Ecological Indicators 137 (2022) 108770

Contents lists available at ScienceDirect

Ecological Indicators

journal homepage: www.elsevier.com/locate/ecolind

A new index to assess the state of dune vegetation derived from true colour images

Lara Talavera [*], Susana Costas, Óscar Ferreira

Centre for Marine and Environmental Research (CIMA), FCT, Universidade do Algarve, Campus de Gambelas, 8005-139 Faro, Portugal

ARTICLE INFO

Keywords:
Unmanned Aerial Systems
Dune vegetation state index
Gull impact
Dune conservation
Dune vegetation mapping
Image classification

ABSTRACT

Vegetation on coastal dunes is a key element, as it promotes the growth and stabilization of these landforms while contributing significantly to biodiversity. Physical (e.g. impact of storms), ecological (e.g. animal grazing) and human-related (e.g. farming and recreation) factors may disturb coastal dune vegetation, changing dune dynamics and eventually inducing ecogeomorphic state shifts. Therefore, understanding vegetation dynamics and state turns crucial to predict dune evolution paths. The latter must be supported by observations combined with the development of tools (e.g. indexes) able to detect eventual changes and to automatically categorize the state of the vegetation. Here, a multi-step index to characterise the dune vegetation state (DUVES) was developed and tested in Barreta Island (South Portugal), where grey dune vegetation has declined in recent years. The index was computed using classified true colour orthophotos and orthomosaics derived from UAS (Unmanned Aerial Systems) surveys. Google Earth images were used as complementary data to analyse the evolution trends. The possible sources of disturbance (i.e. human-related activities and gull occupation) were also investigated by comparing their distribution with the vegetation changes. DUVES successfully identified different states of vegetation cover that expressed its stability, perturbation or growth based on temporal changes and allowed the analysis of their evolutionary trends. The distribution of perturbation was mostly associated with gull nesting areas, increasing over time, and to a less extent to human-related activities. The observed grey dune habitat loss was due to replacement of plants typical from this habitat by ruderal species promoted by the positive feedback established between gulls and vegetation. The developed index proved to be of great utility to define dune habitat evolution and understand the associated drivers, being a tool with a wide range of applications, namely for improving future coastal management actions aimed at conserving dune habitats. Moreover, DUVES is potentially transferable due to its easy adaptability depending on the particularities of each study site or goal.

1. Introduction

Coastal dunes are sedimentary landforms present in nearly any coast of the world (Hesp, 2011), including temperate and humid tropical areas, arid climates, and even regions covered by snow during the winter (Moreno-Casasola, 2008). Where present, dunes may occupy small extents or expand along several kilometres inland and/or alongshore, and display elevations that range from less than one meter to hundreds of meters (Martínez et al., 2013). The formation and evolution of dunes are mainly conditioned by the availability of sediment, the adequate wind conditions to promote its aeolian transport and by the plant community, its density, distribution and height (Hesp, 2008). Pioneer plants adapted to colonise the unstable beach-dune transition interact with the aeolian sediment flux causing sediment retention and accumulation while growing, ultimately leading to the formation and vertical growth of incipient foredunes. In prograding sandy coasts, the formation of new incipient foredunes will evolve into established foredunes, transforming the former into relict features and leading to the formation of foredune plains over time (Hesp, 2011). The increasing distance to the sea and the varying topography across these foredune plains result in distinct cross-shore environmental gradients (e.g. salinity, sedimentation, nutrients, flooding, organic matter, soil acidity, and shelter, among others) that define considerably the spatiotemporal cross-shore zonation and diversity of plants (Hesp, 2011; McLachlan and Defeo, 2018). This zonation also influences the diversity of fauna (e.g. insects, mammals, seabirds) and ultimately leads to the establishment of a variety of habitats from sea to land. These include foredune habitats dominated by sand movement and high salinity (beach, embryo or incipient dunes,

---

* Corresponding author.
E-mail addresses: ltmadrigal@ualg.pt (L. Talavera), scotero@ualg.pt (S. Costas), oferreir@ualg.pt (Ó. Ferreira).

https://doi.org/10.1016/j.ecolind.2022.108770
Received 20 October 2021; Received in revised form 6 March 2022; Accepted 8 March 2022

foredunes, blowouts, and active dunes), interdune habitats prone to inundation (wet slacks or depressions) and back-dune habitats stabilized by a continued vegetation cover (also known as secondary or grey dunes) (Hesp, 2011; Hesp and da Silva, 2016; Miller et al., 2010). The definition of the habitat specificity is linked to the dune morphology (Bazzichetto et al., 2016; Miller et al., 2010) and the cross-shore variability of the plant functional traits (e.g. height, diameter, leaf size, root depth) (García-Novo et al., 2004; Hesp, 1991).

Physical (e.g. climate variations, impact of storms, sea-level rise, overwash, flooding events), ecological (e.g. animal grazing) and especially human-related (e.g. grazing, farming, construction, and recreation) agents are known to disturb vegetation in coastal dunes (Delgado-Fernandez et al., 2019; Martínez et al., 2013; Provoost et al., 2011). Such disturbances can cause perturbations, inducing significant shifts in the state, evolution and dynamics of the dune system (Robin et al., 2021). This may, in turn, induce habitat fragmentation and the existence of patchy dune fields (even within the same habitat type) due to disruption pulses (Laporte-Fauret et al., 2020; Martínez et al., 2001). Dune vegetation mapping and monitoring are then fundamental to identify and understand the causes of vegetation change (Laporte-Fauret et al., 2020) in order to apply informed dune conservation and management strategies and ensure the perpetuation of dune ecosystem services provision to society.

The mapping and monitoring of dune vegetation have been increasingly relying on airborne remotely-sensed data obtained from different platforms and sensors offering various spatial, temporal, spectral, and radiometric resolutions, which are often complemented with ground-based measurements and *in situ* observations. This technological evolution allowed the study of dune vegetation using images with different spectral bands, such as RGB (e.g. Delgado-Fernandez et al., 2019; García-Romero et al., 2019; Hilgendorf et al., 2021), multispectral (e.g. Hague, 2016; Marzialetti et al., 2019; Özdemir et al., 2005) and hyperspectral imagery (e.g. Shanmugam et al., 2003; Valentini et al., 2020; Zhang and Baas, 2012), or their combination. The different spectral bands allow the computation of a variety of vegetation indices, including the widely used Normalized Difference Vegetation Index (NDVI) (e.g. De Giglio et al., 2019; Hague, 2016; Jackson et al., 2019; Marzialetti et al., 2019), which offers valuable quantitative information of dune vegetation characteristics (e.g. state, cover, density) and their changes over time and space.

