool offers the possibility of specifying various factors. In the case of both data sets for wind and waves, the cardinal directions were limited to eight (N ,NE, E, SE,...), the period was set to "Global" instead of "Seasonal" or "Monthly" and the time span was selected from 1958 to 2023. In the case of significant wave height (m), it was decided to divide the data into five segments (from one to five metres), as the wave height does not usually exceed the four metre mark. The rose of mean wind speed (m/s) was displayed under the "Delta" tab at intervals of three metres per second. Data points with exceptionally low wave heights and wind speeds were automatically excluded from the analysis. In the case of wave heights, measurements below 0.2 meters were categorized as negligible wave activity. And winds below the speeds of 1 metre per second were considered negligible wind activity. In context, these negligible values were called “calms”.

It is important to mention, however, that the wind speeds were evaluated separately. Since the grain sizes on the different sides of the system differ from each other (Costas et al. 2020), the threshold velocities for setting a grain of sand in motion also differ. In the case of wind speeds for the western part of the island, a threshold of 9 meters per second was adopted, aligning with the findings of Costas et al. from 2020.

The threshold velocity (υ_t) for aeolian sediment transport on the eastern side of the Ria Formosa was estimated using a transport limiting approach based on the aeolian sediment transport model developed by Bagnold (1936). The threshold velocity was calculated for a grain size (D) of 0.3 mm, representing the mean grain size of the sediment in the eastern part of the study area. The calculation was performed using the following parameters, based on the evaluation of the critical shear velocity from the work of Costas et al. from 2020.:

- Roughness length of the surface (z_0) = 10 m
- Prandtl-Von Karman constant (k) ≈ 0.4
- Air density (ρ_a) = 1.225 kg/m^3
- Gravitational constant (g) = 9.81 m/s^2
- Mean grain size of a standard sand (D_{ref}) = 0.00025 m
- Constant (A) = 0.085
- Sediment density (ρ_p) = 2.65 g/cm^3 (quartz)

$$\upsilon_t = A\sqrt{g \cdot D \cdot \frac{\rho_p - \rho_a}{\rho_a}}$$

By substituting the values, the estimated threshold velocity for a 0.3 mm grain size in the study area is approximately 7.12 m/s.

5.2.4. PLANT DISTRIBUTION

The collected data was introduced in Excel sheets to prepare it for description and analysis. The main objective was to to know how the plant species varied across the dune and along the system and if these species were the same or not. To find out, it was necessary to analyse the number of plant species within different Cross-Shore Zonation Lines (CZLs). The initial stage encompassed the development of a table for documenting individual plant species along with their corresponding counts, utilizing data collected during the fieldwork.

The plants found were classified into different functional types based on the terminology proposed by García-Mora et al. (1999). Type 1 represented winter annuals of moderate size with soft leaves, lacking specific adaptations to the dune environment. Type 2 primarily consisted of perennials with a below-ground spreading root network and leaves that were adapted to withstand coastal environmental stress. Type 3 encompassed perennial or summer annual plants that were capable of dispersal by sea-water and could endure sand burial. To gain a comprehensive understanding of plant distribution, the analysis initiated by examining the total number of plant species present, which were subsequently classified into distinct plant types.

In addition, the recorded cross shore zonation lines (CZLs) were categorised in which specific zone they were located within the dunes (incipient foredune, slope, crest, lee). In certain cases, several CZLs were located in the same zone of the dune, so in some cases the data from several CZLs within the same zone were combined for a more comprehensive assessment. With this extensive dataset it was possible to analyse the spatial distribution of vegetation along the transects. The number of species, as well as the species composition and abundance, were examined across the dune, from the incipient dune/stoss slope to the lee.

The statistical software "PAST4" was utilized for further statistical analysis, namely to explore differences in the plant composition across profiles and along the system. PAST4 is an open-source software freely available for use. Among the various analysis options, the Detrended Correspondence Analysis (DCA) method was chosen as a suitable approach. DCA is a method of arranging samples in the ordination space (Gauch, 1982) to reflect the dissimilarities in their species composition through the distances between them. During this process, rare species were not given less weight or significance. This means that the presence and abundance of each species, regardless of its frequency of occurrence, were considered equally important when examining species composition and their contribution to the observed shoreline variability. Because even fewer common species could potentially reveal meaningful ecological patterns or relationships with other variables. To perform the Detrended Correspondence Analysis (DCA), the data encompassing plant species occurrences within transects of identical zones was systematically organized. These zones included the incipient foredune, slope stoss, dune crest, and lee areas (as detailed in section 3.1). Moreover, the abundance of each plant species within its corresponding zone was computed (see Appendix A). These values were subsequently integrated into the software for comprehensive evaluation and analysis.

6. RESULTS

6.1 MORPHOLOGICAL VARIABILITY

This section delves into the distinct dune profiles of the Ria Formosa, spanning from the western sector, encompassing AncãoA, AncãoB, AncãoC, and Barreta, to the eastern sector, which includes CulatraA, CulatraB, TaviraA, TaviraB, Cabanas, CacelaA, and CacelaB. These profiles exhibit unique characteristics that will help to understand the dynamics within this coastal environment. Throughout this section, detailed morphological description of each profile is provided, followed by an overview of alongshore variability in the closing segment. Table 1 lists the morphological characterisation of each of the aforementioned profiles. Starting with the distance to the beginning of the Ria Formosa, the height of the crest, the dune, and the dune toe as well as the width of the backshore, stoss, dune, and the stoss slope. Another evaluation of the profiles is that of the evolution rates in meters per year. These are explained in more detail in the following chapter (6.2). Also, the peninsula has been significantly influenced by fishing communities. To ensure unbiased data, the profiles were deliberately located away from any urbanised areas.

TABLE 1 MORPHOLOGICAL CHARACTERISATION ALONG THE RIA FORMOSA COAST.

Island	distance (m)	height crest (m)	height dune (m)	height toe (m)	width backshore (m)	width stoss (m)	width dune (m)	slope stoss	Evolution (m/yr)
AncãoA	2612	8.58	4.84	3.73	22.87	14.06	61.05	0.35	-0.12
AncãoB	6947	6.91	3.25	3.66	30.18	34.08	56.80	0.10	0.11
AncãoC	7925	7.16	3.28	3.89	29.77	92.58	44.34	0.04	0.95
Barreta	16308	5.55	2.16	3.39	48.01	38.62	53.75	0.06	4.42
CulatraA	21616	5.38	1.78	3.59	31.81	13.33	57.92	0.15	0.24
CulatraB	24619	3.30	0.73	2.57	31.38	16.35	22.78	0.06	9.99
CulatraC	25286								29.19
TaviraA	39297	4.44	2.13	2.31	35.56	7.47	56.06	0.30	-1.06
TaviraB	41432	6.02	3.23	2.79	43.32	21.66	41.97	0.30	-0.05
Cabanas	52482	1.71	0.15	1.56	7.80	6.40	18.08	0.04	-5.45
CacelaA	55227	4.72	1.99	2.74	20.61	27.34	28.46	0.07	1.02
CacelaB	55482	4.30	1.57	2.73	28.69	11.60	32.41	0.16	-0.41
MEAN		5.28	2.28	3.00	30.00	25.77	43.06	0.15	3.57

The initial data collection focused on studying the morphological variability of the Ancão Peninsula. Three profiles were strategically chosen, covering different sectors of the island: West (AncãoA), central (AncãoB), and east (AncãoC). Similar to Costas et al. (2023), the peninsula was practically divided into these distinct sectors (Figure 10).

The dune toe height is consistent at around four meters across all profiles of the peninsula. However, the dune crest height of the western profile stands out, surpassing the other two profiles by approximately 1.5 meters (Table 1). The same applies to the height of the dune in general, as it is the difference between the height of the crest minus the dune toe. It is worth noticing, that these heights are very high, looking at other values. AncãoB and AncãoC share similarly wide backshore widths of around 30 meters, AncãoA is just under 23 meters. All the dunes displayed relatively wide widths, ranging from the west to the east from 61 to 44 meters. There are significant differences in the width of the stoss and the associated slope. Whereas the profile on the westernmost side has a short width and a strong slope, the slope becomes wider along the peninsula and decreases in inclination. Especially in the profile of AncãoC there is a very wide stoss of 93 meters (Table 1).

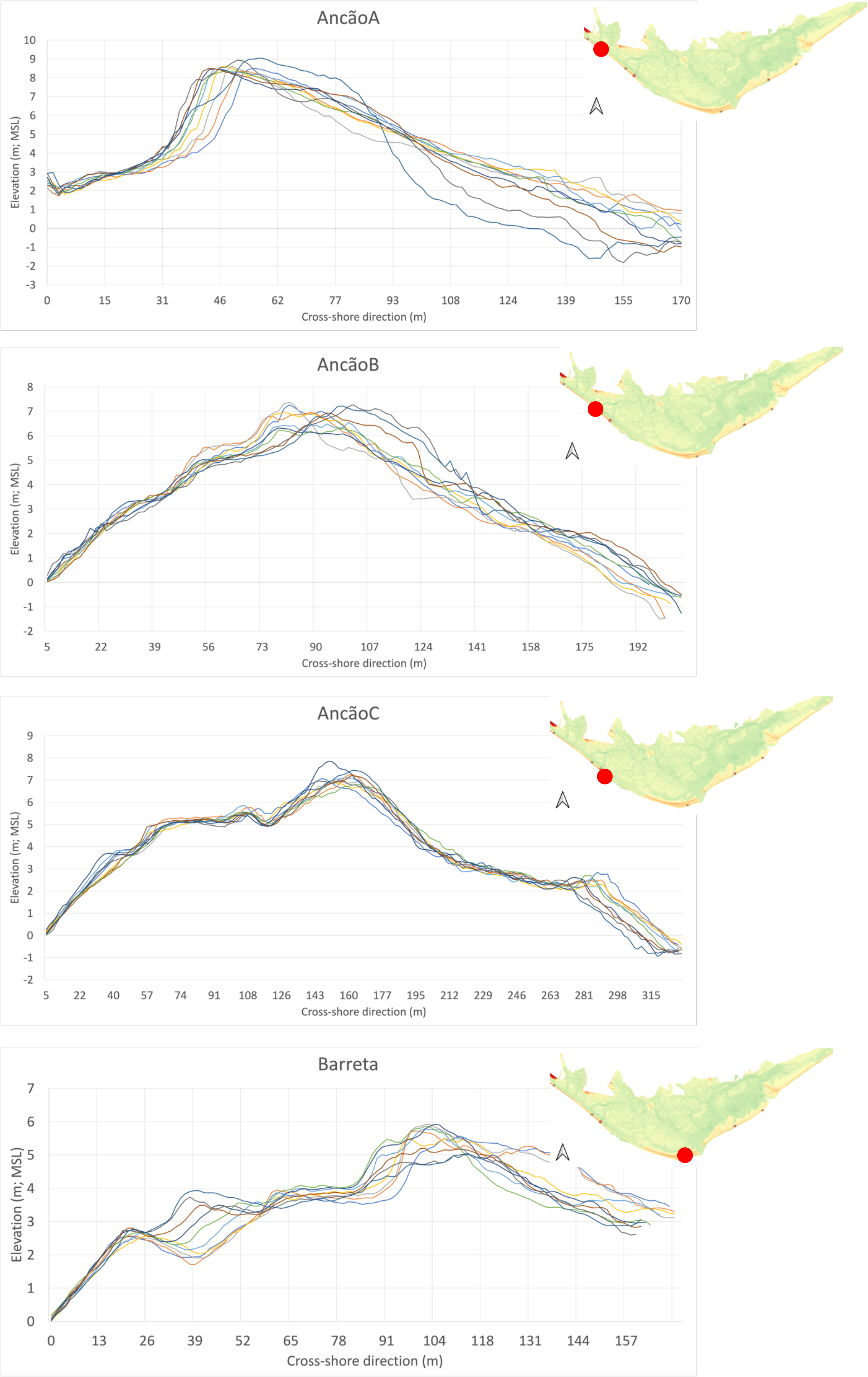


FIGURE 10 CROSS-SHORE PROFILES ALONG THE WESTERN SIDE OF THE RIA FORMOSA. THE TOP CORNER DISPLAYS THE LOCATION IN THE MAP WITH A RED DOT, WHILE THE BOTTOM PLOT SHOWS THE CORRESPONDING CROSS-SECTIONAL PROFILES. MSL STANDS FOR MEAN SEA LEVEL.

The subsequent profile towards the east was taken from Barreta Island, which acts as a dividing point between the eastern and western sections of the Ria Formosa. Despite most of the island being on the western side, the profile was positioned closer to the eastern side, but in this work, the profile is presented as the profile in the central area. The dune crest height is almost six meters, but since the dune toe sits at a similar height to the profiles in Ancão, the height of the dune is measuring just under 2.2 meters. Notably, the backshore (beach) width is quite wide with around 53 meters. The dune stoss is also relatively broad, and due to the moderate height dune, the slope of the stoss is notably gentle (Table 1). In this profile, only the first foredune was mapped, not the entire dune system, which here is rather wide and presents several former foredune ridges. The beach of this profile is very steep and typically features prominent beach berms, suggesting a highly dynamic area (Figure 10).

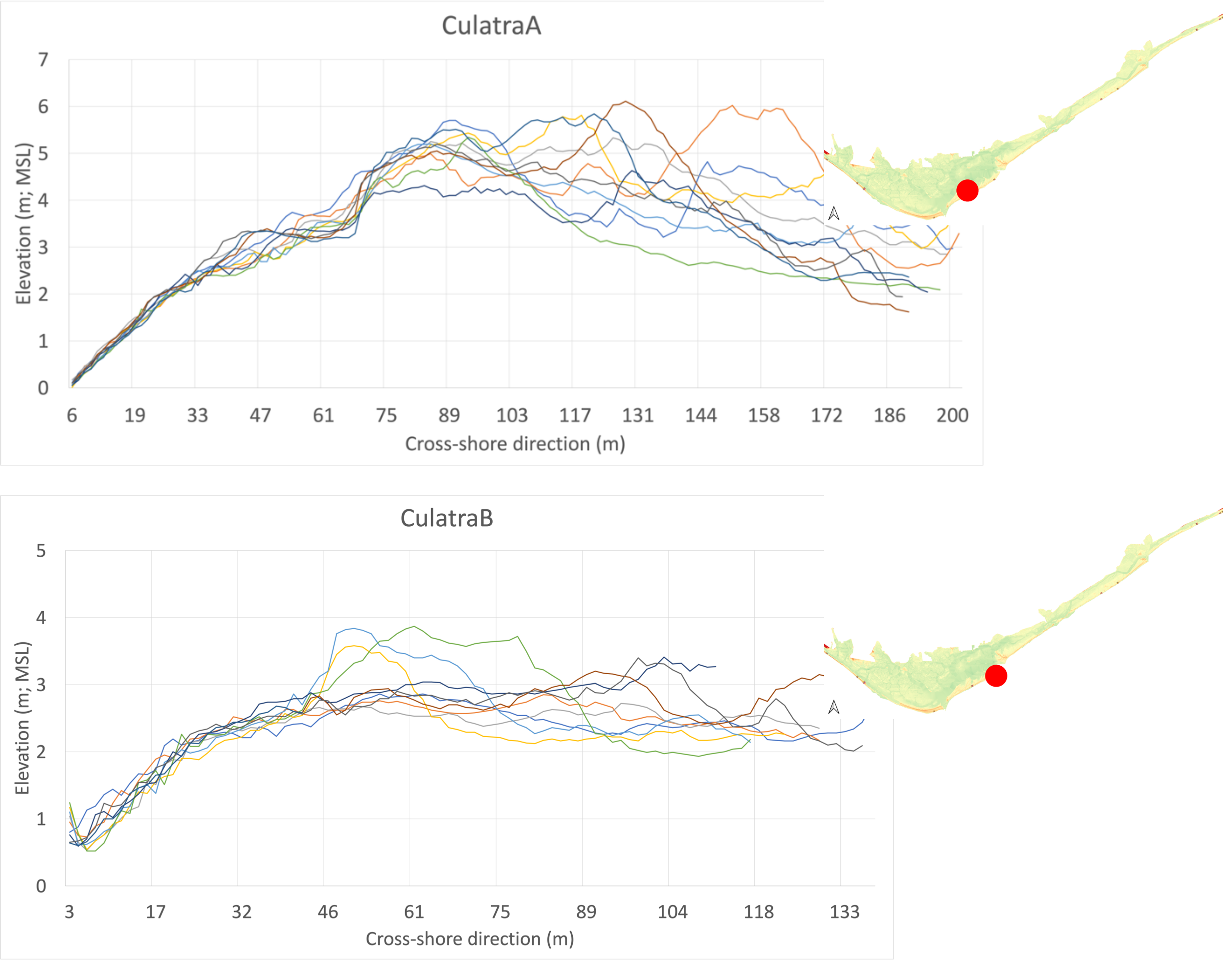


FIGURE 11 CROSS-SHORE PROFILES REPRESENTING THE TRANSECTS OF THE ISLAND OF CULATRA IN THE EASTERN SIDE OF THE RIA FORMOSA. THE TOP CORNER DISPLAYS THE LOCATION IN THE MAP, WHILE THE BOTTOM SECTION SHOWS THE CORRESPONDING CROSS-SECTIONAL PROFILES.

Profiles in the island of Culatra exhibited remarkable variations in dune morphology. It is noteworthy that there is considerable variability, particularly within each site on the island. For instance, the various profiles in CulatraA (Figure 11) illustrate that dune crest heights can differ by as much as 1.5 meters. This internal variability is quite significant, given that the different profiles are measured within a mere 200-meter span. CulatraA, situated at the westernmost point of the island, showcased higher dune crest heights, a taller dune, and a higher dune toe compared to CulatraB. The backshore widths for both CulatraA and CulatraB measured around 32 meters, reflecting an average value in comparison to all the other profiles. CulatraB presented a broader stoss width than CulatraA, contributing to a flatter stoss slope (Table 1). Notably, the height of the dunes played a pivotal role in distinguishing these profiles, as evident from our field visits. CulatraB and CulatraC featured much smaller and younger dunes in comparison. CulatraC, identified as the "twelfth profile," is not discussed further in the context of morphological variability due to the unavailability of a current LIDAR dataset for mapping the current morphology. At the time the data was collected in 2011, the CulatraC-part did not exist as part of the island.

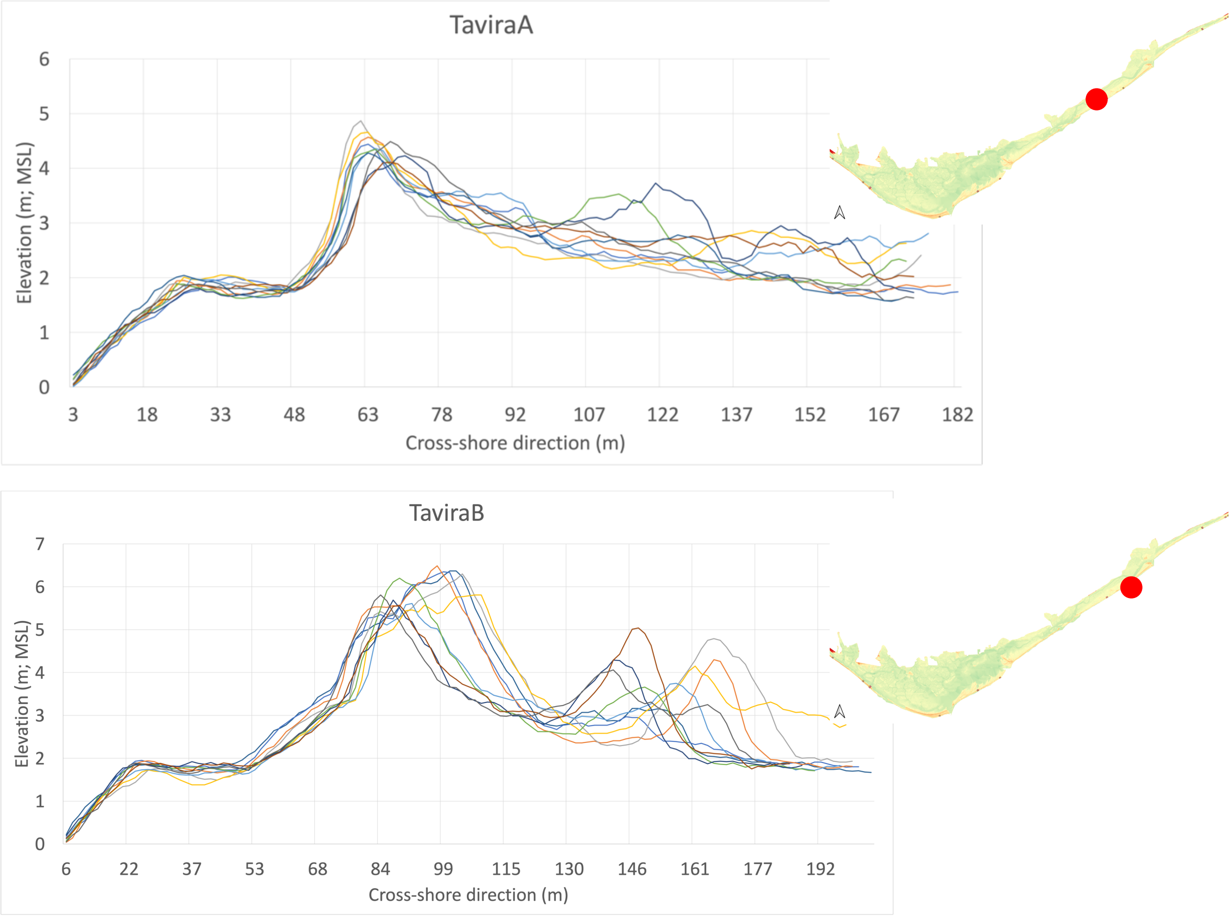


FIGURE 12 CROSS-SHORE PROFILES REPRESENTING THE TRANSECTS OF THE ISLAND OF TAVIRA IN THE EASTERN SIDE OF THE RIA FORMOSA. THE TOP CORNER DISPLAYS THE LOCATION IN THE MAP, WHILE THE BOTTOM SECTION SHOWS THE CORRESPONDING CROSS-SECTIONAL PROFILES.

Tavira Island showcased two distinct profiles, TaviraA and TaviraB. In comparison to Culatra, the profiles appear relatively homogeneous when considering the first foredune (Figure 12). The dune toes in both TaviraA and TaviraB are situated at approximately the same height. However, a significant disparity arises when examining the crest height, with TaviraB towering over TaviraA. Standing at over 6 meters, the crest height in TaviraB surpasses TaviraA by 1.5 meters, resulting in an overall taller dune. Furthermore, both backshore widths are relatively wide, with TaviraB exhibiting a notably larger dry beach. Similarly, the stoss width is wider in TaviraB, although this difference is balanced by the corresponding difference in dune height, as both profiles share the same values for the dune stoss slope (Table 1). Additionally, TaviraA showcases a more extended first dune ridge, which, as depicted in Figure 12, gently levels out towards the rear.

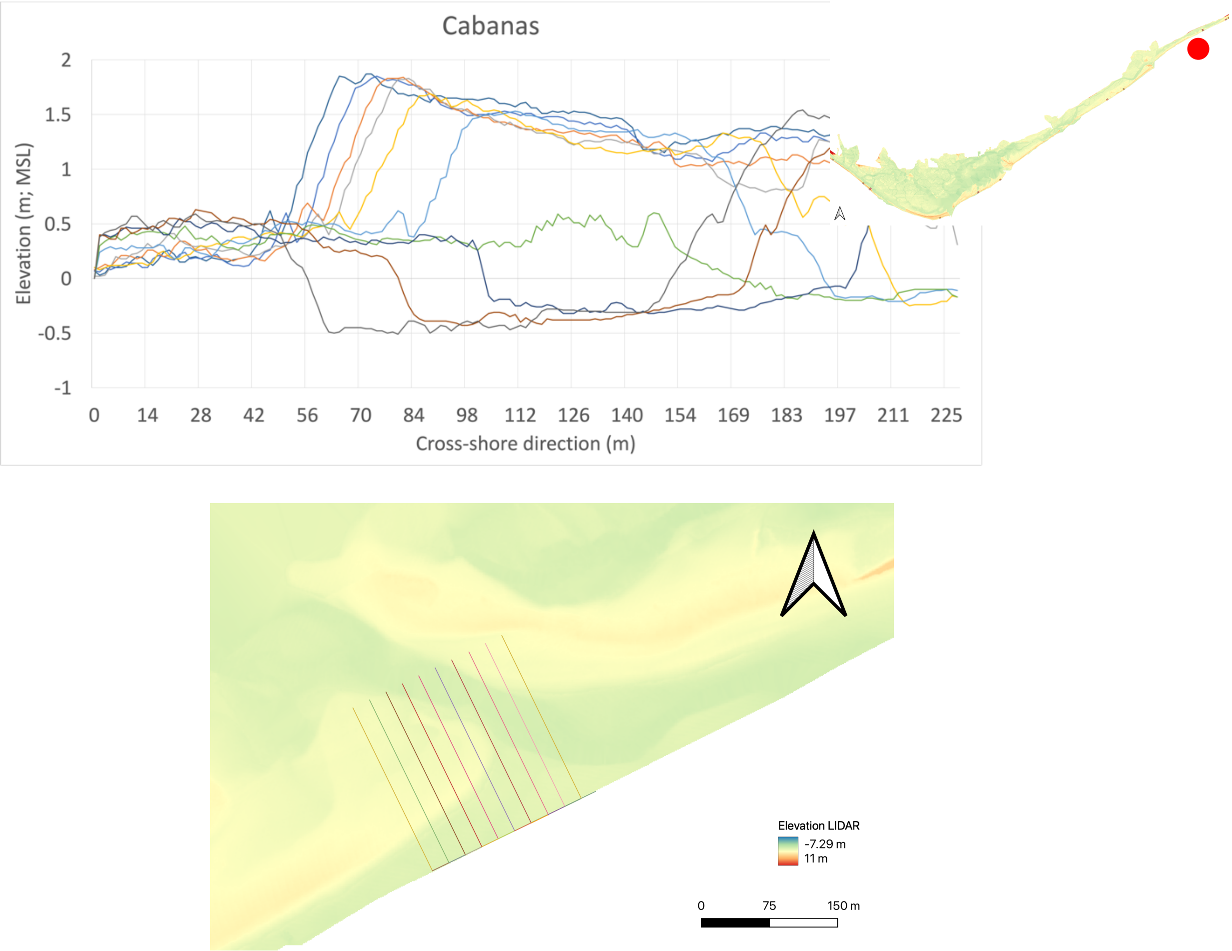


FIGURE 13 CROSS-SHORE PROFILES REPRESENTING THE TRANSECTS OF THE ISLAND OF CABANAS IN THE EASTERN SIDE OF THE RIA FORMOSA. THE TOP CORNER DISPLAYS THE LOCATION IN THE MAP, WHILE THE BOTTOM SECTION SHOWS THE CORRESPONDING CROSS-SECTIONAL PROFILES. ADDITIONALLY, A SECTION OF THE ENTIRE PROFILE FROM THE 2011 LIDAR RECORDING IS PLACED.

Moving further east, the profile of Cabanas Island (Figure 13), located at a distance of approximately 42 kilometers, presented the lowest dune crest height of 0.15 meters and dune height in the study area. The dune toe in Cabanas measured at 1.71 meters, and the backshore width extended around 7.8 meters. The stoss width of the dune was 6.40 meters, resulting in a flat slope stoss for this profile (Table 1). As seen in Figure 13, it is evident that not all transects could be included in this profile due to the absence of visible dunes. This can be attributed to significant spatial variability within the analyzed section, which, in certain areas, likely experienced overwash and the presence of small backbarrier channels.

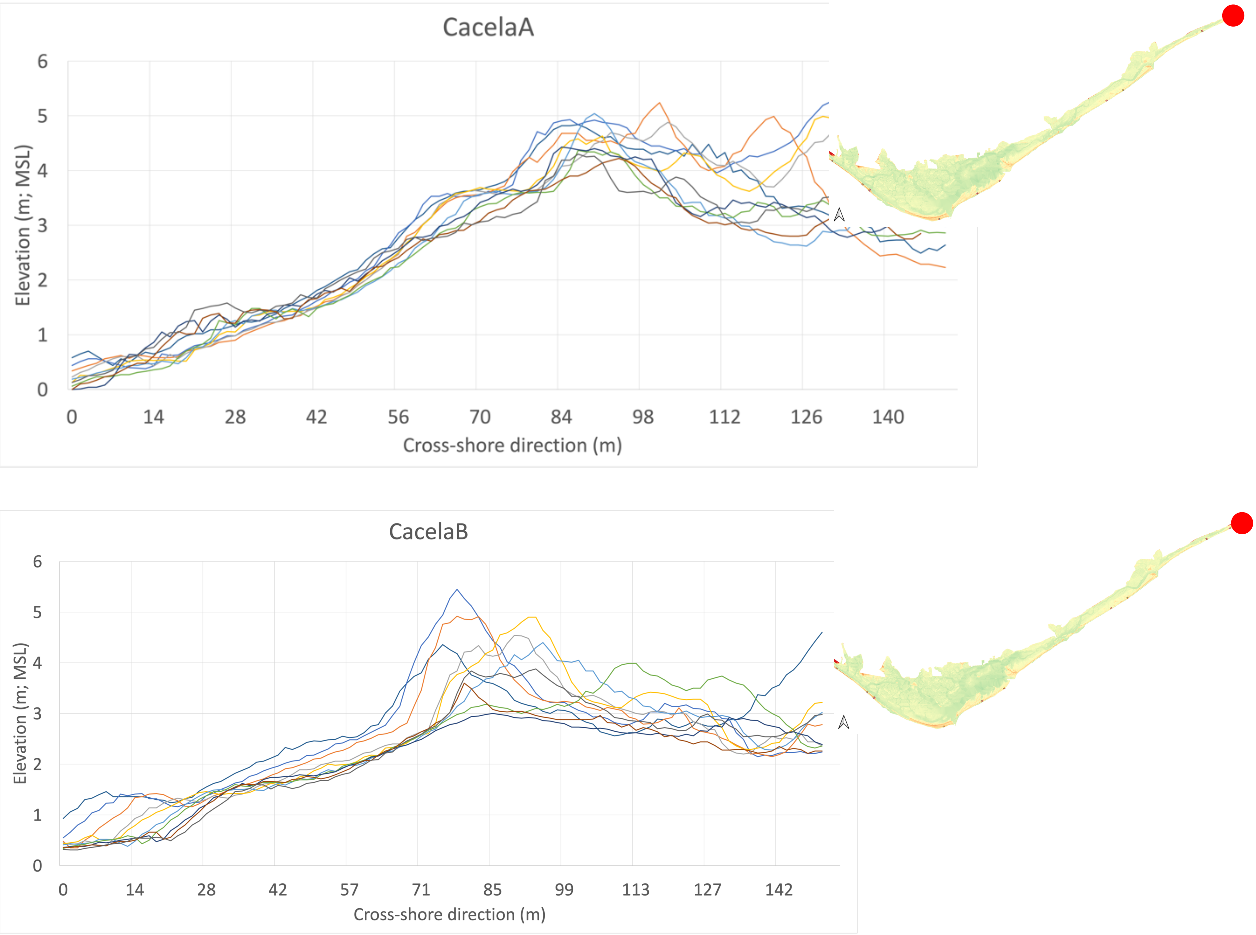
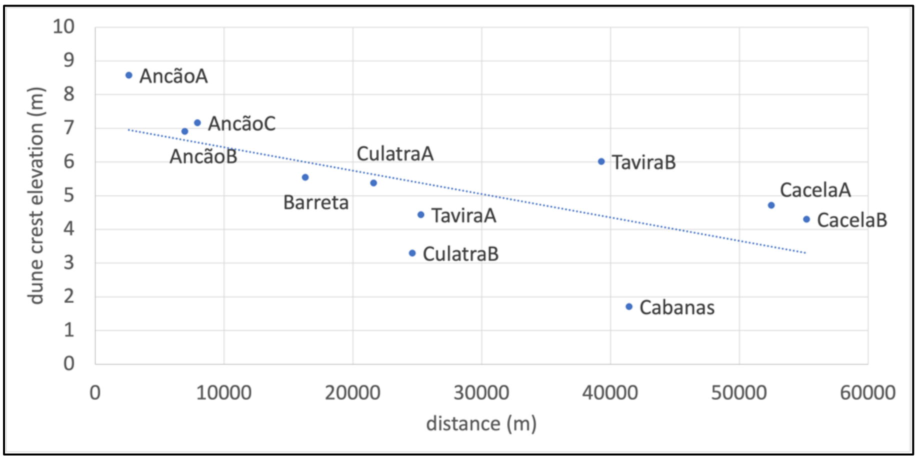


FIGURE 14 CROSS-SHORE PROFILES REPRESENTING THE TRANSECTS OF THE PENINSULA OF CACELA AND CABANAS ISLAND IN THE EASTERN SIDE OF THE RIA FORMOSA. THE TOP CORNER DISPLAYS THE LOCATION IN THE MAP, WHILE THE BOTTOM SECTION SHOWS THE CORRESPONDING CROSS-SECTIONAL PROFILES.

Lastly, the Cacela Peninsula featured two profiles, CacelaA and CacelaB. Both profiles share similar characteristics with the dune toe at the same elevation, and their dune crests are nearly at the same height. CacelaA's dune reaches a height of almost two meters, while the dune of CacelaB stands at approximately 1.6 meters in height. As illustrated in Figure 14, the dune stoss of CacelaA extends over a longer distance, resulting in a smoother slope incline. In terms of width, both dunes are quite comparable, measuring around 30 meters on average, indicating a moderate width. Notably, both profiles exhibit significant variability along their length.

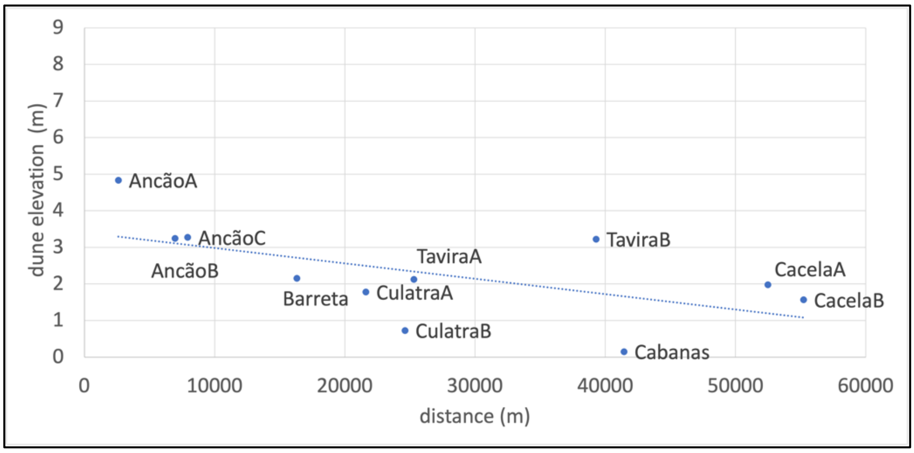
In analysing the alongshore variability, it was observed that the study area exhibits significant spatial variations along the entire coastline (Figure 15). The dune system displayed distinct variables, particularly in terms of dune width, height, and slope. In the western and central sectors, represented by the profiles AncãoA, AncãoB, AncãoC, and Barreta, the dunes consistently demonstrated greater heights, reaching nearly 5 meters, and showcased broader dune formations. The stoss width values here are also marginally greater. Moreover, the dune toe elevation distinctly indicates a decreasing trend towards the eastern part, with profiles in the western sector generally positioned at least one meter higher than those in the east. Relatively constant remained backshore width along the profiles, which gives similar values along the Ria Formosa. In general, however, they are a little wider in the eastern part. In this sector, represented by CulatraA, CulatraB, TaviraA, TaviraB, Cabanas, CacelaA, and CacelaB, the dunes displayed lower heights ranging from 0.15 to 3.59 meters. The dunes were relatively narrower but have in general steeper stoss slopes. In the analysis of the alongshore variability, the evolution of the coastline was also considered. The results of this analysis are presented in the next chapter (6.2).