The extraction and analysis of vegetation characteristics from airborne data depend on image pre-processing procedures and require the application of image classification techniques such as the supervised and the unsupervised classification methods (Xie et al., 2008). The election of the previous may vary depending on the goal of the study, the image resolution and the complexity and knowledge of the area of interest (Jensen, 1986). The identification and analysis of vegetation changes in coastal dunes require the availability of multi-temporal datasets and the application of qualitative and quantitative change-detection techniques, such as image differencing, vegetation index differencing, and/or post-classification comparisons (Vinet and Zhedanov, 2011). Indices that have been developed to investigate coastal dune vegetation changes are mainly focused on exploring natural or artificial coastal dune disturbance sources (e.g. Delgado-Fernandez et al., 2019) or identifying dune stability patterns (e.g. Laporte-Fauret et al., 2020), while overlooking vegetation growth and the colonization of dune systems. In addition, some were computed using data of very high spatial, temporal, spectral and/or radiometric resolutions acquired with remote-sensing techniques of high cost, whose extraction, processing and analysis is time-consuming and involves complex approaches, thus making their use unaffordable for many potential end-users. More importantly, the mentioned indices explore dune vegetation perturbation or stability without quantifying the expected (or typical) spatiotemporal variability of the vegetation cover, which is paramount to understand and evaluate ecosystem change. For instance, Delgado-Fernandez et al. (2019) estimated qualitatively the vegetation cover that would be expected due to regional climate conditions using dune mobility functions, which in turn can be influenced by complex landscape dynamics (e.g. lag response times, morphological resistance, different stabilization rates). In the work of Laporte-Fauret et al. (2020), dune stability patterns were characterized spatially across different dune habitats offering a temporally static view of the system stability. In this work, a new, adaptable and relatively simple dune vegetation state index (DUVES) is proposed to identify, assess, and quantitatively monitor spatiotemporal trends of dune vegetation perturbation at the landscape scale, and stability and growth, using cost-effective and easily accessible true-colour images. The different dune states were defined using a baseline period assumed to be representative of the expected variability of the system. The index was tested in Barreta Island (Ria Formosa, South Portugal) and computed using classified true colour (RGB) orthophotos and orthomosaics derived from UAS surveys covering four 6-years periods, from 2002 to 2020. To understand the observed evolution in the island, the possible sources of dune vegetation disturbance were also investigated by looking at the human infrastructures and activities developed in the island, as well as to the spatiotemporal distribution and demography of two gull breeding colonies.

2. Study area

Ria Formosa is a multi-inlet barrier system, located in South Portugal (Fig. 1). This system, declared Natural Park in 1987, is a wetland area comprised of dunes, marshes, and tidal flats of high ecological and socio-economic value. These environments are protected under the Ramsar convention and included in the list of protected areas within the EU Natura 2000 network. Ria Formosa is a cuspate-shaped system consisting of five barrier islands and two sandy spits separated by six tidal inlets that connect the lagoon with the Atlantic Ocean. The barrier system is located at a maximum distance of 6 km from the mainland and extends along 55 km (Fig. 1), having Santa Maria Cape (located in Barreta Island) as the outer-most point (Fig. 1).

The average annual significant wave height is 0.92 m while the mean annual peak period is 8.2 s (Costa et al., 2001). Waves reach the area from west-southwest (W-SW) and east-southeast (E-SE) directions, with 71% and 23% occurrence, respectively (Costa et al., 2001). This duality in the wave direction is also reflected in the wind regime, which is dominant from the west (W), northwest (NW) and southwest (SW) directions. Eastern winds are less frequent, although they can be intense and may affect this region, mostly during spring and autumn (Andrade, 1990). The most frequent storms impacting the area come from the W-SW and are associated with low-pressure Atlantic systems typical of the winter, with wave heights up to 7 m (Almeida et al., 2011). The less frequent E-SE storms are linked to Levante (easterly) winds originated in the Strait of Gibraltar, between October and May, which generate smaller waves due to the limited fetch (Almeida et al., 2011). According to the previous, the western flank of the barrier system concentrates higher wave power than its eastern counterpart (Vila-Concejo et al., 2002). The tides in this region are semidiurnal, with neap and spring tides presenting average ranges of 1.3 and 2.8 m, respectively. The maximum spring tidal range can reach up to 3.5 m (Pacheco et al., 2008). The main source of sediment in the system comes from the cliffs located up-drift, whose material is eroded and then transported eastwards by the longshore currents (Dias and Neal, 1992). The regional climate falls within the Mediterranean hot summer Koppen type (Csa) according to the Portuguese Institute for Sea and Atmosphere (IPMA, 2019), which is characterised by a humid (October to April) and a dry (May to September) season. During the former, the lowest average temperature is 10 °C and the average precipitation values are 50 mm/month. During the latter, the average temperature is 20 °C, and the precipitation is often close to zero (IPMA, 2019).

Barreta Island is the southernmost island of the system and its western updrift limit consists of a relatively small migrating inlet (Ancão

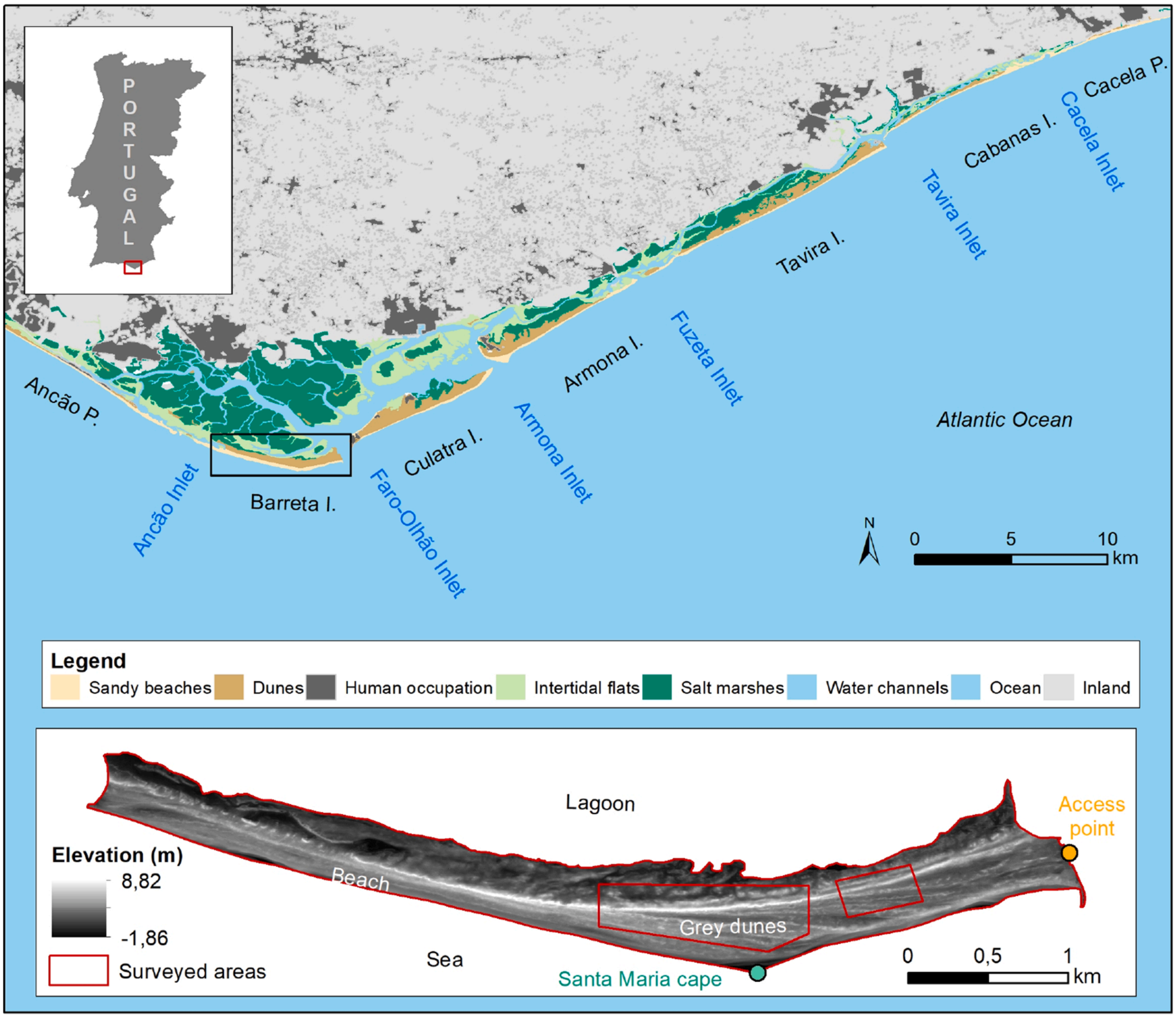

Fig. 1. Location and distribution of ecosystems within the Ria Formosa Natural park (South Portugal) and a high-resolution Digital Elevation Model of Barreta Island, with the surveyed areas highlighted in red.

Inlet) while the eastern downdrift one is the artificially fixed Faro-Olhão Inlet (Fig. 1). Management actions affecting both inlets have influenced significantly the morphology of this island. After its first relocation (1997), the Ancão Inlet rapidly migrated eastwards, eroding the western part of Barreta Island, which was low and prone to overwash (Matias et al., 2008). The new relocation (2015) of the inlet allowed Barreta Island to regain an extension of about 3 km, mostly composed of an unvegetated washover platform (Kombiadou et al., 2019).

The jetties built between 1929 and 1955 to stabilize the Faro-Olhão Inlet functioned as sediment traps, inducing significant accretion and subsequent barrier progradation along the eastern part of Barreta. A set of 17 dune ridges have been identified in Barreta Island due to differences in the alongshore response and progradation of the island (Herrero et al., 2020). Single-ridge dunes with heights lower than 7 m above mean sea-level characterise the western part of the island, whereas in the central-eastern part the dune ridges are high and continuous (Kombiadou et al., 2019). Three dune habitats, as defined by the European Habitats Directive, can be identified within Barreta Island, including the 2110 Embryonic shifting dunes, 2120 Shifting dunes along the shoreline with *Ammophila arenaria* (also known as 'white dunes') and the 2130 fixed coastal dunes with herbaceous vegetation (also known as 'grey dunes'). According to *in situ* observations, the present grey dunes are threatened by tourism, invasive alien species (e.g. *Carpobrotus*) and pressure from Yellow-legged (*L. michahellis*) and Audouin's (*L. audouinii*) gull colonies (hereafter referred as YLG and AG, respectively). Human occupation has been traditionally low on this island, and it is currently limited to a restaurant and a few fishermen huts and warehouses located close to the eastern end of the island. Additionally, a wooden path was built running mostly along the backbarrier, which connects the visitors' access point to the beach nearby Santa Maria Cape (Fig. 1).

3. Materials and methods

3.1. Image collection and processing

The dune vegetation state and its evolution in Barreta Island were investigated using different remote-sensed RGB datasets from 2002 to 2020: three orthophotos and two high-resolution orthomosaics, all of them georeferenced to the PT-TM06/ETRS89 coordinate system (Table 1). The orthophotos (2002, 2008, and 2014), covering the entire Barreta Island, were provided by the Portuguese Direção-Geral do Território (DGT) while the high-resolution orthomosaics (2020) were obtained from UAS flights that covered the two areas in which habitat perturbation was visually identified during field visits (see red polygons in the lower panel of Fig. 1). The air vehicle used was a DJI Mavic 2 Pro quadcopter equipped with a 20 Mpx RGB camera and the surveys were performed at an elevation of 90 m and with a front and side image

Table 1
Datasets used for the dune vegetation analyses and their characteristics (O = Orthophoto, GE = Google Earth).