$R^2 = 0.44$

p-value = 0.0014

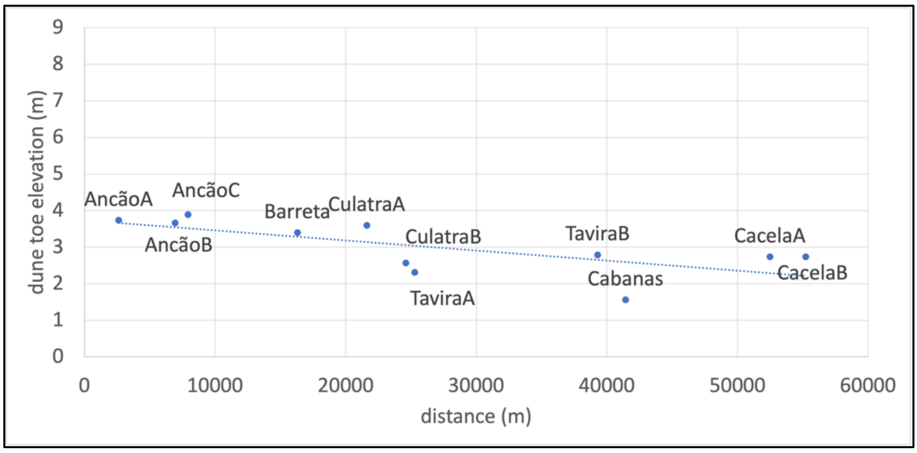
y = -7E-05x + 7.136



$R^2 = 0.34$

p-value = 0.0012

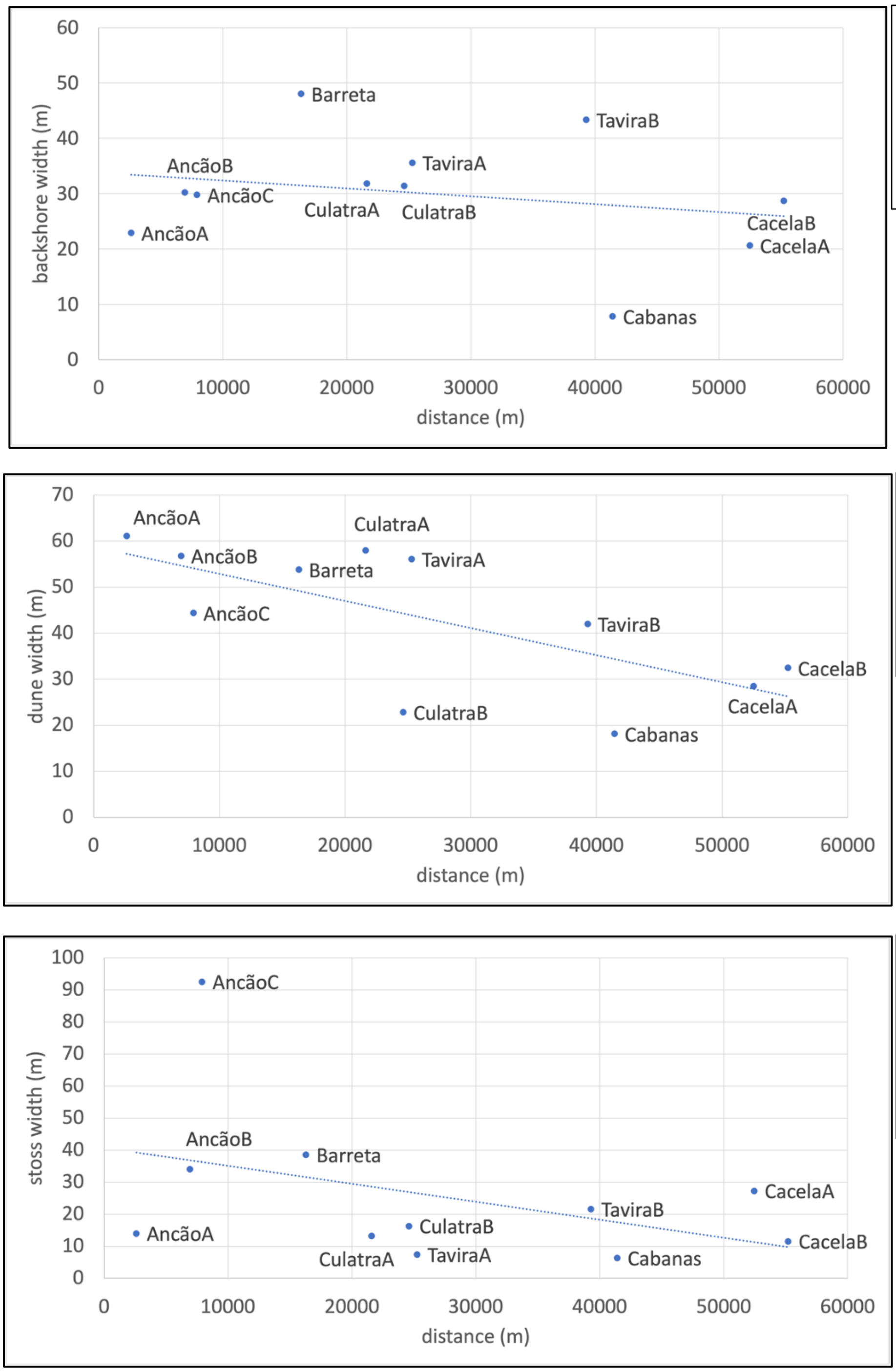
y = -4E-05x + 3.4059



$R^2 = 0.48$

p-value = 0.0021

y = -4E-05x + 3.4059



$R^2 = 0.05$

p-value = 0.0512

y = -0.0001x + 33.81

$R^2 = 0.48$

p-value = 0.0009

y = -0.0006x + 58.78

$R^2 = 0.17$

p-value = 0.0016

y = -0.0006x + 40.76

FIGURE 15 ALONGSHORE VARIABILITY IN ALL PROFILES ALONG THE RIA FORMOSA.

The longshore variability provides a visual representation of the spatial distribution of the results and any potential alongshore trends. Notably, the backshore width does not display a clear pattern, as indicated by the p-value. It remains rather homogeneous within the western part and shows greater variability in Barreta, TaviraB, and Cabanas. The values appear to be more randomly distributed throughout the system. However, excluding Cabanas, where the measurements are not very accurate, would reveal a clearer trend. In contrast, the remaining correlations exhibit clear trends, with one exception – the stoss shore width, where AncãoC stands out as an outlier.

The interpretation of these correlations gains support from the calculated p-values, affirming that, overall, all parameters exhibit a decrease in that direction. Consequently, consistent negative slopes are observed for these trends, indicating an inverse correlation between the parameters characterizing the dune and the distance along the system. An exception arises in the case of backshore width, where the evidence, although not meeting the criteria for a statistically significant relationship, suggests a decreasing trend.

6.2 SHORELINE EVOLUTION

Two types of coastline indicators have been identified along the entire system. Just as in the work by Kombiadou et al. (2019), the data set was supplemented by the same work for the year 2018. The shoreline of the Ria Formosa is examined systematically, progressing from east to west. Initially, this evaluation assesses the shoreline stability of each individual island, followed by an exploration of shoreline trends. Subsequently, these trends are integrated into a comprehensive system graph, illustrating the corresponding variability along the entire system. In addition, a graph of evolution trends is also shown along the system. Finally, a streamlined representation of the same trend is presented for the second coastal indicator.

The profiles on the Ancão Peninsula demonstrate relatively stable shoreline evolution. Particularly, the AncãoA profile has exhibited remarkable stability over the years. From 1958 to 1968, there is a notable increase, which subsequently normalizes over the next three decades and even experiences a slight decrease. By 2008, another increase is observed, following a similar pattern from the outset (Figure 16). This results in an overall slightly negative trend of approximately twelve centimeters per year, as detailed in Table 1. It is essential to clarify that this trend indicates the direction of development rather than suggesting an average annual shoreline reduction of twelve centimeters. Instead, it serves as a guiding reference for forecasting purposes. The closer individual values align with this trend line, the more accurately they reflect the actual evolution. Conversely, the AncãoB profile displays a pronounced decrease from 1952 to 1958, followed by a relatively stable period with minimal deviations until 2005. Afterward, a gradual decrease occurs, with exceptions in certain years, such as 2008, which could potentially stem from data analysis errors (Figure 16). Although the trend value is close to zero, it slightly leans toward the positive range, indicating non-linear evolution with occasional outliers (Table 1). Lastly, the last profile on the peninsula exhibits a notably more stable evolution with a stronger positive value, suggesting an average increase of nearly one meter per year (Figure 16).

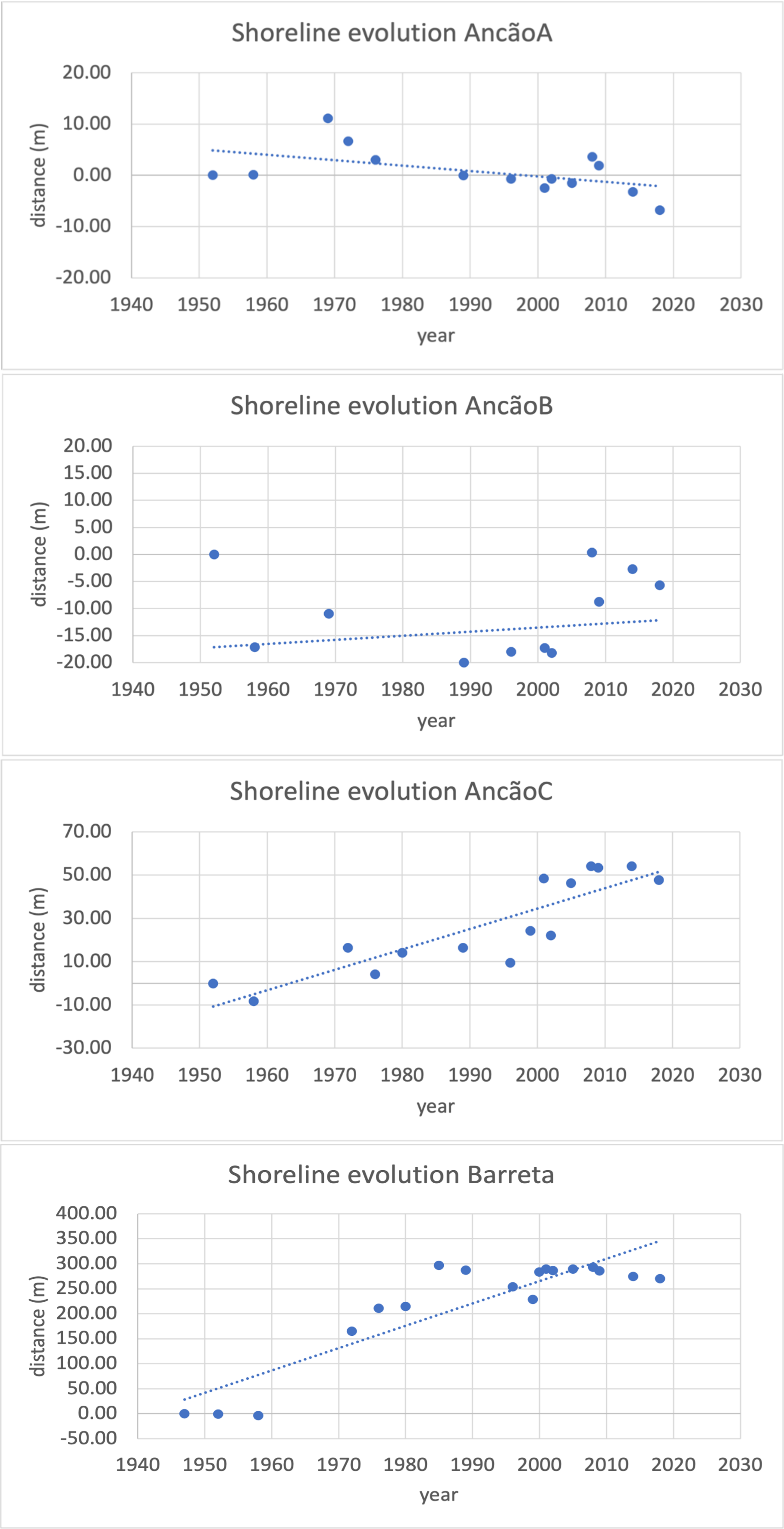


FIGURE 16 SHORELINE EVOLUTION WITH REGARD TO THE SEAWARD VEGETATION LIMIT IN THE PROFILES OF ANCÃOA, ANCÃOB, ANCÃOC AND BARRETA.

The profile in Barreta Island, in general, showcases a robust shoreline evolution of approximately four and a half meters per year (Table 1; Figure 16).

Moving to the eastern part of the Ria Formosa, Culatra Island features three profiles. The evolution of the first profile is not particularly linear, it seems to have experienced a sharp increase from 1952 to 1958 followed by a retreat until 1980 and a further increase until 2000, after which it appears quite stable until 2009, after which it experiences a retreat (Figure 17). Overall, it exhibits slightly positive evolution values (Table 1). However, in CulatraB and CulatraC, the largest shoreline evolutions of nearly ten and thirty meters per year is observed. It is important to note that this trend is attributed to the young age of these two eastern profiles, with the third profile only being identifiable after 2009. Because of the limited data over the few years, there is no substantial amount of data to analyze, and the shorelines appear to exhibit a highly linear development.

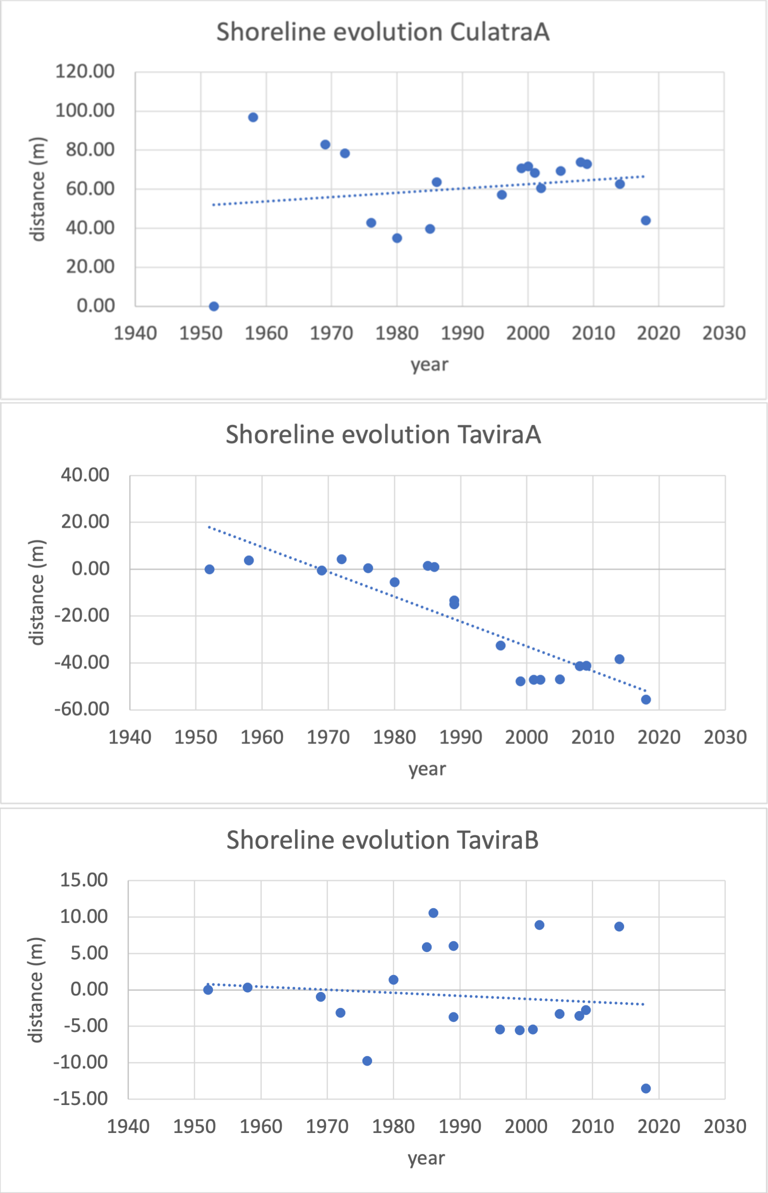


FIGURE 17 SHORELINE EVOLUTION WITH REGARD TO THE SEAWARD VEGETATION LIMIT IN THE PROFILES OF CULATRAA, TAVIRAA AND TAVIRAB.

Continuing eastward, two profiles on Tavira Island indicate distinct patterns. The profile in TaviraA seems to be quite stable, with a strong accumulation only in 1986 and a stronger retreat around 1999. Overall, however, there are no major deviations. It displays a clear retreat, with a negative evolution rate of around one meter per year. In contrast, TaviraB does not demonstrate a distinct trend; rather, it presents outliers in both the low and high ranges, making these trends relatively unpredictable. The last recorded data point shows retreat (Figure 17). Both the trendline and the evolution rates indicate a sense of relative stability over the years.

The island of Cabanas exhibits the most notable retreat compared to all the other islands, with a decline of approximately five and a half meters as indicated by the evolution trend (Table 1). The trend appears to maintain a certain degree of stability over the years. In 2014, there was a significant retreat, followed by a substantial accumulation in 2018 (Figure 18).

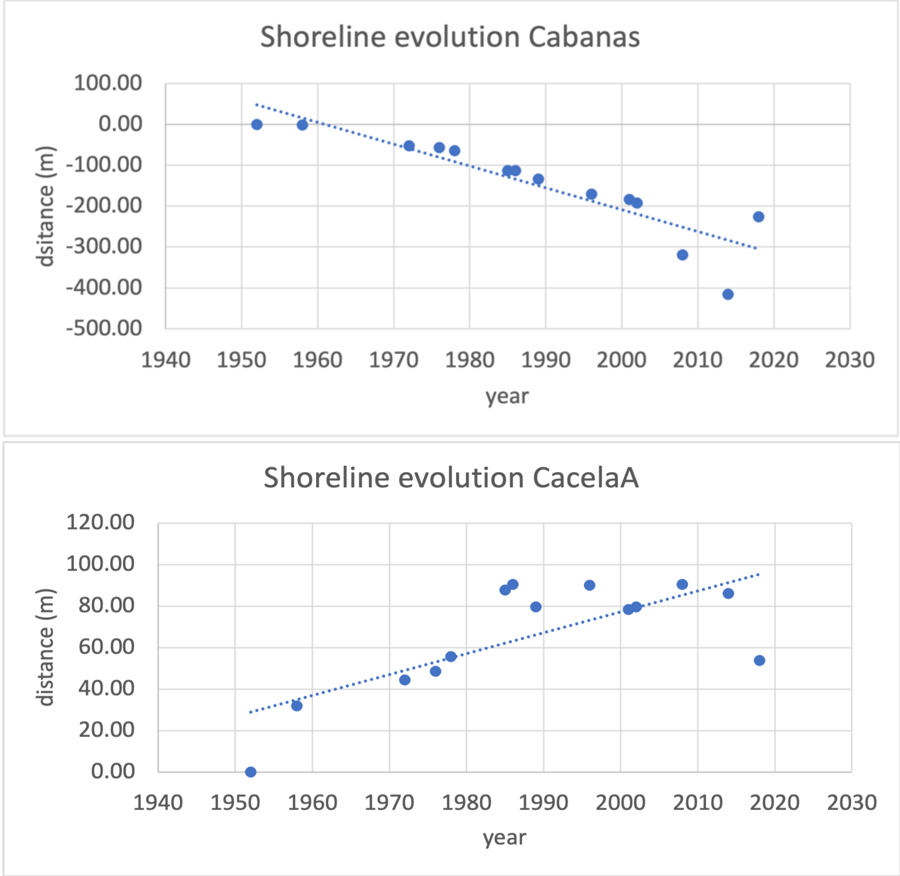


FIGURE 18 SHORELINE EVOLUTION WITH REGARD TO THE SEAWARD VEGETATION LIMIT IN THE PROFILES OF CABANAS AND CACELAA.

The last two profiles on the Cacela Peninsula reveal varying trends. The first profile demonstrates a clear advance of the shoreline which is also quite stable over the years. However, it is important to acknowledge that the last year of evaluation (2018) represents a value going to a retreating direction (Figure 18). The evolution trend suggests an advancing of the shoreline of about one meter per year (Table 1). For the last profile, CacelaB, a slight retreat can be observed (Table 1). Furthermore, this profile could only be evaluated from the year 2007 onwards, which is why there is not much data available.