Year	Month	Method	Resolution (m × m)	Island Cover	Dune vegetation analyses	
					Quantitative	Qualitative
2002	Jul	O	0.5 × 0.5	Full	o	
2008	Oct	O	0.1 × 0.1	Full	o	
2011	Jun	GE	0.25 × 0.25	Full		o
2013	Apr	GE	0.25 × 0.25	Full		o
2014	Ago	O	0.1 × 0.1	Full	o	
2017	Nov	GE	0.25 × 0.25	Full		o
2020	May	Mavic 2 Pro	0.02 × 0.02	Partial	o	

overlap of 75 and 70%, respectively. The acquired images were processed using Agisoft Metashape software and georeferenced with the coordinates of 64 ground control points that were evenly deployed on the field and measured using a RTK-DGPS. The re-projection errors associated to the east (0.081 m) and west (0.088 m) high-resolution mosaics were estimated using 17 and 25 individual check points, respectively.

In addition, several Google Earth images (2011, 2013, and 2017) were used as mid-points to support qualitatively the dune vegetation analysis performed by DUVES due to the low temporal resolution that the orthophotos and orthomosaics provided. These were downloaded from Google Earth Pro with the highest available resolution (4800 × 2869) ensuring equal eye's altitude as well as no tilting during the download process. Afterwards, they were georeferenced using invariable features (e.g. fishermen warehouses, wooden paths and/or easily identifiable shrubs) and the temporally closest orthophoto as a basemap. The associated RMSE after the georeferencing procedure was below 0.5 m for all the images.

3.2. *Dune vegetation state index*

The different steps involved in the workflow followed to compute DUVES (Fig. 2) are explained in the next sections and were performed using different tools of ArcMap (®ESRI) GIS software. The proposed workflow is versatile and allows each user to adapt the parameters within the different steps according to the purpose of each particular study, site characteristics, available imagery, and the user's technical capabilities.

3.2.1. *Image classification*

DUVES defines the dune vegetation state by considering the magnitude of the observed cover changes (or stability) in consecutive images and relative to the typical or expected variability of the vegetation changes within the system, thus informing about the occurrence and significance of possible changes in the vegetation cover during a given period. To compute the index, the orthophotos and UAS-derived orthomosaics (Table 1) were classified using the Iso Cluster

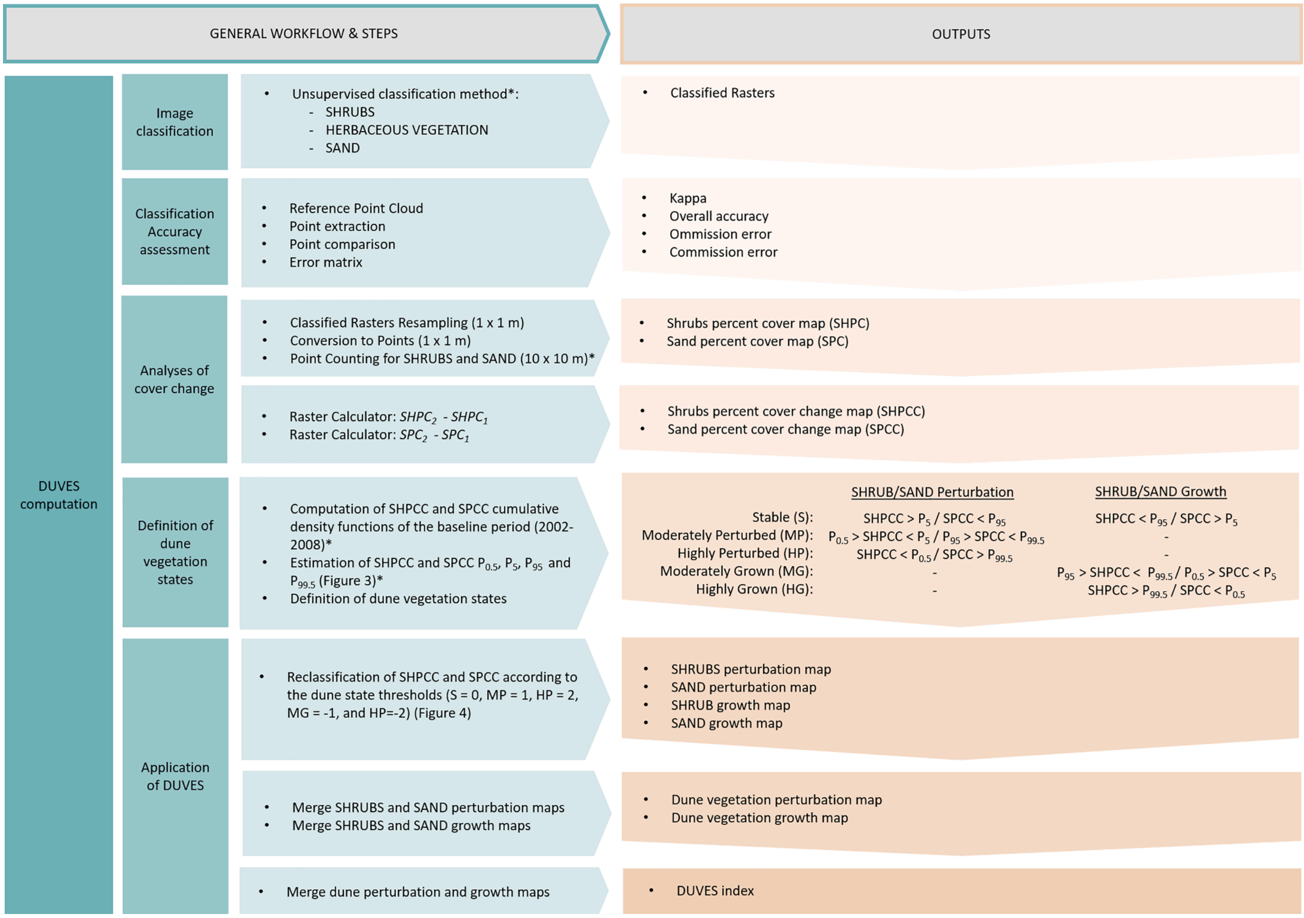

Fig. 2. DUVES, with the example application for Barreta Island (the asterisks represent the customisable steps).