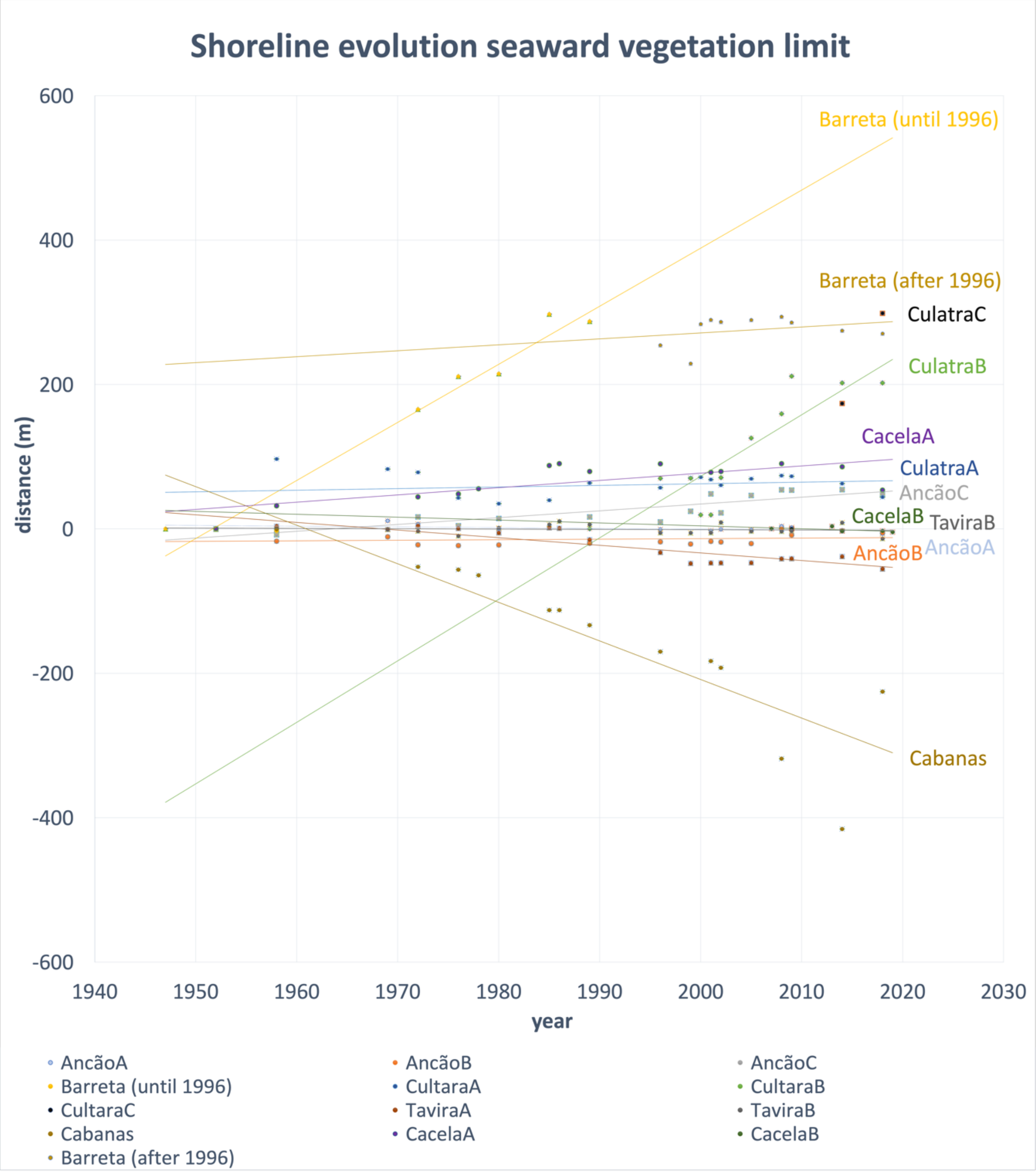


FIGURE 19 SHORELINE EVOLUTION WITH REGARD TO THE SEAWARD VEGETATION LIMIT. THE CONTINUOUS LINES REPRESENT THE TRENDS, WITH THE NAME AT THE END INDICATED IN THE CORRESPONDING COLOR.

In the shoreline evolution depicted in Figure 19, it is evident that the values exhibit relative similarity with minimal deviations. However, upon closer examination, notable changes were observed on individual islands. A set of transects displays remarkable resemblance. This set encompasses AncãoA, B, and C, CulatraA, TaviraB, and CacelaA and B.

For the sake of simplicity, the profile of Barreta has been divided into two: one before and one after 1996. The profile after 1996 shows a much more stable and not too strong growth. Before, the profile grew comparatively fast like CulatraC. This profile was intentionally not represented as a trendline in Figure 19 nor as a value in Figure 20, as it would be an extreme outlier with values of about 30 meters per year. For a more detailed examination of the data, the corresponding values to Figure 19, can be found in Appendix B.

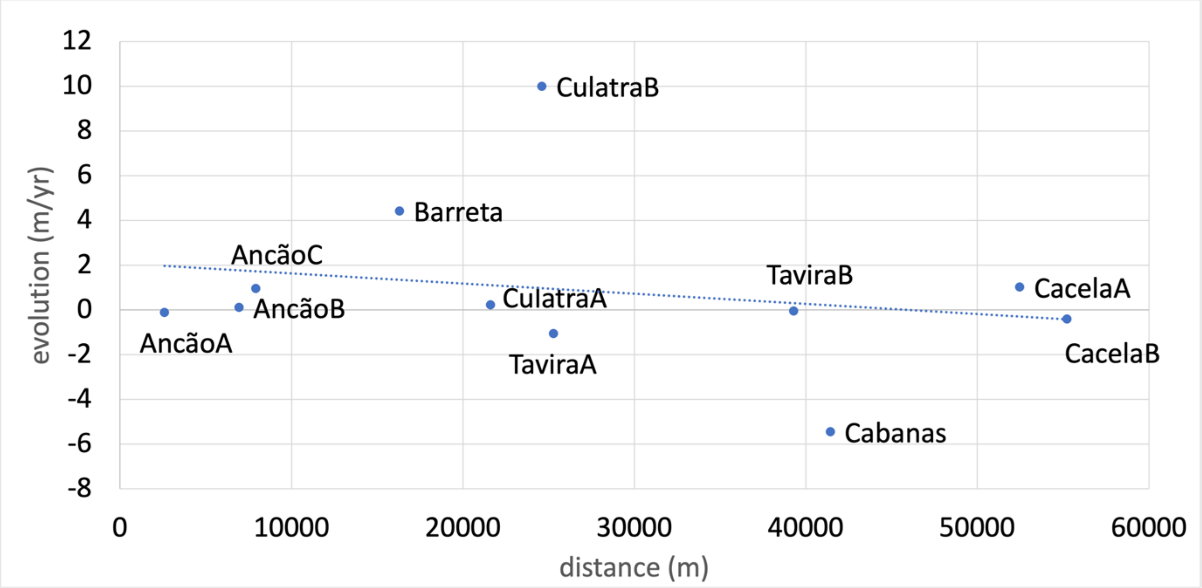


FIGURE 20 TRENDS OF EVOLUTION IN THE INDIVIDUAL STUDY SITES ALONG THE RIA FORMOSA ISLAND BARRIER SYSTEM BASED ON THE SEAWARD VEGETATION LIMIT.

Regarding the alongshore variability, an increase in evolution can be observed from the western to eastern parts of the Ria Formosa. Barreta and Culatra, particularly on the eastern side, are experiencing growth. The values decrease after Tavira, with Cabanas showing a clear retreat. CacelaA and CacelaB, although relatively stable, also exhibit tendencies towards retreat.

The same process was carried out for the debris line to baseline, yielding results that are almost identical, but somewhat less pronounced in most cases. On the Ancão Peninsula, the first profile displays a slightly more noticeable retreat, while the middle one remains relatively stable, and the last profile shows a slightly weaker progression. In Barreta, the advancement is not as substantial. The evolution seems relatively steady, which is why the profile was not divided for illustration purposes. CulatraA exhibits a small retreat, and the last two profiles in Culatra depict a much stronger advancement, especially CulatraB, which is similar to CulatraC at almost 30 meters per year. The other islands on the eastern side do not differ significantly from those previously described in the comparison of the baseline and the seaward vegetation limit. The values for Cabanas are also smaller. CacelaA and CacelaB likewise present lower values, and a clear retreat trend is particularly noticeable in the second profile.

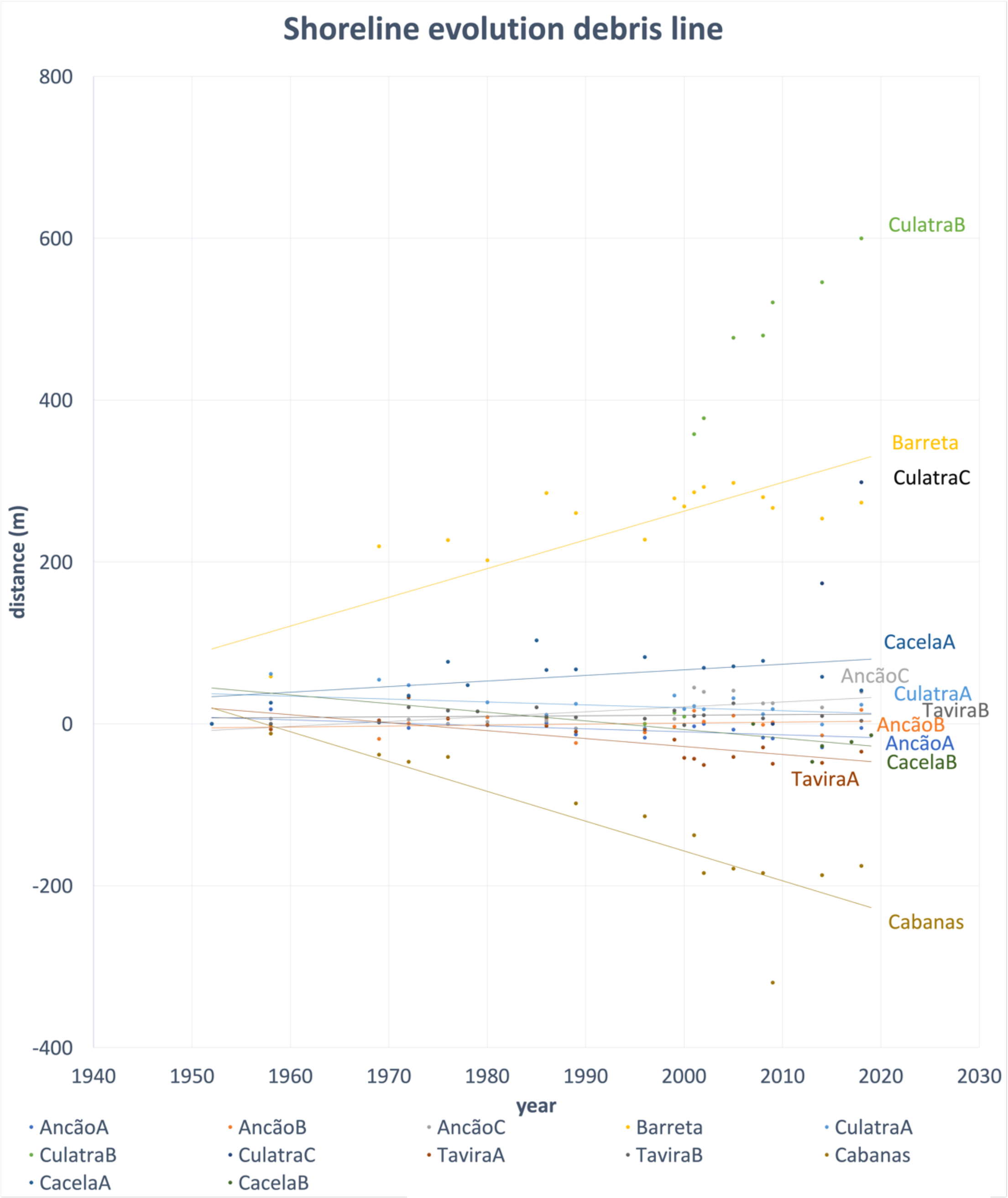


FIGURE 21 SHORELINE EVOLUTION WITH REGARD TO THE DEBRIS LINE. THE CONTINUOUS LINES REPRESENT THE TRENDS, WITH THE NAME AT THE END INDICATED IN THE CORRESPONDING COLOR.

The same process was carried out for the debris line to baseline, yielding results that are almost identical, but somewhat less pronounced in most cases. On the Ancão Peninsula, the first profile displays a slightly more noticeable retreat, while the middle one remains relatively stable, and the last profile shows a slightly weaker progression. In Barreta, the retreat is not as substantial, measuring around 4 meters. The development seems relatively steady, which is why the profile was not divided for illustration purposes. CulatraA even exhibits a small retreat, and the last two profiles depict a much stronger increase, especially CulatraB, which is similar to CulatraC at almost 30 meters per year. The other islands on the eastern side do not differ significantly from those previously described in the comparison of the baseline and the seaward vegetation limit. The values for Cabanas are also smaller, indicating a retreat of just under 4 meters. CacelaA and CacelaB likewise represent lower values, and a clear decrease is particularly noticeable in the second profile. For a more detailed examination of the data, the corresponding values to Figure 21, can be found in Appendix C.

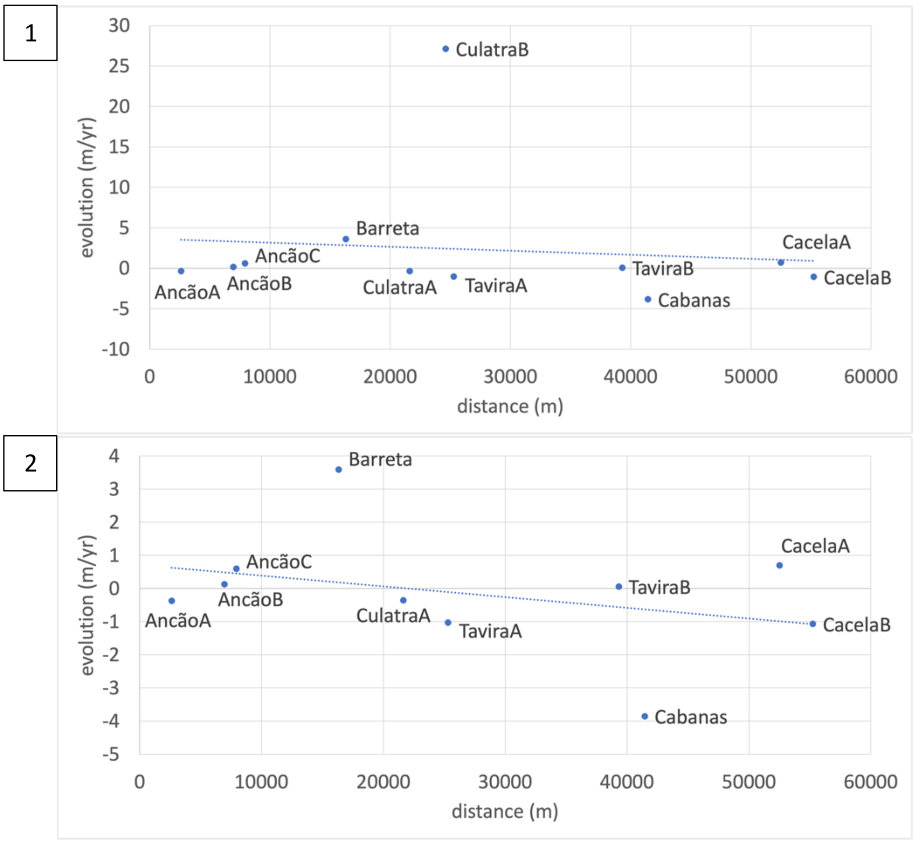


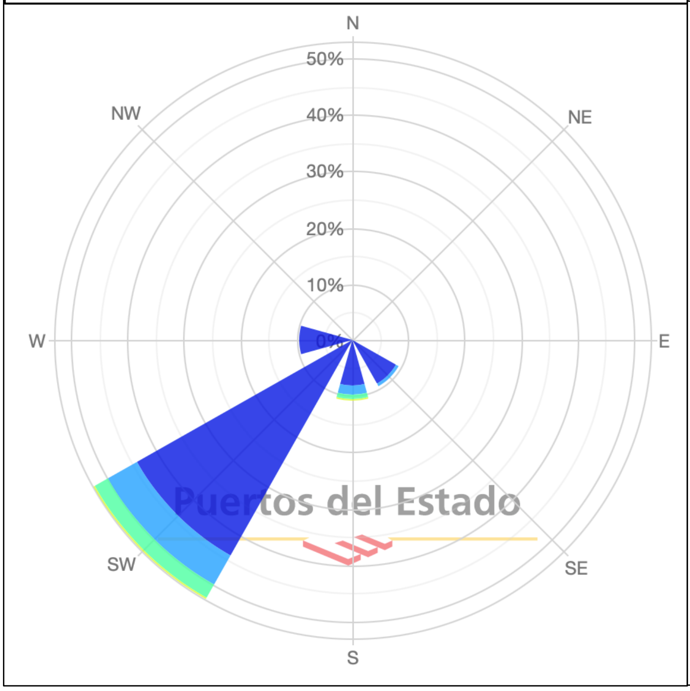
FIGURE 22 TRENDS OF EVOLUTION IN THE INDIVIDUAL STUDY SITES ALONG THE RIA FORMOSA ISLAND BARRIER SYSTEM BASED ON THE DEBRIS LINE.

Examining the alongshore variability graph reveals that the observed differences are not significant, and the trend line appears relatively straight and horizontal (Figure 22). In the second graph, the values for CulatraB and CulatraC were intentionally omitted because they are extreme values that skew the overall perception of similarity among the other values. The overall pattern of shoreline evolution changes follows a similar trend as observed in the seaward vegetation limit, although with lower values across the board. The data relating to shoreline evolution with the debris line will not be evaluated further in this work. This decision stems from the similarity in trends between the two coastline indicators, with the primary focus on the dune. Although combining both indicators could provide insights into dry beach size trends, but given the dynamic nature of the beach in the cross-shore profiles, it is preferable not to continue its analysis.

6.3 WIND AND WAVES

The results of the wave direction analysis along the Ria Formosa are presented below. The dataset was categorized into celestial directions to determine the percentage distribution of wave directions in each region (western and eastern parts of the Ria Formosa). The objective was to identify the prevailing directions at each location. Another point is the intensity of the waves, for which the significant wave height was discussed.

Rose of Significant Height (m) for Waves



Location: SIMAR 5018021 (west)

Analysed Series: 1958 - 2023

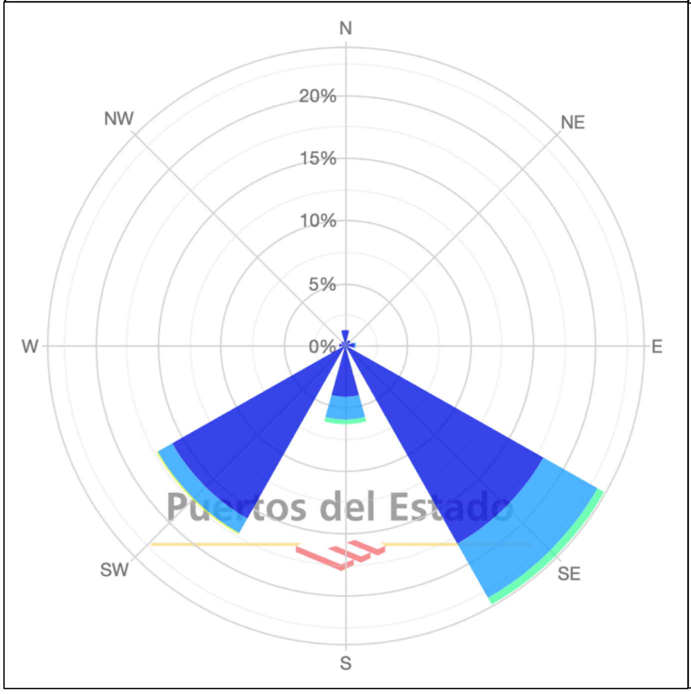
Percentage of calms: 17.21%

Calm interval: 0 - 0.2

Period: Annual

Significant wave height (m):
- <= 0.2
- 0.2 - 1.0
- 1.0 - 2.0
- 2.0 - 3.0
- 3.0 - 4.0
- 4.0 - 5.0
- 5.0 >

Rose of Significant Height (m) for Waves



Location: SIMAR 5023022 (east)

Analysed Series: 1958 - 2023

Percentage of calms: 50.72%

Calm interval: 0 - 0.2

Period: Annual

Significant wave height (m):
- <= 0.2
- 0.2 - 1.0
- 1.0 - 2.0
- 2.0 - 3.0
- 3.0 - 4.0
- 4.0 - 5.0
- 5.0 >

FIGURE 23 SIGNIFICANT HEIGHT WAVE ROSES OF THE SIMAR POINTS 5018021 AND 5023022 CAPTURING THE WESTERN AND THE EASTERN PART OF THE RIA FORMOSA (PUERTOS, 2023).

A detailed examination of the data presented in Figure 23 reveals insights into the significant wave heights along the Ria Formosa. The first thing noticeable is the proportion of waves that are considered "calms" and therefore fall out of the rating for true waves. On the western flank of the Ria Formosa, waves are a constant presence, with calm conditions accounting for only about 17% of the time. The east, on the other hand, is much calmer, with about 51% of the waves here considered not to be real waves. Analyzing the wave roses from the different SIMAR points, it is apparent that waves in the Ria Formosa primarily originate from the west to the southeast. The dominant wave direction in the western region is from the southwest, with occasional instances of strong waves also originating from the south. In the eastern part, the predominant wave direction is clearly from the southeast, where most of the stronger waves also occur. Another highly frequented direction is from the southwest. The strongest waves also come from this direction. From the south there are also some waves and comparatively many stronger waves.

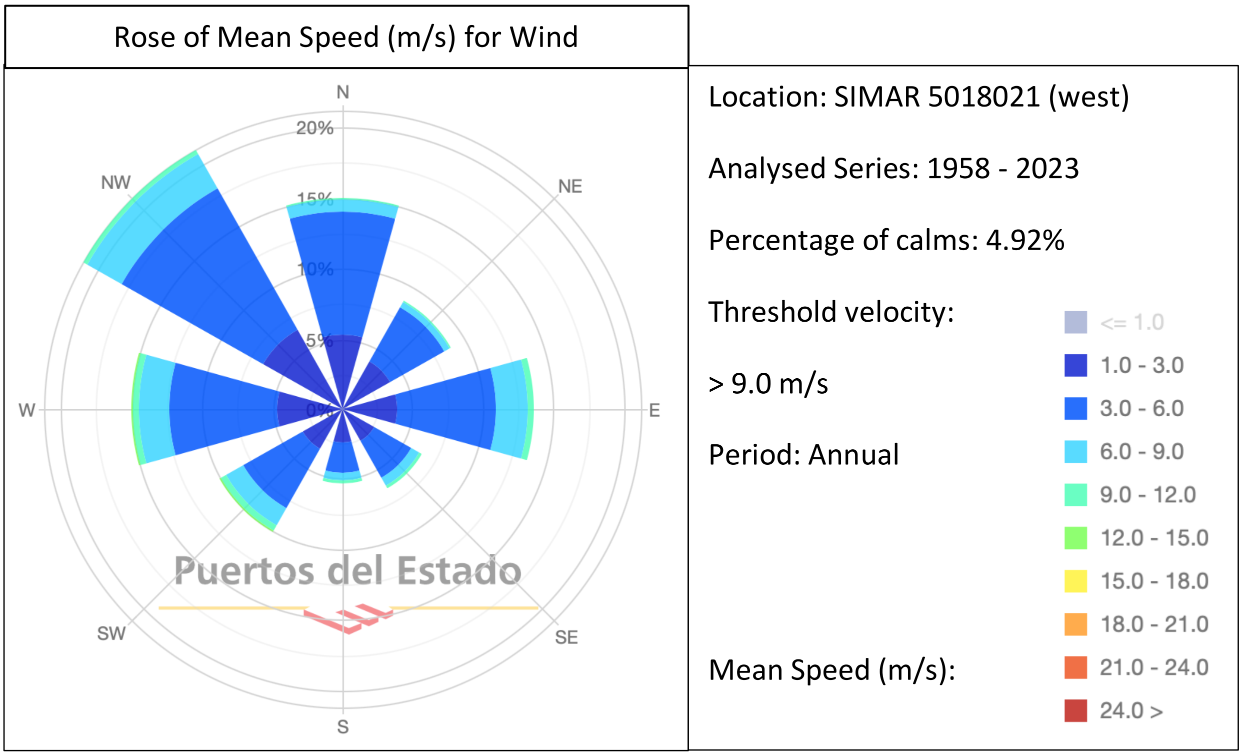
TABLE 2 AVERAGE PROCEEDING WIND AND WAVE INCIDENT DIRECTION FROM THE SIMAR POINTS 5018021 AND 5023022 CAPTURING THE WESTERN AND EASTERN PART OF THE RIA FORMOSA.

	Wave		Wind	
Wind direction	West (%)	East (%)	West (%)	East (%)
NORTH (337.5°-22.5°)	0.02	1.52	15.59	18.46
NORTHEAST (22.5°-67.5°)	0.02	0.68	9.44	10.41
EAST (67.5°-112.5°)	0.07	1.2	14.27	11.03
SOUTHEAST (112.5°-157.5°)	12.02	28.83	7.01	7.47
SOUTH (157.5°-202.5°)	11.88	9.55	5.76	7.4
SOUTHWEST (202.5°-247.5°)	50.65	51.83	10.55	14.87
WEST (247.5°-292.5°)	24.87	5.66	15.62	13.54
NORTHWEST (292.5°-337.5°)	0.48	0.73	21.76	16.81

As illustrated in Table 2, both points (western and eastern flanks) exhibit a dominant prevailing wave direction from the southwest, accounting for just over 50% of the recorded data. On the western side, the second most frequent wave direction is from the west, constituting almost a quarter of all recorded data. This wave direction is rarely occuring on the eastern side with just under 6%. Whereas the second most frequent wave direction at the eastern point is the southeast, with almost 29% of the total occurrences. Conversely, on the western side, waves from this direction are less frequent, representing just around 12% of all recorded data. A significant proportion of waves on both sides approach from the south, with percentages ranging between 9-12%. The remaining wave directions have a minor impact on the overall wave patterns shaping the Ria Formosa.

The following part presents the results of the wind direction analysis. Similar to the wave direction analysis, the dataset underwent categorization by cardinal directions to determine the percentage distribution of wind directions in each region. Table 2 presents the average prevailing wind directions for both the western and eastern regions of the Ria Formosa. A closer examination reveals subtle variations in the distribution of dominant wind directions between these two locations. In the western area, a prevailing wind pattern is observed, with northwest winds being the most prominent. Additionally, north and west winds each account for 15% of occurrences. Conversely, in the eastern area, there is a higher frequency of winds from the southwest and north, indicating a relatively greater prevalence of these directions. This side experiences more winds from the east and southwest. While northwest, west, and east winds are still common, their occurrence is less frequent compared to the western region.

In this study, a threshold wind velocity of 9 meters per second (m/s) was employed, based on the research conducted by Costas et al. in 2020. This threshold was utilized to identify winds capable of initiating aeolian sediment transport within the western part of the Ria Formosa. Winds exceeding this threshold were considered as having the potential to move sand particles, and their occurrences were analyzed. In the eastern part, the value established by Since the grain size in this region is about 0.3 millimeter in diameter, the wind speed that allows the grain to be transported is adjusted to 7.12m/s.



Rose of Mean Speed (m/s) for Wind

Location: SIMAR 5018021 (west)

Analysed Series: 1958 - 2023

Percentage of calms: 4.92%

Threshold velocity:

> 9.0 m/s

Period: Annual

Mean Speed (m/s):

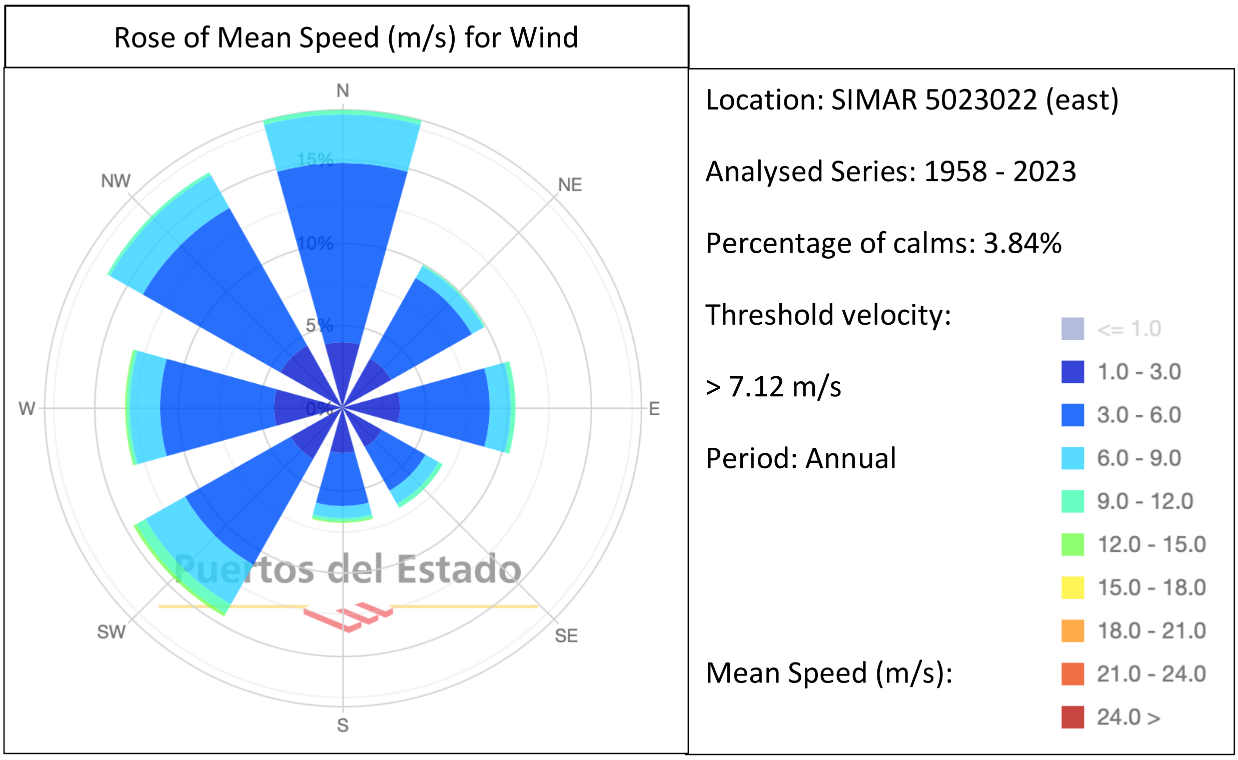


FIGURE 24 AVERAGE PROCEEDING WIND DIRECTION FROM THE SIMAR POINTS 5018021 AND 5023022 CAPTURING THE WESTERN AND THE EASTERN PART OF THE RIA FORMOSA.

Based on this value, 4.92% of all number of occurrences on the western side and 3.84% of all number of occurrences on the eastern side of the Ria Formosa result in a wind strength that is considered “calms” (Figure 24). Adding the threshold velocity, the values for the "calms" diverge significantly, as these wind speeds exceed one metre per second. On the western side of the Ria Formosa, the threshold velocity is 9m/s, which excludes 97.67% of all values, as these do not have the possibility to transport the sand particles. Another crucial consideration is wave runup, which must not surpass the berm height to maintain the sediment's transportability (Costas et al. 2020). To account for this, a value of 1.5 meters was included in the assessment, as the dune toe in the western sector generally measures around three meters. After this evaluation, only 0.94% of all values remain. Another crucial aspect for sediment accumulation on the dune is the wind direction, specifically, it must carry sediment toward the dune, which, in this context, corresponds to a wind from the southwest. This criterion further narrows the conditions, resulting in only 0.05% of the values. When combining all these factors, the assessment reveals that approximately 0.05% of the time provides conditions conducive to sand accumulation on the dune. Consequently, the rarity of favorable transport conditions makes large-scale dune growth a challenging endeavor.

It is important to note that the profile of Barreta is situated on the eastern side in terms of wind and wave directions, which is why it was considered in the evaluation of the respective data on the eastern side.

On the eastern side, a threshold velocity of 7.12 m/s is needed to transport sand particles, here the wind has the possibility to transport them 7.82% of the time. The wave runup also plays a crucial role in determining transportability. To narrow down the criteria for potential sediment transport, the analysis focuses on significant wave heights exceeding 1.25 meter, since the dune toe in the eastern sector measures around 2.5 meters on average. This factor also excludes further events, leaving only 5.2% of events. In order to transport the sand towards the dune, the wind must come from the southeast. The evaluation reveals a significantly higher percentage of potential sediment transport in the eastern part of the island, accounting for approximately 0.1% of the time. This makes it a system more prone to active wind-driven sediment transport.

6.4 VEGETATION COVER DISTRIBUTION

Across the 12 study sites in the Ria Formosa, a total of 40 distinct plant species were identified. These species were classified into functional groups based on the framework established by García-Mora et al. (1999). The analysis revealed 14 species falling under type I plants, closely followed by 13 species in the type II category, and an additional 10 species categorized as type III plants. Furthermore, three plant species, could not be definitively assigned to specific plant functional types and were classified as "woody species." This classification is presented in Table 3.

The subsequent table provides a comprehensive overview of the identified flora species (sps) and their associated plant functional types, along with their burial tolerance characteristics. In this context, the acronyms THB and TLB signify high and low burial tolerance, respectively, while NT denotes non-tolerant. It is important to note that type 1 plants typically exhibit low burial tolerance or are non-tolerant, type 2 plants possess low burial tolerance, and type 3 plants present high burial tolerance.

TABLE 3 COMPREHENSIVE OVERVIEW OF SPECIES AS WELL AS THEIR LIFE SPAN (A: ANNUAL, B: BIANUAL, P: PERENNIAL), APPEREANCE (H: HERBACEOUS, W: WOODY) AND IN WHICH PLANT FUNCTIONAL TYPES THEY CAN BE CATEGORISED IN AS WELL AS THE BURIAL TOLERANCE (THB: HIGH BURIAL RATES TOLERANT, TLB: LOW BURIAL RATES TOLERANT, NT: NOT TOLERANT).

sps	life span	appereance	Plant Functional Types	Burial Tolerance
Ammophila arenaria	p	h	3	THB
Anthemis maritima	p	w	2	NT
Armeria pungens	p	h	2	NT
Artemisia crithmifolia	p	w	2	TLB
Cakile maritima	a	h	3	TLB
Calystegia soldanella	p	h	3	TLB
Carpobrotus	p	h	2	TLB

Coristospermum lucidum	p	h	1	NT
Corynephorus canescens	p	h	1	NT
Crucianella maritima	p	h	2	TLB
Cynodon dactylon	p	h	1	NT
Elymus farctus	p	h	3	THB
Erodium cicutarium	a	h	1	NT
Eryngium maritimum	p	h	3	TLB
Helichrysum picardii	p	w	2	NT
Linaria lamarkii	a	h	2	NT
Linaria pedunculata	a	h	2	NT
Lotus creticus	b	h	2	TLB
Malcolmia littorea	b	h	2	NT
Medicago littoralis	a	h	1	NT
Medicago marina	p	h	3	TLB
Opuntia sp.	p	w	w	NT
Otanthus maritimus	p	w	3	THB
Pancratium maritimum	p	h	3	TLB
Paronychia argentea	p	h	1	NT
Polygonum maritimum	p	h	3	NT
Polycarpon alsinifolium	a	h	1	NT
Polycarpon polycarpoides	a	h	1	NT
Polycarpon tetra subsp. alsinifolium	a	h	1	NT
Pseudorlaya pumila	a	h	1	NT
Reichardia gaditana	a	h	2	NT
Retama monosperma	p	w	w	NT
Salsola kali	a	h	3	TLB
Scabiosa spp	p	h	1	NT
Sedum sediforme	p	h	1	NT
Silene nicaeensis	a	h	2	NT
Sonchus asper	a	h	1	NT
Suaeda vera	p	w	w	NT
Thymus carnosus	p	w	2	NT
Vulpia	a	h	1	NT

As previously explained, a variety of Cross-Shore Zonation Lines (CZLs) was carefully chosen within the individual profiles in situ. Primarily based on parameters like the dune width or specific characteristics, as detailed in section 5.1.4. Consequently, for each profile along the coastal system, a range of 3 to 13 CZLs were identified. During the field visits, the landscape was documented, which allowed to identify the different cross-shore zonation lines in their respective dune zones, as explained in section 5.2.4. The spatial distribution of these zones, depicted in Figure 25 below, displays a noticeable variation. A particularly large number of CZLs is attributed to the profiles on Barreta, Cabanas, Culatra and AncãoC.

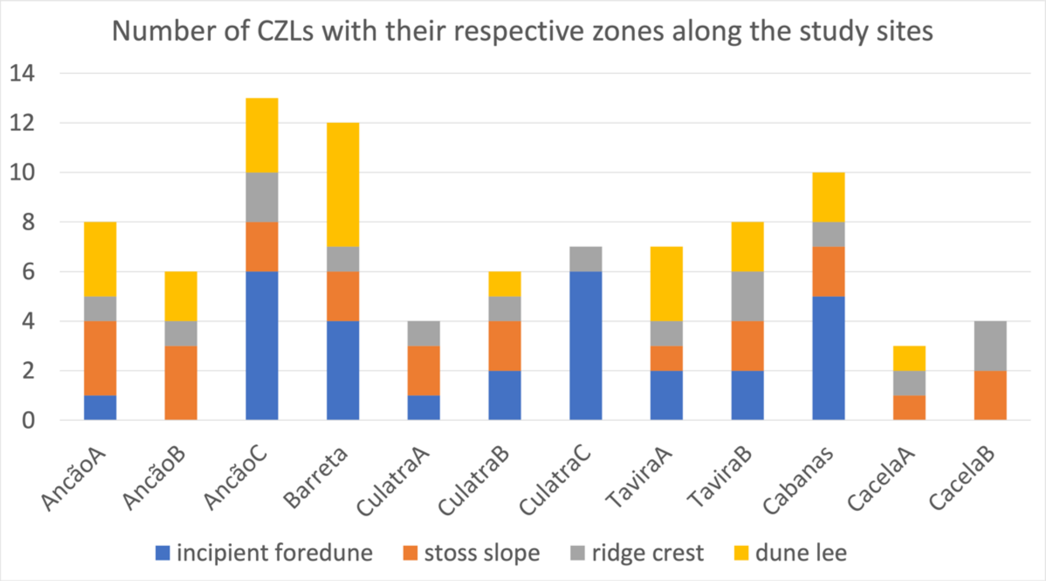


FIGURE 25 NUMBER OF CZLS WITH THEIR RESPECTIVE ZONES ALONG THE STUDY SITES.

In In the subsequent phase, the investigation delved into understanding the distribution of plant species abundance within various zones of the dunes. The graphical representation in Figure 26, provided below, underscores a similarity in distribution across different profiles. Notably, some profiles lacked data entries for specific areas, such as the incipient dune zones (AncãoB, CacelaA & B) or the dune lee (CacelaB, CulatraA & C) as those zones were not present in the profiles. The dune lee has a little more species on average. Especially in TaviraA there are comparatively many species in the lee. Consequently, comparatively fewer plant species are observed in the zones of the incipient foredune.