Unsupervised Classification tool that grouped shrubs, herbaceous vegetation and bare sand into three different classes (classes 1, 2, and 3, respectively; Test 1) (Fig. 2). These classes represent the main land cover types present in Barreta Island. The unsupervised classification method was selected for its simplicity and automation and, more importantly, because it is recommended in cases lacking spatiotemporal ground truth information over large areas (Xie et al., 2008). Thus, it was assumed that some incorrectly classified pixels may appear linked to the varying environmental conditions (e.g. sun angle) and quality within each image (e.g. image over-exposure), which are known disadvantages of this classification method that have been previously highlighted, for instance by Delgado-Fernandez et al., (2019). Nevertheless, this approach has been applied with success in several vegetation mapping studies as stated in Hague (2016). The dominant plant species belonging to classes 1 and 2 were identified during an *in situ* field survey and summarised in the supplementary material (Table S1). Due to the varying image resolutions available (Table 1), a second classification test (Test 2) was performed using five classes instead, which were then grouped into three. The results of both tests were compared in order to select the best classification approach for each dataset. This step is customizable, and choosing the number of classes should depend on the characteristics of each site and/or the purpose of the study.

3.2.2. *Classification accuracy assessment*

The assessment of the accuracy of the obtained classification, for both tests, and each image, was performed using a set of 80 points randomly placed along the island. The sample size was estimated based on the binomial probability theory for an expected accuracy of 95% and an allowable error of 5%. The points were used to extract the information from the classified images and an error matrix was built comparing the classified values in each point of every image to the classification criteria of an observer in the same points, thus determining the degree of discrepancy among classes (Fig. 2). This error matrix approach allowed the calculation of several statistics to assess the classification accuracy of each image: the agreement accuracy, omission and commission errors, overall accuracy, and Kappa coefficient (Cohen, 1960; Sen, 1968) (Fig. 2). The herbaceous vegetation (class 2) was, after this analysis, excluded from the index as it exhibited lower classification accuracies than the other classes, as will be shown in the Results section.

3.2.3. *Analyses of cover change*

The estimate of the cover change of shrubs and sand in consecutive images (or periods) involved several steps. First, given that the classified images had different spatial resolutions (Table 1), they were resampled into rasters of 1×1 m cell size to facilitate the comparison between the different datasets, using the Nearest Resampling algorithm. Secondly, due to the extensive area being considered and to avoid slow processing times and high computer memory demands, the per cent cover of shrubs (class 1) and sand (class 3) were estimated in areas of 10×10 m^2, allowing to compute raster maps displaying the per cent cover of each class separately for every available image (Fig. 2). Two per cent maps (shrubs and sand cover) were obtained from each image. Lastly, the per cent cover maps of both classes were compared between different time intervals to obtain the change of coverage for each type over time (SHPCC = Shrub per cent Cover Change; SPCC = Sand per cent cover change) (Fig. 2). The selection of the spatial resolution of the analysis can be adapted according to the purpose of the users.

3.2.4. *Definition of dune vegetation states*

Natural systems present an inherent spatial and temporal variability due to changes in the environmental conditions, including seasonal or inter-annual changes, which may not induce permanent shifts but regulate the intrinsic natural system variability. In addition, natural systems may be affected by additional external agents, which may provoke a shift of state or regime (Fraterrigo and Rusak, 2008). According to Landres et al. (1999), a crucial part of describing natural variability in a particular system is selecting the time period and spatial extent used to characterize the system dynamics, which should be always based on specific goals and explicitly stated values. To distinguish the system expected variability from external agents inducing disturbances of high magnitude and/or persistence, the magnitude of the changes between 2002 and 2008 were analysed and assumed to be representative of the expected intrinsic system variability. This period was used as the baseline for the natural variability because the major perturbations in Barreta Island occurred between 2008 and 2014. To define thresholds of vegetation stability, perturbation and growth for both cover types during this baseline period, the cumulative distribution functions (CDFs) from the SHPCC and SPCC maps 2002–2008 were computed. First, the cover changes between the percentiles P_5 and P_{95} were considered as the most common and frequent, and thus assumed to represent the typical variability (or dune vegetation stability). Second, the cover changes between $P_{0.5}$ and P_5 were assumed to represent dune vegetation under moderate perturbation (in the case of shrubs) or moderate growth (in the case of sand) while those between P_{95} and $P_{99.5}$ were assumed to represent the opposite (vegetation under moderate growth in the case of shrubs or under moderate perturbation in the case of sand). Lastly, cover changes below $P_{0.5}$ and above $P_{99.5}$ (less frequent) were assumed to represent high perturbation in the case of shrubs (or high growth for sand) and high growth in the case of shrubs (or high perturbation in the case of sand), respectively (Fig. 3). The estimate of these percentiles helped to identify thresholds of normal or unusual cover change variability of both shrubs and sand, and to define five dune vegetation states in Barreta Island (Figs. 2 and 3). These are the following:

- Stable state (*S*): defined as the normal loss/gain of both shrubs sand cover resulting from seasonality and inter-annual fluctuations in the precipitation regime or other agents.
- Moderately Perturbed (*MP*) and Highly Perturbed (*HP*) states: defined as moderate and high loss (gain) of shrubs (sand) cover induced by any type of natural (e.g. overwash) or anthropogenic (e.g. trampling) disturbance.
- Moderately Grown (*MG*) and Highly Grown (*HG*) states: defined as moderate and high gain (loss) of shrubs (sand) cover induced by natural processes (e.g. ongoing vegetation growth, post-disturbance vegetation recovery) or anthropogenic interventions (e.g. vegetation re-planting).