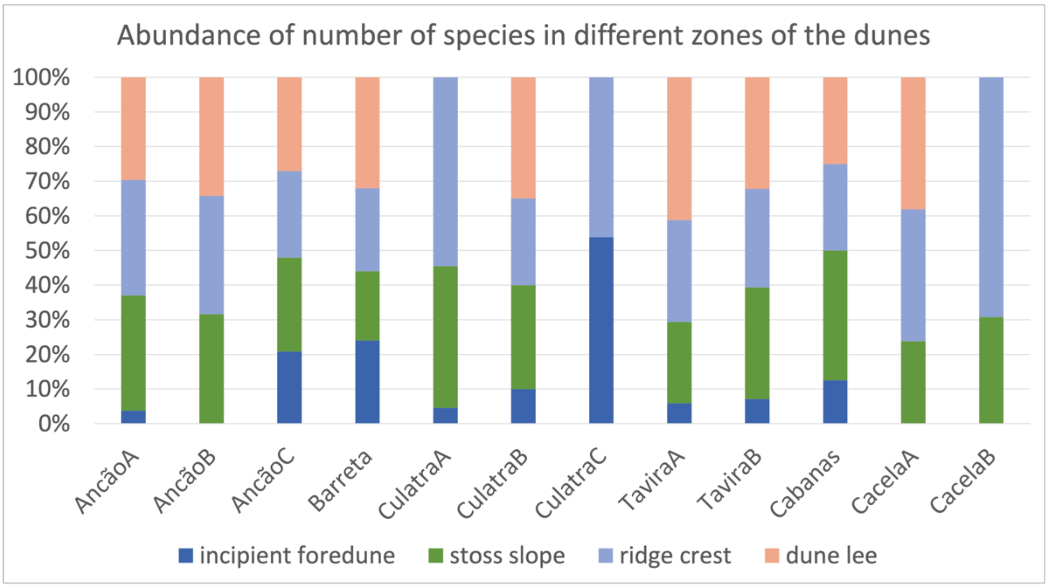


FIGURE 26 ABUNDANCE OF NUMBER OF SPECIES IN DIFFERENT ZONES OF THE DUNES

Another aspect is the array of plant types and their specific distribution within the study areas (Figure 27). The subsequent graph reveals a relatively consistent correspondence between the species types across the study sites and the number of CZLs, along with their corresponding zones. The profile in AncãoB stands out, where a comparatively low count of cross-shore zonation lines was recorded, yet a relatively abundant number of plant species was identified. A similar pattern emerged in the first profile of Culatra and the second profile of Tavira, characterized by a notably rich variety of species. Conversely, the final profile of Culatra and Cabanas displayed the opposite trend, featuring fewer species despite multiple transects. The data of these two profiles reveals a prominent trend of lower species richness, where most dunes were categorized as incipient foredunes. The diagram shows a relatively even distribution for type II and III plants, with type II predominating, followed by type III. The only exception is CulatraB and Cabanas, where this distribution is reversed. Type I plants, on the other hand, do not appear in every profile (e.g., CulatraB & C, TaviraA and Cacela), with comparatively higher occurrences in AncãoC and Barreta. A final type of plant is the woody species, which cannot be classified according to García-Mora et al. (1999) but were nevertheless recorded during the field visits. They are particularly visible in the profiles of Cacela as well as in the second profile of the island of Tavira.

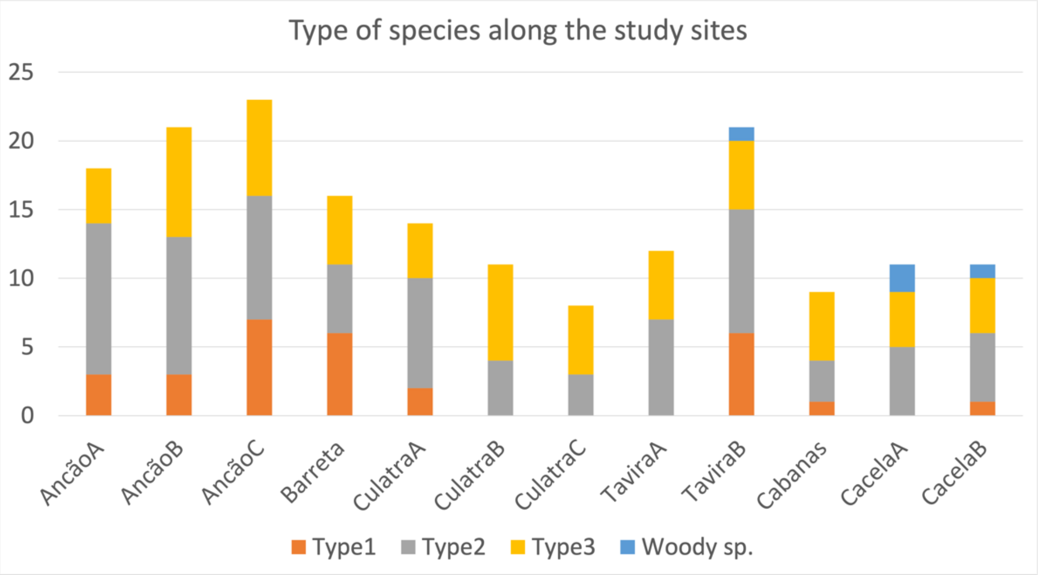


FIGURE 27 TYPE OF SPECIES ALONG THE STUDY SITES WITH THEIR RESPECTIVE PLANT FUNCTIONAL TYPES

The findings obtained through the performed Detrended Correspondence Analysis (DCA) clearly depict the variations across both the cross-shore and longshore gradients in terms of species composition and abundance, as shown in Figure 28 and Figure 29. The data used to create this graph can be found in AppendixA. To interpret the upcoming graph, the abbreviations are explained below. Initially, the profile names are as follows: Ancão to Anc, Barreta to Bar, Culatra to Cul, Tavira to Tav, Cabanas to Cab, and Cacela to Cac. Different parts of the individual dune profiles are described using the following abbreviations: "I" indicates the incipient foredune, "S" represents the stoss slope, "C" signifies the crest, and "L" denotes the lee of the dune.

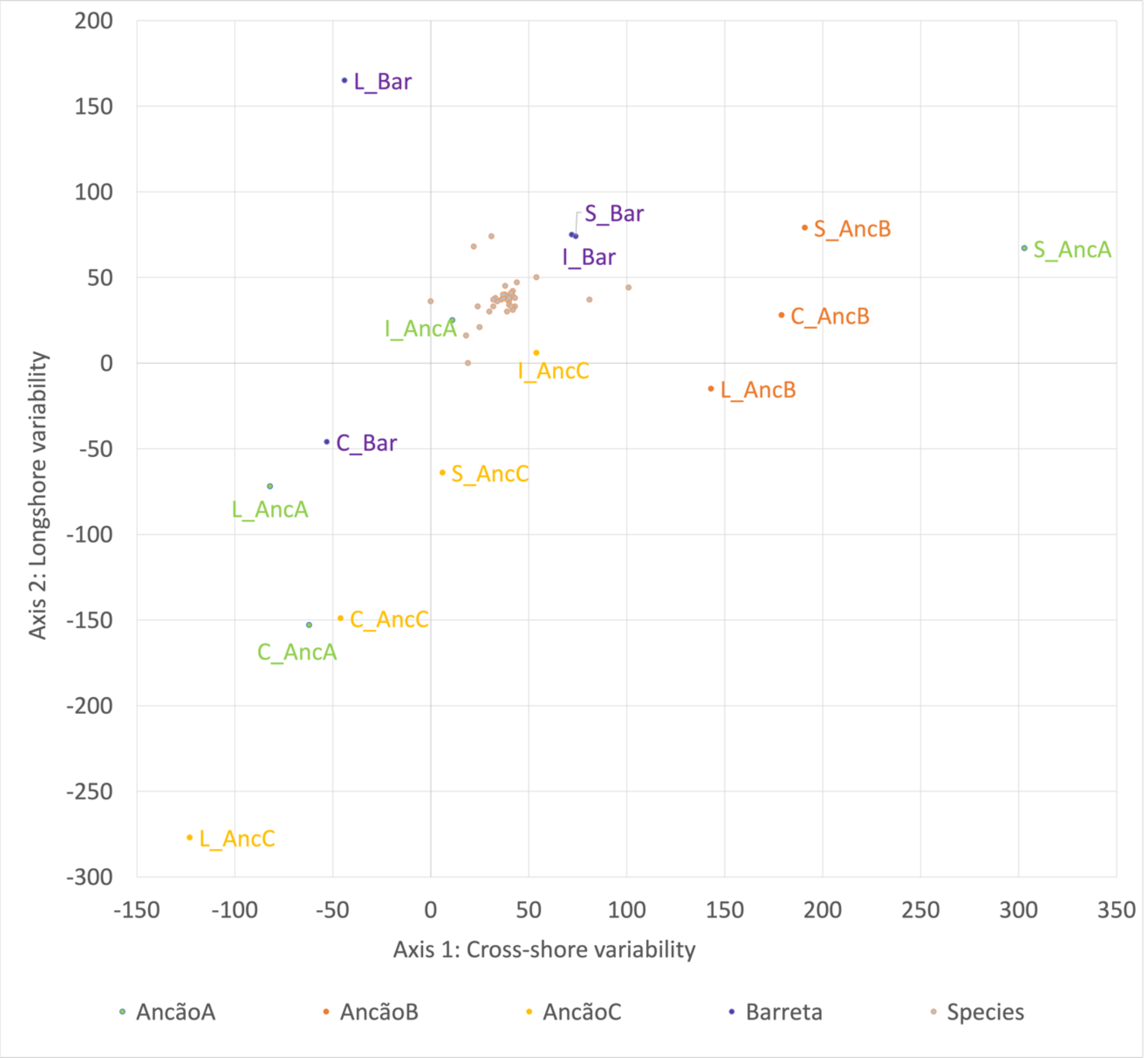


FIGURE 28 VISUALIZATION OF THE DETRENDED CORRESPONDENCE ANALYSIS (DCA), BASED ON THE PLANT COMPOSITION AND ABUNDANCE, SURVEYED ALONG AND ACROSS THE DUNE PROFILES IN THE WESTERN PART OF THE RIA FORMOSA. EIGENVALUES OF AXIS 1 AND AXIS 2 WERE 0.03 AND 0.013, RESPECTIVELY. SPECIES ARE REPRESENTED BY GREY DOTS. EACH PROFILE HAS IST OWN COLOUR, AS SHOWN IN THE LEGEND.

The greater spatial separation between the dune zones suggests more marked differences in their respective compositions (Costas et al. 2023). For the purpose of improved data visualization and analysis, the Barreta profile was designated as part of the western section in this assessment (Figure 28). In this line, the incipient foredunes in all profiles show a similar community, except of the second profile of AncãoB since here were no incipient foredune recorded. The stoss zones can also be found in the same longshore variability region, they just differ in their cross-shore variability. Except of AncãoC which species composition is more similar to the crest zone in the Barreta profile. Also, the species composition in the zone of incipient foredune is interestingly very similar to the zone of stoss slope in the same profile. In the western part, there is no commonality between the species composition of the crests or lees. Only the crests of the AncãoA and AncãoC profiles are similar. Particularly in the case of AncãoC, a clear trend is evident both cross-shore and along the shore, extending from the incipient foredune to the lee of the dune. AncãoB follows a comparable pattern. In contrast, AncãoA exhibits an interesting departure from this trend, with the slope zone demonstrating considerably greater values in both cross-shore and alongshore variability compared to the incipient foredune. Moreover, the lee of AncãoA surpasses the crest zone in terms of these values. The Barreta profile similarly displays deviations from the expected patterns, notably in the lee zone.

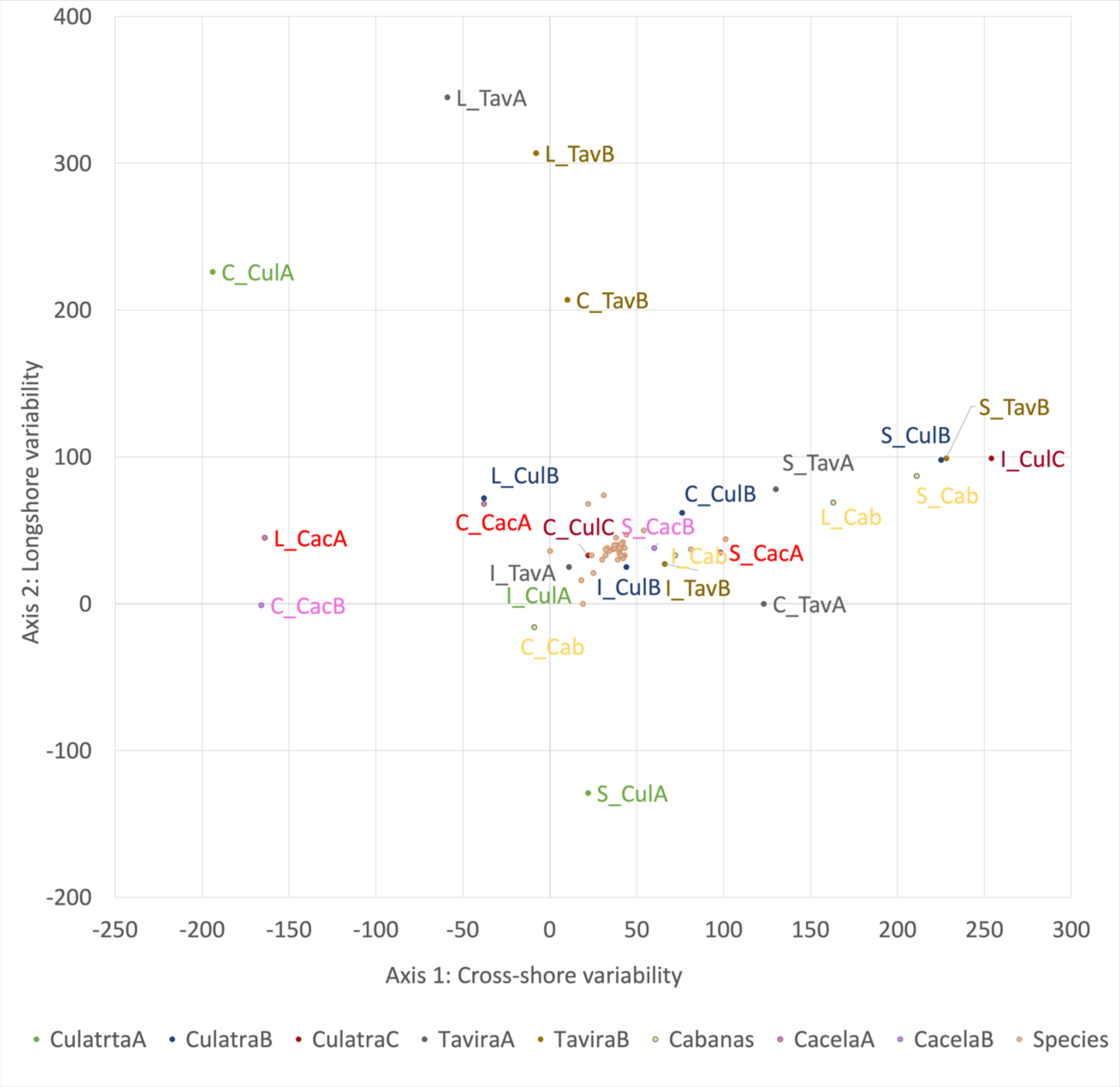


FIGURE 29 VISUALIZATION OF THE DETRENDED CORRESPONDENCE ANALYSIS (DCA), BASED ON THE PLANT COMPOSITION AND ABUNDANCE, SURVEYED ALONG AND ACROSS THE DUNE PROFILES IN THE EASTERN PART OF THE RIA FORMOSA. EIGENVALUES OF AXIS 1 AND AXIS 2 WERE 0.03 AND 0.013, RESPECTIVELY. SPECIES ARE PRESENTED BY GREY DOTS. EACH PROFILE HAS IST OWN COLOUS, AS SHOWN IN THE LEGEND.

It is also worth noting that the composition of the incipient foredunes across these profiles is quite similar. In fact, in the Tavira A and Culatra A profiles, the composition is identical (Figure 29). The only exception here is Culatra C, which notably differs, particularly in terms of its cross-shore variability. The slopes, too, tend to cluster in a similar region, showing similarities to the incipient foredune of Culatra C. Moving further across the cross-shore variability spectrum, we find the stoss slopes of Culatra B and C, as well as Cacela A and B. Interestingly, these zones share similarities with the incipient foredunes. One exception in their alongshore variability is the composition of Culatra A. Crest formations tend to cluster around the central region but exhibit more dispersion. Profiles like Culatra A display distinct directions. Cacela B and Tavira A also deviate, although their variations extend more positively and negatively across the cross-shore direction. Tavira B, on the other hand, exhibits more pronounced variability in the longshore direction. When examining the lee zones of the dunes, we observe a similar pattern of scattering. The Tavira profiles demonstrate the most significant deviation from the central cluster. Interestingly, the lee of Cacela A exhibits a species composition similar to the crest zone of Cacela B. Likewise, the lee profile of Culatra B shares a similar species composition with the crest zone of Cacela A. Finally, the lee profile of Cabanas shares similarities in its composition with most of the stoss zones in the different profiles.

7. DISCUSSION

Data analysis is essential for uncovering insights and patterns within collected information. It involves using methods to extract valuable details and find important trends. This analysis spans various aspects, including morphological variability, shoreline evolution, wind and wave conditions, and plant distribution, both cross-shore and alongshore. In this discussion, there will be a close examination of each dune profile to understand its characteristics and dynamics within the Ria Formosa coastal system. The objective is to uncover the underlying factors driving the distribution of plant communities by examining dune morphology, shoreline evolution, and meteocean conditions. The question is, if the distribution of these communities is primarily shaped by dune morphology, influenced by shoreline evolution, or governed by meteocean conditions. It is evident that shoreline trends also exert an influence on dune morphology, highlighting the multifaceted nature of these relationships. Rather than being one-directional or straightforward, these interactions are intricate, marked by complex synergies.

Western Sector

The following section will address the western sector of the Ria Formosa, focusing on the Ancão Peninsula and its associated study sites,. The examination of specific profiles along this sector, such as AncãoA, AncãoB, and AncãoC aims to explore the different drivers of habitat and species distribution and seek to understand the possible links between these.

An in-depth analysis of the AncãoA dune profile reveals distinctive features. AncãoA possesses the highest dune among all the examined sites. This observation aligns with findings by Psuty (2004), which suggest that taller dunes are indicative of stable to retreating coasts.

Additionally, AncãoA stands out as the widest foredune ridge in our study, also indicating a high level of stability. Comparatively, AncãoA exhibits a steeper slope than other profiles on the western side of the Ria Formosa. This pronounced slope is indicative of possible scarping, a phenomenon often observed in this context, as suggested by Davidson et al. (2020). The most recent event in which waves reached the base of this dune occurred during the storm Emma in late February 2018 (Costas et al., 2023). Although a minor incipient foredune is visible in form of a small mound, which has not fully developed. This is because it represents an ongoing recovery process following the erosion event of 2018. The backshore width in this profile is notably smaller compared to others within the system. The width of the backshore and other local factors play crucial roles in determining sediment availability for dune growth (Costas et al., 2020; Ruz and Meur-Ferec, 2004; Cohn et al., 2018; Roelvink and Costas, 2019). This suggests that the sediment budget along the beach may be somewhat reduced or, at least, not enough to promote active dune growth. In fact, intermittent storms are able to reach the toe of the dune, leading to an overall retreat of the system that subsequently strives to recover.

Typically, dune stability can be deduced from the trends in shoreline evolution rates, as highlighted by Psuty (2004). Normally, stable dunes tend to grow taller over time, as they have more opportunity to do so with the shoreline remaining relatively fixed. In the case of AncãoA, it does exhibit relatively stable rates, although in a retreating direction, also pointed by Kombiadou et al. (2019). Retreat in this area, although very small or almost negligible, is evidenced by the fragmentation of the dune crest and, notably, the presence of a scarp, even though it is partially concealed by an incipient dune, which may have low survival expectations if new big storms impact the area.

Regarding wave patterns, it is important to mention that most waves, including strong ones, come from the southwest direction. Storm waves not only erode the beach but can also lead to the accumulation of sediment on the upper beach in particular circumstances (Cohn et al., 2018; Roelvink and Costas, 2019). In this context, the presence of higher waves could account for the higher dune toe. Additionally, the narrower backshore might allow waves to reach the dune toe more easily.

When examining the vegetation, it is important to note that denser and taller vegetation is often indicative of greater site stability and more resilient coastal geomorphological features (Bush & Young, 2009). In the AncãoA profile, a total of 18 different plant species were identified. Among these, three species can be attributed to type I, which are typically associated with more stable areas. The majority of the species fall under type II, a common occurrence throughout the entire coastal system, and these also exhibit the highest abundance. Additionally, four plants of type III were identified, which typically thrive in relatively unstable conditions, such as incipient foredunes. However, these plants are burial tolerant and known to play a significant role in dune-building processes, contributing to the formation of dunes. The diversity of vegetation at this particular study site, as depicted in

Figure 28, highlights that the composition of the stoss slope and dune lee in this profile differs from the other profiles on the same island. Interestingly, the lee of this profile shares more similarities with the crest of Barreta, possibly indicating signs of retreat by hosting species that are typically found on the stoss slope. This variation could potentially be linked to ongoing retreat, as this profile, particularly the stoss slope, is experiencing dynamic changes. The influencing factor in this respect will be the sediment beach budget, as less sand is available as well as the force of the waves, which ensure the formation of a scarp in the dunes (Figure 30).

FIGURE 30 PICTURE TAKEN DURING THE FIELDWORK IN THE FIRST PROFILE OF THE ANCÃO PENINSULA.

Following AncãoA, AncãoB and AncãoC stand out as the third and second largest dunes in the Ria Formosa. These dunes are characterized by their considerable width and size, traits that typically indicate stability and a reduced vulnerability to flooding events (Sallenger, 2000). However, in contrast to AncãoA, the other two profiles on the peninsula exhibit gentler stoss slopes, suggesting a less retreating area. When analyzing the evolution of these dunes, the assumption is confirmed and a trend towards progradation becomes evident.

Among these profiles, **AncãoB** appears to maintain a stable condition with no significant growth. Notably, during fieldwork, no incipient foredunes were observed in this profile. However, there is a significant presence and abundance of type III plants in this area, particularly on the stoss slope, indicating active sand accumulation in this area. This dune also supports type I and type II plant species, with type II being the most prevalent. It is important to note that the dune hosts plants with low burial tolerance across its expanse, with the exception of the stoss slope. In line with the findings of Costas et al. (2023), this dune seems to be entering a phase of roll-over driven by aeolian processes, signifying its instability in this regard. The detrended correspondence analysis reveals that the species composition in the profile is well separated but also more compressed. There is not much cross-shore variability in species composition, which indicates an unstable system or one that is in flux. In this context, the factor will be the shoreline evolution trend which is also driven by the sediment budget.

AncãoC exhibits a shoreline evolution that leans more evidently towards progradation. It is important to note that in 1997 there was a man-made relocation of the Ancão Inlet, which led to changes in sediment supply patterns and thus influenced the shape and stability of the dunes (Costas et al., 2020). The impact of these sedimentary alterations are likely to have had a substantial effect, particularly within this section of the Ria. This aligns with the data on stoss width, a measure of the dune seaward extent. AncãoC has the widest stoss width among all the profiles. This is because of the steady shore progradation in recent decades and in in the profile a new incipient foredune with the former foredune ridge was merged. Analyzing the plant species reveals a high number of type III but with a comparatively low abundance to the other profiles on the island. AncãoC also boasts the highest number of type I plant species, known to be more representative for more stable dunes. A closer look at the evaluation of the detrended correspondence analysis shows that cross-shore zonation in this profile is well developed with clear separation among the different habitats across the gradient. Considering the available data, AncãoC seems to exhibit a stable dune formation characterized by a prograding dune pattern. However, the relatively low presence of burial-tolerant and dune-building species suggests that sediment accumulation in the incipient dunes might not be as crucial as in other cases. Consequently, the primary factors influencing species composition are the favorable conditions created by shoreline evolution and the dune's morphology, which provides stable conditions.

It is worth noting that all the profiles on the Ancão Peninsula showcase a rich diversity of plant species. This diversity is indicative of the stability of the dune system in this area. The presence of various species capable of responding to distinct environmental stressors can contribute to the preservation of ecosystem functions, even in changing conditions (Ciccarelli et al., 2012).

Regarding sediment transport, the findings for the same study area in the Ria Formosa by Costas et al. (2020), revealed that the critical wind fetch required for optimal aeolian sediment transport was rarely met along the coastline of the Ancão Peninsula. The sediment transport potential depended on strong winds coinciding with low runup levels, yet this pattern alone could not explain all the variations. This highlights the importance of local factors like the surficial grain size or morphology of the profiles, and local sediment budgets.

Central Sector

Barreta is positioned within the central sector, as it spans both the western and eastern sides. Upon closer examination, the profile falls on the eastern side of the Ria Formosa. Therefore, the assessment of wind and wave conditions pertains specifically to the eastern side.

The foredune at **Barreta**, while not exceptionally large, boasts a relatively substantial width, signifying a stable condition. The extensive nature of the incipient foredunes (depicted by the morphology and plant community) means that this profile is still evolving. Since the backshore width is comparatively big, the dune seems to have a lot of space for development. Also, the beach of this profile is very steep and usually present very prominent beach berms, suggesting a highly dynamic area. Examination of the evolution rate of its shoreline reveals a clear progradation trend, with the shoreline advancing at a rate of approximately 5 meters per year in the last 71 years. Figure 19 provides an insightful division of the development of Barreta into two phases: before and after 1996. Until that year, the trend displayed pronounced progradation. Subsequently, the rate of progradation decreased, leading to a stable trend. Here, it is assumed that this trend shift was mostly dictated by the infilling of the accommodation space created by the jetty downdrift (Herrero et al., 2019). The species diversity in this profile is not notably high. However, a variety of different species have been found in the incipient foredunes. Analyzing the plant types, high-burial tolerant plants are predominant. The number of these plants and the other factors considered indicate that the profile at Barreta provides stable conditions so that the dune continues to develop. The detrended correspondence analysis for this profile shows that the species composition in the stoss and the incipient foredune are identical. The crest and the lee have a different composition and especially the lee is more similar in composition to the first two zones than to the crest. Especially in this profile, the width of the beach and its evolutionary trends have the greatest influence on species composition.

Overall, in the western and central sectors, encompassing profiles like AncãoA, AncãoB, AncãoC, and Barreta, several notable characteristics emerge. These dunes consistently exhibit higher crest heights and broader dimensions, which collectively contribute to their larger overall size. These features, imply that they offer enhanced protection against erosive forces. The presence of steep and high beach berms suggests that the western profiles are characterised by reflective beaches. In terms of species composition, the profiles of AncãoB and AncãoC are similar in sequence, evolved and with very well defined cross-shore zonation. Barreta also follows a similar trend, only the lee differs significantly in its alongshore variability.

Eastern Sector

The upcoming section will concentrate on the eastern sector of the Ria Formosa, namely on the islands of Culatra, Tavira, Cabanas, and the Peninsula of Cacela. These distinct areas exhibit their own array of sedimentary patterns and coastal processes, contributing to the mosaic of this coastal ecosystem. The objective is to understand the various factors influencing habitat distribution and species composition while striving to establish potential correlations among them. Moving from west to east, the first island under consideration is Culatra. To ensure a comprehensive analysis, Culatra was divided into three different study areas, as there are large differences in morphology and species composition along the island.

CulatraA boasts a wide dune, although not particularly tall, with a stoss zone that is relatively narrow, creating a steep stoss slope. By consulting the shoreline evolution rates might imply slight progradation of the dune. However, a closer look at the data reveals a consistent retreat trend since 2009, as shown in Figure 17. During the fieldwork, four cross-shore zonation lines were established and documented. Interestingly, the crest of this dune displayed the highest species diversity among the recorded lines, hosting a diverse community of 14 different plant species. Most of these species fall into type II, as depicted in Figure 27, signifying a relatively mature and distinct ecosystem that has likely remained stable for some time. Additionally, a few type I plant species were identified. About one-third of the plant species belong to type III, and these species are notably abundant in the area, as indicated in Figure 26. This suggests dynamic environmental conditions at the frontal area of the dune. According to the DCA, the incipient foredune exhibits a composition similar to that of other profiles, sharing commonalities with the same zone in TaviraA. However, the stoss and crest zones show considerable differences and do not align closely. Taking these evaluations into account, it becomes clear that the stability of the seaward part of this profile is relatively low, primarily due to the prevailing trend of shoreline retreat. The fact that it has only appeared recently could also be the reason why only the plants at the front show instability.

In profile **CulatraB**, the dune is lower, notably with a very small foredune and stoss width. There is an interesting pattern in the evolution rates – this profile barely existed before 1989 - but since then, there has been a significant trend of shoreline progradation, as seen in Figure 19. In fact, only the first three transects recorded for morphological evaluation from the year 2011 show a small pronounced dune (Figure 11). During the field visit an already stable dune with incipient foredune was visible, but in general this area shows smaller and younger dunes in comparison to CulatraA. This suggests that a pronounced progradation has taken place in the last 12 years since the Lidar was recorded (2011) to the current conditions (2023). Six cross-shore zonation lines were recorded and depicted a well-developed dune with all zones. When compared with the plant types found in the profile, it is very clear that the largest proportion of plant species belongs to type III. Notably, the dominant plant species, prevailing in all the zones, include *Elymus farctus* (Type III) and *Silene Nicaeensis* (Type II), with the latter not being tolerant to burial (AppendixA; Table 2). In essence, the vegetation composition indicates the presence of a developed dune that is actively prograding but not growing vertically, due to the prevalence of Silene Nicaeensis, which is not dune-builder. The DCA proves that the different zones of this profile do not differ much in their composition. Especially the zone of incipient foredune as well as crest and lee differ only slightly in their cross- and alongshore variability. The composition of the stoss slope is in a different region of the graph, but it also shows similarities with other profiles of the same zones. Especially the similarity between the incipient foredune and the zones of the dune further to the back marks the dynamic of this area which is strongly prograding. The determining influencing factor in this case seems to be the shoreline evolution trend.

The **CulatraC** profile is not included in the morphological evaluation due to the absence of a dune at the time of LIDAR recording, with initial records dating back only to 2011. Remarkably, the evolution rates are highly significant, indicating a clear progradation of nearly 30 meters annually. During the field visit, six of the seven recorded cross-shore zonation lines were incipient foredunes. A dune was observed and therefore one CZL was recorded as a crest, which also proves that this is a developing and young area. The zone of the incipient foredunes as well as the crest is characterized by a few plant species that are capable of withstanding burial and actively contribute to dune formation. But in the zone of the crest there are also a significant number of plants that require more stable conditions, indicating developed or stable dune. In this context, it is crucial to mention that overall, more Type III plants were found than Type II. Considering these factors, it is reasonable to infer that this area represents a minimally established dune undergoing active progradation. The fast progradation can also explain the many and very low foredune ridges because the area probably did not have enough time for successional change, meaning that some areas might not have active sediment transport, but the plant succession is still happening. In relation to the DCA, it is quite clear that the crest is also in a similar composition to most of the incipient foredunes of other profiles of the eastern part of the Ria Formosa. The incipient foredune zone of this area differs from the crest in its cross-shore variability and is similar to other stoss zones. This suggests a highly dynamic profile, clearly driven by shoreline evolution, driven in turn by a positive sediment budget.

It is important to mention that the inlet between Barreta and Culatra, the so-called Faro-Olhão Inlet, is an artificially opened and fixed inlet. It is nowadays the main inlet in the entire system and is stabilised by two jetties, one in Barreta and one in Culatra. Previously, the main inlet was Armona Inlet between Culatra and Armona (Pacheco et al. 2010; Kombiadou et al., 2019). By moving eastwards along the Culatra Island rates increase as approaching the Armona Inlet. This is more the expansion of the island less the progradation. It grew when the inlet closed because the Faro-Olhão inlet gained hydraulic competence and thus tidal prism. These trends are bigger because the island did not exist before. According to the calculations in the work of Kombiadou et al. (2019), the coast has since grown by about 3.2 kilometers towards the east, which is about 50 meters per year. Promoting the rapid formation of Culatra B and C, and explaining their plant composition, dominated by plants typical of incipient dunes.

Tavira Island presents two distinct profiles, starting with **TaviraA**. The dune here, like the width of the beach, is relatively average compared to all other profiles. It is striking that the dune is very wide, which indicates strong protection against erosion by storm events. The stoss width is very short, which also makes the slope very inclined (Table 1). This inclination usually stands for a scarp. And when examining the evolution rates, a decline becomes evident. The profile seems to inhabit an evolved dune which appears to be in a retreating state. Taking a closer look at the fieldwork evaluation, seven cross-shore zonation lines were established in TaviraA, with the majority covering the lee of the dune, which underlines the retreating state since there is more profiles recorded in the back of the dune than in the front. Also, this dune lacks any species of plant type I, typically associated with stable dune environments. Instead, many type II and III individuals are concentrated in the slope and crest, while the lee predominantly hosts two species, *Anthemis maritima* and *Helichrysum picardii*, which are not burial tolerant and grow in a bushy manner (AppendixA). Since many of the plant species are burial tolerant, especially up to the lee, the profile seems to be in a dynamic environment. However, taking a look at the lee of the dune, there are no burial tolerant plants which describe a more evolved area. This contradiction may serve as evidence of a retreating trend. In a stable dune system undergoing retreat, the absence of tolerant plants but the presence of such a mixing phenomenon becomes apparent. In this context, the DCA notes that the individual dune zones have greater distances in their composition. Whereas the zone of incipient foredunes, the stoss and the crest are relatively similar and differ mainly in their cross-shore variability. The lee part of the dune differs significantly in alongshore variability. That underlines that this system is in retreat because the crest in particular is very similar to the species composition of the incipient foredune. The reason for this is the evolution rates of the shoreline and the influence of waves that create the scarp in the dune.

TaviraB profile exhibits only slight morphological differences from its neighboring profile on the same island (Figure 12). The crest height, and consequently the foredune, is approximately one meter higher than in TaviraA. Although it is slightly narrower, it still maintains a comparatively substantial width. Therefore, the dune seems to be in a stable environment. Another factor is the size of the beach, which is almost more than half of the average size. Also, both profiles share the same slope value for the stoss slope of the dune, suggesting it might be a scarp and potentially an unstable environment. The examination of the shoreline evolution rates supports this assumption, as this environment is characterised by strong fluctuations in progradation and retreat in relation to the shoreline (Figure 17). Eight CZLs were recorded in this profile, with each dune zone covered twice. This profile boasts rich plant diversity, ranking second among profiles with 21 different plant species. Notably, it has a substantial presence of plant type I species, in comparation to other profiles. Type III plants are predominantly found in the incipient foredune and the stoss slope, while the crest hosts mainly type II plants. In the lee, type I plants are prevalent, even including the identification of a woody species. Overall, these records suggest a stable dune with dynamic features. The results of the DCA are almost identical to those from the TaviraA profile, except that the zone of the stoss has slightly higher alongshore variability. And the biggest difference being the crest, which stands out from the space around the zone of incipient foredunes and has a slightly more stable resemblance to the zone of lee. Here, it could be concluded that there is a more stable dune. The composition of this profile, aside from being influenced by the dynamic evolution rates, can also be attributed to the width of the beach and the impact of waves. These factors provide the area with the potential for both progradation and retreat. This dynamism indicates a history of alternating erosive and accumulative or growth episodes over time.

The **Cabanas** profile presents a unique dune landscape across its lines. In some, there is hardly any discernible foredune morphology, lacking notable height, width, or stoss (Figure 13 & Table 1). This profile shows incipient morphologies and is partially affected by a channel in the back of what was interpreted as the incipient foredune.

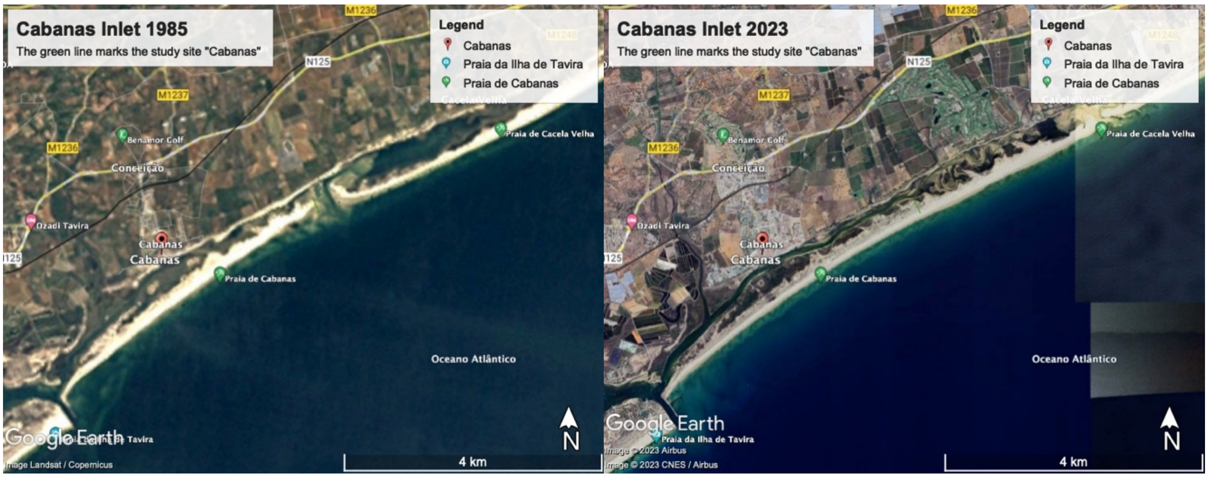


FIGURE 31 AERIAL VIEW OF THE CABANAS INLET IN 1985 AND 2023.