3.2.5. *Application of DUVES and analyses of spatiotemporal changes in dune vegetation state*

The changes in cover of shrubs (or sand) could individually be used as indicators of dune vegetation stability, perturbation and/or growth. However, DUVES, by combining the information given by both cover types, allows understanding if the increase in sand is directly related to a decrease of shrubs and vice-versa. For DUVES computation an initial set of four maps is produced (shrubs perturbation, shrubs growth, sand perturbation and sand growth maps) for a given period (Figs. 2 and 4). The shrubs and sand perturbation maps are obtained from the per cent cover change maps of shrubs and sand (SHPCC and SPCC, respectively) reclassified according to the thresholds estimated in the previous step (Fig. 3) into 0, 1, and 2 to represent stability, moderate perturbation and high perturbation, respectively (Fig. 4). Similarly, the shrubs and sand growth maps are obtained from the SHPCC and SPCC maps reclassified into 0, −1, and −2, representing stability, moderate growth and high growth, respectively (Fig. 4). Once the individual shrub and sand perturbation maps were computed, these were merged and the value of the output raster cell was assigned selecting the maximum value of the overlapping cells (0, 1 or 2), obtaining the overall perturbation map (Figs. 2 and 4). This way ensures the representation of the higher degree of perturbation recorded in each cell (either attributed to a decrease in shrub cover and/or an increase in sand cover). The overall growth map is obtained following the same procedure. Lastly, both overall

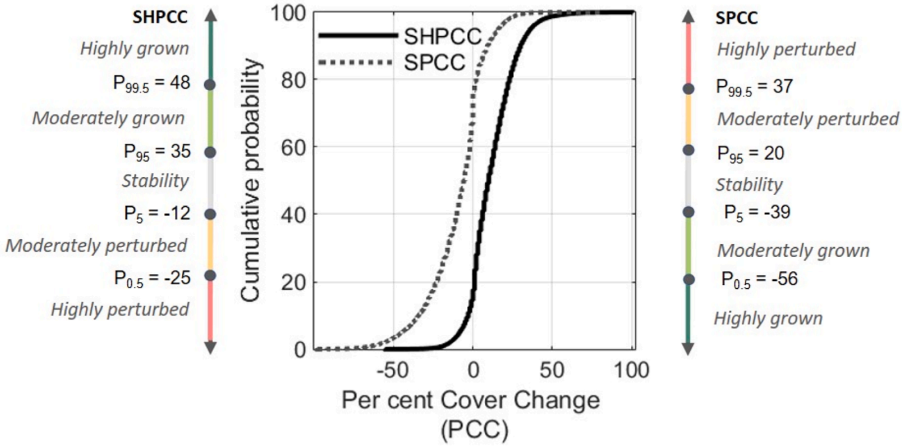

Fig. 3. Cumulative Distribution Functions (CDFs) obtained from the Shrubs Per cent Cover Change map (SHPCC) and the Sand Per cent Cover Change map (SPCC) from 2002 to 2008. The vertical lines show the $P_{0.5}$, P_5, P_{95} and $P_{99.5}$ percentiles estimated from each SHPCC (left) and SPCC (right) CDFs, and the thresholds within them define the different dune vegetation states for each cover type (Note: The percentile positions included in the vertical lines were added to illustrate better the different thresholds, but are not related to the percentile positions in the CDFs).

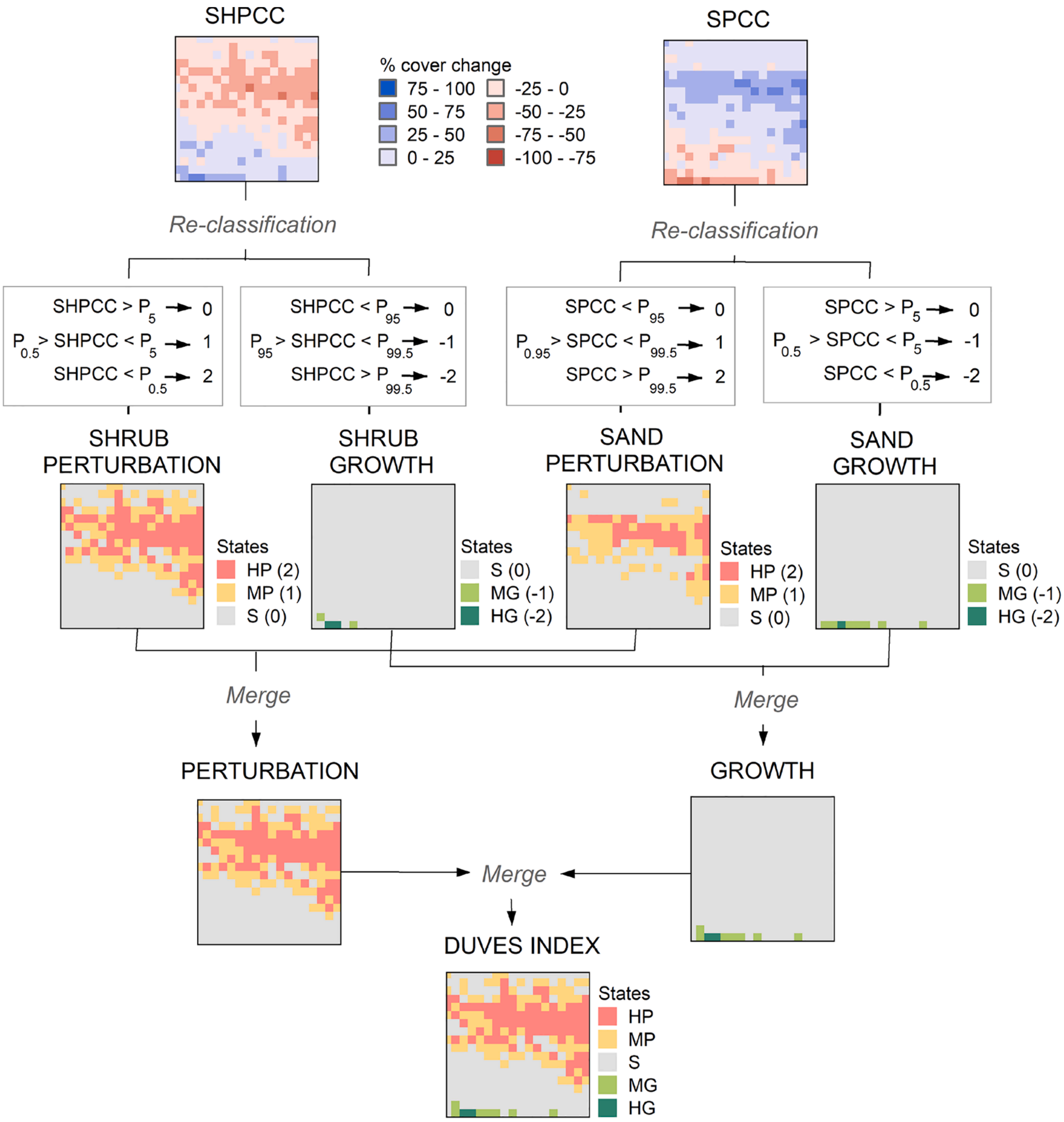

Fig. 4. Steps followed for the application of DUVES (SHPCC = Shrubs per cent cover change map, SPCC = Sand per cent cover change map; HP = Highly Perturbed, MP = Moderately Perturbed, S = Stable, MG = Moderately Grown, HG = Highly Grown).

perturbation and growth maps are joined to get the final dune vegetation state index map (Figs. 2 and 4). The previous procedure was applied to the four periods of analysis and the resulting dune vegetation state index maps were used to estimate and analyse the spatiotemporal changes of the dune vegetation state.

3.3. Human and gull occupation

To understand the contribution of possible direct human interference (activities and/or trampling) in the perturbation of the dune, infrastructures and human-related elements present across Barreta Island (2002–2020) were digitised as polylines and polygons in ArcMap using the available images (Table 1). These included hard structures such as the jetties in the Faro-Olhão Inlet, buildings such as fishermen houses, warehouses and a restaurant, wooden paths and trampling paths. The results of seven annual gull censuses performed during every breeding season (from mid-April to mid-July; Matos et al., 2018), facilitated by the University of Coimbra (2014–2019) and SPEA (2020), were compiled to understand if the demography and spatial distribution of the gull colonies breeding in the island had a role in the changes observed in the vegetation. The gull counting method was performed by a group of ten to fifteen people aligned and equally separated (2 m), covering the entire gull colony extension. Each person counted the encountered clutches and marked them with a tooth stick to avoid repetition.

4. Results

4.1. Classification accuracy

Test 1 (unsupervised classification using three classes) led to a better classification of the UAS-derived mosaics than Test 2 (unsupervised classification using five classes and grouped into three). For instance, Kappa values in Test 1 were 0.61 and 0.82 for the east and west mosaics, respectively, while in Test 2 the west area showed a Kappa value of 0.65. Likewise, the overall accuracy values for the 2020 east and west mosaics were 80.00% and 93.33% in Test 1 and 60.00% and 80.00% in Test 2, respectively. (Table 2). In contrast, Test 2 was more suitable for classifying the orthophotos. These showed Kappa values below 0.78 in Test 1 and above 0.85 in Test 2, and overall accuracy values increasing from values below 88% in Test 1 to values above 91% in Test 2 (Table 2). Based on these results, the classified images exhibiting the best classification accuracies for the computation of the dune vegetation state index were used, regardless of the classification approach (highlighted in grey, Table 2).

The accuracy of the classifications obtained was excellent as almost all the datasets used to compute DUVES showed Kappa values above 0.85, and Kappa values above 0.75 indicate excellent agreement (Fleiss et al., 2013). The only exception was the 2020 east orthomosaic, which showed a Kappa value of 0.61. Nevertheless, Kappa values between 0.4 and 0.75 indicate an intermediate to a good agreement (Fleiss et al., 2013). Classes 1 and 3 (shrubs and sand, respectively) showed the highest agreement accuracies (values above 90% and equal to 100%, Table 2) while the agreement accuracy of class 2 (herbaceous vegetation) was below 90%. The highest omission errors obtained corresponded to class 2 and to a minor extent to class 1, meaning that pixels belonging to class 2 have failed to a major extent to be classified as such, and they have been likely classified as class 3, as suggested by the higher commission errors of this class (sand) compared to classes 1 and 2. The commission error represents pixels that belong to a given class (class 2 in this case) but are labelled as belonging to another one, in this case, class 3 (Table 2). The agreement accuracy, omission and commission errors of class 1 in the eastern area in 2020 could not be estimated, as this class was not represented in any of the random points used for the accuracy assessment due to the smaller extension of this particular area (Fig. 1). Based on the lower agreement accuracy and higher omission errors of class 2, this class was discarded from being used as an indicator of vegetation change in DUVES and solely classes 1 and 3 were used for that purpose. The low classification accuracy obtained for class 2 was probably due to the fact that the areas with herbaceous vegetation in Barreta Island could be more sensitive to the quality of the different images used (e.g. colour, illumination) and to changes in vegetation seasonality. The classified maps obtained are included as Supplementary Material (Fig. S1).

4.2. Evolution of the dune vegetation cover

Results from the analysis of the vegetation cover in Barreta Island point towards a general increase (decrease) in shrubs (sand) cover during the period of analysis but with a high spatial and temporal variability. From 2002 to 2008 (baseline situation), shrubs grew significantly in the central grey dunes and along the white dunes (see the colour transitions from grey or light green to dark green, Fig. 5a), exhibiting shrubs cover increases that reached 75–100% in some areas (see blue patches in Fig. 5b). The shrubs also increased in the grey and white dunes at the eastern flank, whose vegetation cover incremented up to 50–75% from 2002 to 2008 (Fig. 5b, left panel). In parallel to the previous, the sand cover declined, especially from the central to the eastern regions of the island (see the colour transition from dark to light brown or grey, Fig. 5a), which showed areas in which sand cover decreased by 50–75 and even 75–100% (Fig. 5b, right panel).

During the second period of analysis (2008–2014), the cover of shrubs (sand) continued increasing (decreasing) in the island, although two areas in the central grey dunes (located between the southern face of the highest dune ridge and the foredune in the central part of the island) exhibited the opposite trend (see the colour shifts from dark green to grey for shrubs, and from grey and light brown to dark brown for sand, Fig. 5a). In these areas, the shrubs cover diminished by 25–50%, with maximum reductions of 75–100% (Fig. 5b, left panel). The sand cover

Table 2
Results from the classification accuracy assessment for each dataset (O = Orthophoto) and area analysed (WB = Whole Barreta Island, E = East Area, and W = West Area) using Test 1 and 2 (AA = Agreement accuracy, OE = Omission Error, CE = Commission Error, K = Kappa, OA = Overall Accuracy).