Historical records, notably a 1985 satellite image from Google Earth Pro, reveals that the site was previously occupied by an inlet, now transformed into a dune-like structure (Figure 31). During fieldwork, the presence of a dune was confirmed and examined in ten cross-shore zonation lines. Most of them were assigned to the part of the incipient foredune. As the picture in Figure 32 illustrates, the first cross-shore zonation lines are also on a flat surface without clear dune morphologies on the side of the former inlet. Among these lines, CZLs one, three, and five contained bare sand, while two and four exhibited more vegetation. Multiple small incipient foredune crests are evident ahead of the primary dune. On the slopes, crests, and in the lee, plant type III predominates both in terms of species and individuals. While there are sporadic occurrences of type II and even a few instances of type I plants, they are in limited numbers. It is worth highlighting that this profile exhibits relatively low species diversity (Figure 27). These findings collectively signify a young and dynamic system, hosting low incipient foredunes with progradation potential. However, a closer look at the evolution rate reveals a significant retreat. Cabanas Island exhibits the most substantial retreat among the islands, with an approximate annual decline of five and a half meters per year (Table 1). Intriguingly, Figure 18 indicates a recovery as well as regrowth trend at the last measured point in 2018, suggesting a possible progradation phase within the whole evolutionary history of the island. This mobility aligns with findings from Kombiadou et al. (2019), emphasizing the inlet dynamic nature. Between 1986 and 2014, the central area of the Cabanas Island and Cacela Peninsula experienced accretion, with limited erosion in the west and more significant coastal retreat and dune erosion in the east. The results of the DCA also show that it is more of a dynamic system. The composition of the individual zones is very close to each other, and crest and lee

FIGURE 32 PICTURE TAKEN DURING THE FIELDWORK IN THE ISLAND OF CABANAS.

even have more similarities with the zone of the incipient foredunes. The influencing factor here is the sediment beach budget and the morphology, which grants space for progradation.

The last two profiles, situated on the Cacela Peninsula, lie in close proximity, separated by only about 250 meters, resulting in a rather similar appearance. The height of the dune in **CacelaA** compared to the mean of all other values suggests that this dune has an average height. But looking at the width of the dune, it is comparatively narrow and therefore not very stable. Also, the width of the backshore is quite narrow, which suggests an unstable system as well. However, a closer examination of shoreline evolution rates reveals a nuanced scenario. While there is evidence of significant progradation, a more recent trend from the recordings after 2008 suggests a shift toward retreat (Figure 18). The assessment of vegetation reinforces the impression of a system with low stability, potentially in retreat. The absence of incipient foredunes and the limited prevalence of type I plants are notable features. Additionally, the presence of woody species, primarily in the dune rear portions, hints at an unusual situation, as these species are typically found inland and not part of the dune structure. Yet, here they have become integrated into the dune. It is worth noting that no major population of dune-forming plants is concentrated in the frontal area of the dune. Instead, type II plants dominate across all sections of the dune. Thus, no incipient morphology can be discerned, nor can the typical community associated with prograding dunes be seen. Woody species are observed in the lee and even on the crest. It is also worth mentioning that the roots of some woodie species (Retama) were under wind and wave erosion related to the retreat. These botanical observations collectively suggest a system currently undergoing retreat, supported by the trend. In this context, the detrended correspondence analysis also shows that the species composition in the crest as well as in the lee is similar to many other profiles of the zone of incipient foredunes. Only the lee differs in cross-shore variability. A retreat is also recognised here, as even the crest is similar in its composition to other dynamic zones. The reason for this is the shoreline trends in combination with the wave action, which causes the system to slowly retreat.

The final profile within this system is **CacelaB**, which, as previously noted, shares a resemblance to its neighboring profile in terms of morphology, though the dune here is about half a meter smaller. A narrow dune width also hints at a lack of stability. Moreover, the relatively steep slope suggests a dune that has already been scarped. And a closer examination of the evolution rates implies that this dune has likely experienced erosion, possibly even partial collapse somewhere after the year of 2013 (AppendixC). This profile exclusively encompasses the stoss slope and crest sections, as incipient foredunes were absent, and a distinct lee section was not evident, because it was covered by Retama and impossible to access. Although all plant types were identified at least once on this profile, the slopes displayed overgrowth, without an excessive abundance of type III plants. The majority of individuals in the crest belonged to type II plants, indicating somewhat more stable conditions. Nevertheless, woody species also make an appearance on the crest, reinforcing their connection to the hinterland. Altogether, these observations suggest that this system is currently undergoing retreat. Looking at DCA, it becomes apparent that the species composition of the stoss is very similar to the incipient foredune zones of other profiles. Except for the crest, which has high similarities with the lee part of the dune in CacelaA. In this case, the species composition is clearly influenced by shoreline evolution.

In contrast to the western sector, the eastern sector, with profiles such as CulatraA, CulatraB, CulatraC, TaviraA, TaviraB, Cabanas, CacelaA, and CacelaB showcased dunes with lower heights and narrower widths, often characterized by steeper stoss slopes. The beaches on this site of the Ria Formosa are more dissipative beaches. And the eastern dunes are more susceptible to change, reflecting a more dynamic environment. These findings hold significant implications for the stability and resilience of the Ria Formosa dunes, as they may be more vulnerable to natural disturbances. Not only are they much smaller in size and extent than the dunes on the western side, but the prevailing dynamics of shoreline evolution are much more influential on the morphology here. Analyzing the wind wave data, a notable distinction between the western and eastern sites emerges. In the west, the waves are considerably more powerful and occur with greater frequency. There are variations in wind directions, particularly in terms of their suitability for sediment transport. Furthermore, due to the somewhat easier mobility of sand particles in the east, this region is twice as susceptible to wind-driven sand transport compared to the west.

8. CONCLUSION

The aim of this study was to shed light on the intricate dynamics between different interconnected drivers of species composition in order to decipher the complex dynamics of the Ria Formosa dune system. Through careful analysis, which included the identification of a total of 40 distinct plant species across the system, important insights have been gained that shed light on the forces that shape this coastal ecosystem.

Throughout the study, a correspondence between morphological parameters and vegetation conditions has been evident. The link between these factors is present to the extent that both morphology and vegetation serve as indicators of the condition of the dune system.

In particular, dunes characterised by greater height and width are often consistent with stable, more evolved ecosystems, consisting of different types of plants in their different zones. In contrast, narrower dunes with steeper slopes often indicate dynamic, evolving landscapes. These observations are also linked to the interaction of environmental factors. One of these factors is the evolution of the shoreline, which exerts a significant influence. Profiles with progradation trends tend to host more stable as well as incipient foredunes, often characterized by a greater prevalence of Type III dune-building plants. While those in retreat represent a system in transition, often characterised by a greater prevalence of Type

III plants in the stoss or even crest of the dune. This duality highlights the profound influence of coastal evolution on dune morphology and vegetation.

In addition, the role of wind and wave dynamics cannot be underestimated. It has been found that strong waves from certain directions, especially from the southwest for the western profiles and from the southeast for the eastern profiles of the Ria Formosa, can influence dune features. Including crest height and prevalence of scarping. These predominant patterns interact with the evolution of the shoreline and contribute to the shaping of the dunes as well as the distribution of plant communities.

The results have wider implications for the understanding and management of coastal dune ecosystems. First, understanding the close relationship between morphology, vegetation and environmental drivers provides valuable insights for ecosystem monitoring and conservation. Dunes that exhibit characteristics of instability may require proactive management strategies to control erosion and maintain biodiversity. Thus, the ability to observe a dune and make statements about its development based on its morphology and species composition can be a very helpful tool. The results also highlight the need for a holistic approach to coastal management that considers both natural and anthropogenic influences. For example, measures to stabilise the coastline can have cascading effects on dune morphology and vegetation, which requires careful balancing between protection and intervention. Given the increasing threat to coastal areas from climate change and sea level rise, understanding the web of factors that shape dune systems is of great importance. This work contributes to this understanding and provides a foundation on which future research and conservation efforts can build.

For the future, there are promising avenues for further research in this area. Future studies could deepen the intricate relationships between certain plant species and dune morphology and provide a more nuanced understanding of their interdependence. In addition, research into the effects of changing shorelines is very interesting to understand where the system is heading, also from the perspective of rising sea levels. Moreover, extending these data to a longer time period, ideally with synchronised data collection for morphology and vegetation, would improve the accuracy of these results. Furthermore, the development of more robust, high-resolution data sources for shoreline evolution could reduce uncertainties in future research.

In conclusion, this work has revealed the complex interactions that shape the coastal dune system and their species composition in the Ria Formosa study sites that have been investigated. The integration of morphological, vegetation and ecological factors provides valuable insights that are relevant for both conservation and management. Although there are limitations, they open doors for further investigation and deeper understanding of this and other coastal ecosystems.

APPENDIX

AppendixA

	AncãoA				AncãoB				AncãoC			
	I	S	C	L	I	S	C	L	I	S	C	L
Ammophila arenaria						1			3			
Anthemis maritima		5	5	2				4				
Armeria pungens		0.4	13	20								
Artemisia crithmifolia			19	8		6	18	25	15	19	26	18
Cakile maritima												
Calystegia soldanella						3	4		8	1		
Carpobrotus			1	1				2				1
Coristospermum lucidum												
Corynephorus canescens												
Crucianella maritima		1		1		6	3	3	5	2	1	1
Cynodon dactylon												
Elymus farctus	12	40	12	1		23	15	13	14	9	5	5
Erodium cicutarium										6	1	2
Eryngium maritimum						6		1	6			
Helichrysum picardii				16								
Linaria lamarkii						1		1				
Linaria pedunculata						7	2		1		1	
Lotus creticus		34	1	2		4	35	24	2	8	11	0.4
Malcolmia littorea		1	19	8		1	6	4		3	1	3
Medicago littoralis		1								9	4	3
Medicago marina						5	2		21	10	5	2
Opuntia sp.												

Otanthus maritimus		2				1	1	1	1			
Pancratium maritimum						6	4	6	2	1	2	2
Paronychia argentea			26	20				1		15	24	42
Polygonum maritimum		4										
Polycarpon alsinifolium						1	6	6	0.2	6	1	
Polycarpon polycarpoides												
Polycarpon tetra subsp. alsinifolium												
Pseudorlaya pumila		1							0.2			
Reichardia gaditana							1			1	3	0.4
Retama monosperma												
Salsola kali												
Scabiosa spp												
Sedum sediforme												
Silene nicaeensis		5	1			1		2	6	5	5	10
Sonchus asper												1
Suaeda vera												
Thymus carnosus				8								
Vulpia						1	3	2		5	4	5

	Barreta				CulatraA				CulatraB			
	I	S	C	L	I	S	C	L	I	S	C	L
Ammophila arenaria	3	1	25	4.5		5				2	7	6
Anthemis maritima						1	9					
Armeria pungens												
Artemisia crithmifolia		6	34	21		14	20					12

Cakile maritima												
Calystegia soldanella												
Carpobrotus												
Coristospermum lucidum				0.3			1					
Corynephorus canescens				3								
Crucianella maritima		1	5	14		30	21			5	9	27
Cynodon dactylon												
Elymus farctus	20	5	5	7.5	31	27	3		47	49	21	5
Erodium cicutarium												
Eryngium maritimum	28	7	1.5	1								3
Helichrysum picardii				16		1.5	32					
Linaria lamarkii												
Linaria pedunculata				1.5								
Lotus creticus						1.5	1					
Malcolmia littorea						4	1					2
Medicago littoralis				0.3			1					
Medicago marina				1						2.5		
Opuntia sp.												
Otanthus maritimus	2	3		0.3						1		
Pancratium maritimum				1.5		2				1	3	
Paronychia argentea										7		
Polygonum maritimum	6	3		0.3			1					
Polycarpon alsinifolium												
Polycarpon polycarpoides												
Polycarpon tetra subsp. alsinifolium												

Pseudorlaya pumila												
Reichardia gaditana				1			1					
Retama monosperma												
Salsola kali												
Scabiosa spp												
Sedum sediforme												
Silene nicaeensis	3	13	1.5	15		3	1		6	21.5	36	28
Sonchus asper												
Suaeda vera												
Thymus carnosus												
Vulpia												

	CulatraC				TaviraA				TaviraB			
	I	S	C	L	I	S	C	L	I	S	C	L
Ammophila arenaria	2	17				7		3		5	4.5	
Anthemis maritima							6.5	39		9	31	19.5
Armeria pungens												
Artemisia crithmifolia	0.3							1			14	3
Cakile maritima												
Calystegia soldanella												
Carpobrotus												
Coristospermum lucidum												
Corynephorus canescens												
Crucianella maritima	3	12					3	4		3	4	1
Cynodon dactylon												22
Elymus farctus	43	10			60	42.5	20	3	67	39		
Erodium cicutarium												

Eryngium maritimum	0.3	1.5										
Helichrysum picardii								18			21	32.5
Linaria lamarkii												
Linaria pedunculata												
Lotus creticus							25	1		2		3
Malcolmia littorea								3		9	5	
Medicago littoralis												1
Medicago marina										1		
Opuntia sp.												
Otanthus maritimus						2						
Pancratium maritimum	0.3							2		1		
Paronychia argentea												1
Polygonum maritimum	2	1.5				6	1.5			3		
Polycarpon alsinifolium												
Polycarpon polycarpoides										4	2	1
Polycarpon tetra subsp. alsinifolium										7	7.5	
Pseudorlaya pumila												
Reichardia gaditana										1		
Retama monosperma												
Salsola kali												
Scabiosa spp												
Sedum sediforme												2
Silene nicaeensis	19	24										
Sonchus asper												
Suaeda vera									1			
Thymus carnosus								2				7

Vulpia												

	Cabanas				CacelaA				CacelaB			
	I	S	C	L	I	S	C	L	I	S	C	L
Ammophila arenaria		3	36.5	2			3	1			8.5	
Anthemis maritima												
Armeria pungens												
Artemisia crithmifolia						4	7	24			19	
Cakile maritima						2	2			13		
Calystegia soldanella												
Carpobrotus												
Coristospermum lucidum												
Corynephorus canescens												
Crucianella maritima				2			23	37		7	27	
Cynodon dactylon												
Elymus farctus	33	34	29	41		15.5		1		16	4	
Erodium cicutarium												
Eryngium maritimum		1		1								
Helichrysum picardii												
Linaria lamarkii												
Linaria pedunculata												
Lotus creticus			2			15.5	10	4		6	1	
Malcolmia littorea							3	10			7.5	
Medicago littoralis												
Medicago marina		3										
Opuntia sp.							3					

Otanthus maritimus												
Pancratium maritimum										1	3	
Paronychia argentea												
Polygonum maritimum		1										
Polycarpon alsinifolium												
Polycarpon polycarpoides												
Polycarpon tetra subsp. alsinifolium												
Pseudorlaya pumila	0.4	3										
Reichardia gaditana												
Retama monosperma								8			1	
Salsola kali						4						
Scabiosa spp											5	
Sedum sediforme												
Silene nicaeensis		2	5.5	15			8	1			1	
Sonchus asper												
Suaeda vera												
Thymus carnosus												
Vulpia												

AppendixB

Years	AncãoA	AncãoB	AncãoC	Barreta (until 1996)	Barreta (after 1996)	CultaraA
1947				0.00		
1952	0.00	0.00	0.00	-0.37		0.00
1958	0.08	-17.14	-8.15	-3.53		96.74
1969	11.13	-10.99				82.80
1972	6.65	-22.24	16.55	165.57		78.34
1976	3.00	-23.22	4.23	211.20		42.80
1978						
1980	-0.07	-22.32	14.24	214.87		34.88
1985				297.38		39.67
1986						
1989		-19.99	16.52	287.29		63.57
1996	-0.71	-18.00	9.57		254.20	57.07
1999		-21.16	24.37		228.87	70.60
2000					283.62	71.57
2001	-2.47	-17.27	48.49		289.41	68.25
2002	-0.70	-18.21	22.07		286.54	60.51
2005	-1.51	-20.40	46.33		289.29	69.26
2007						
2008	3.59	0.33	54.11		293.71	73.76
2009	1.93	-8.75	53.51		285.85	72.75
2013						
2014	-3.21	-2.71	54.20		274.56	62.63
2018	-6.81	-5.68	47.72		270.36	43.93
2019						

Years	CultaraB	CultaraC	TaviraA	TaviraB	Cabanas	CacelaA	CacelaB
1947							
1952			0.00	0.00	0	0.00	
1958			3.78	0.33	-0.84	31.84	
1969			-0.52	-0.97			
1972			4.23	-3.14	-52.59	44.26	
1976			0.55	-9.79	-56.48	48.39	
1978					-64.35	55.50	
1980			-5.49	1.38			
1985			1.54	5.86	-112.66	87.61	
1986			0.89	10.54	-112.58	90.39	
1989	0.00		-14.99	6.03	-133.49	79.55	
1996	69.98		-32.61	-5.48	-170.15	89.98	
1999	70.07		-47.76	-5.55			

2000	19.23						
2001	19.38		-47.14	-5.43	-183.18	78.32	
2002	71.08		-47.07	8.91	-192.44	79.41	
2005	125.72		-47.00	-3.34			
2007							0.00
2008	159.31		-41.41	-3.59	-318.43	90.38	
2009	211.40	0.00	-41.17	-2.79			
2013							3.47
2014	201.98	173.65	-38.28	8.66	-415.76	85.96	-3.10
2018	201.98	298.50	-55.52	-13.57	-225.44	53.71	-2.93
2019							-4.49

AppendixC

Year	AncãoA	AncãoB	AncãoC	Barreta	CulatraA	CulatraB
1952	0	0.00	0.00	0.00	0.00	
1958	18	-3.02	6.24	58.48	61.79	
1969	2	-18.47		219.37	54.69	
1972	-5	0.67	5.57		47.91	
1976	0	6.30	-0.29	227.05	16.43	
1978						
1979						
1980		8.34	2.47	202.21	26.65	
1985						
1986	1	6.45	3.78	285.28	11.24	
1989	-13	-23.60	-5.53	260.53	24.76	
1996	-17	-10.38	0.14	227.62	-5.56	0.00
1999		-3.28	6.29	278.75	35.01	13.95
2000				268.79	18.48	9.08
2001	-3	16.36	44.90	286.26	21.91	358.04
2002	0	2.90	39.68	292.66	18.08	377.66
2005	-7	10.19	41.13	297.84	31.65	476.98
2007						
2008	-17	-1.04	25.44	280.22	12.08	479.86
2009	-18	1.80	25.55	266.94	18.31	520.66
2013						
2014	-29	-14.21	20.22	253.83	-0.78	545.71
2017						
2018	-5	17.34	39.68	273.40	23.75	599.79
2019						

Year	CulatraC	TaviraA	TaviraB	Cabanas	CacelaA	CacelaB
1952		0.00	0.00	0.00	0.00	
1958		-6.68	0.07	-11.91	26.14	
1969		4.37	1.77	-37.95		
1972		32.77	20.76	-46.79	34.99	
1976		6.57	16.67	-40.84	76.78	
1978					47.91	
1979			15.32			
1980		-1.55				
1985			20.56		103.21	
1986		-2.62	8.39		66.55	
1989		-9.49	8.12	-98.17	67.35	
1996		-7.27	6.37	-114.08	82.54	
1999		-19.54	16.54			
2000		-41.95	-1.40			
2001		-43.10	9.70	-137.62		
2002		-50.85	10.64	-184.23	69.32	
2005		-40.76	25.43	-178.83	71.08	
2007						0
2008		-29.09	6.81	-184.24	77.79	
2009	0.00	-49.28		-319.58		
2013						-46.78
2014	173.65	-48.12	9.84	-186.92	58.19	-27.25
2017						-22.32
2018	298.50	-34.19	3.77	-175.47	41.25	
2019						-13.93

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