Test	Year	Data	Area	AA (%) Classes			OE (%) Classes			CE (%) Classes			K	OA (%)
				1	*2*	*3*	*1*	*2*	*3*	*1*	*2*	*3*		
1	2002	O	WB	69.23	88.46	90.24	30.76	11.53	90.24	0.00	25.80	7.50	0.77	86.25
	2008	O	WB	68.42	93.02	94.44	31.57	6.97	5.55	7.14	14.89	10.52	0.78	87.50
	2014	O	WB	77.77	70.96	100.00	22.22	29.03	0.00	0.00	21.42	29.03	0.72	81.25
	2020	Mavic2 Pro	E	–	66.66	100.00	–	33.33	0.00	–	0.00	66.66	0.61	80.00
			W	100.00	88.88	100.00	0.00	11.11	0.00	0.00	0.00	83.33	0.87	93.33
2	2002	O	WB	100.00	73.07	100.00	0.00	26.92	0.00	0.00	0.00	14.58	0.85	91.25
	2008	O	WB	94.11	89.65	100.00	5.88	6.89	0.00	5.88	3.70	5.55	0.92	95.00
	2014	O	WB	96.29	82.35	100.00	3.70	17.64	0.00	0.00	6.66	7.69	0.92	95.00
	2020	Mavic2 Pro	E	–	0.00	100.00	–	100.00	0.00	–	–	60.00	–	60.00
			W	100.00	0.00	100.00	0.00	100.00	0.00	0.00	–	70.00	0.65	80.00

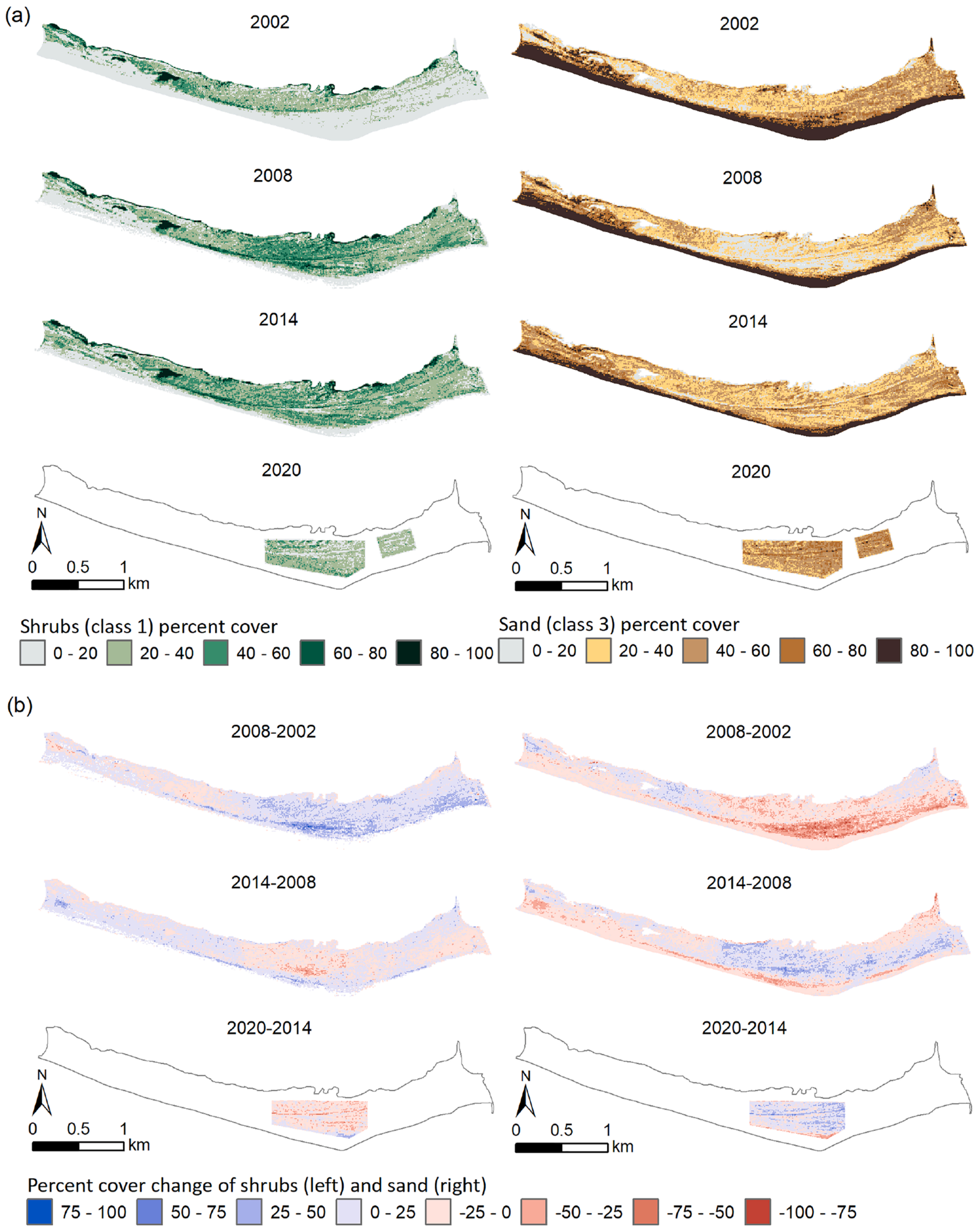

Fig. 5. (a) Per cent cover maps of shrubs (left panel) and sand (right panel), and (b) Per cent over change maps of shrubs (left panel, SHPCC) and sand (right panel, SPCC).

expanded from the central region eastwards, showing cover increases that ranged from 1–25 to up to 75–100%. These results suggest the disruption of the trend that the system appeared to display during the period 2002–2008 and could be indicative of a disturbance causing vegetation perturbation in the island. This perturbation expanded to the north and south directions from 2014 to 2020 (see the grey and dark brown colours in Fig. 5a), as indicated by the ongoing reduction in shrubs cover (up to 75–100%, left panel in Fig. 5b) and the increase in sand (around 50–75% and up to 75–100%, right panel in Fig. 5b).

4.3. *Evolution of the dune vegetation state*

During the first period of analysis (2002–2008) nearly 80% of Barreta Island was characterised by vegetation stability (see upper panels in Fig. 6a and b). Some areas in the island also exhibited moderate and high vegetation growth in the central area as well as along an alongshore narrow stretch of dunes (upper panel in Fig. 6a), which affected 6.5% and 2.5% of the total extension, respectively (upper panel in Fig. 6b). The previous is related to the vegetation growth and natural transition of incipient foredunes towards established and more densely vegetated

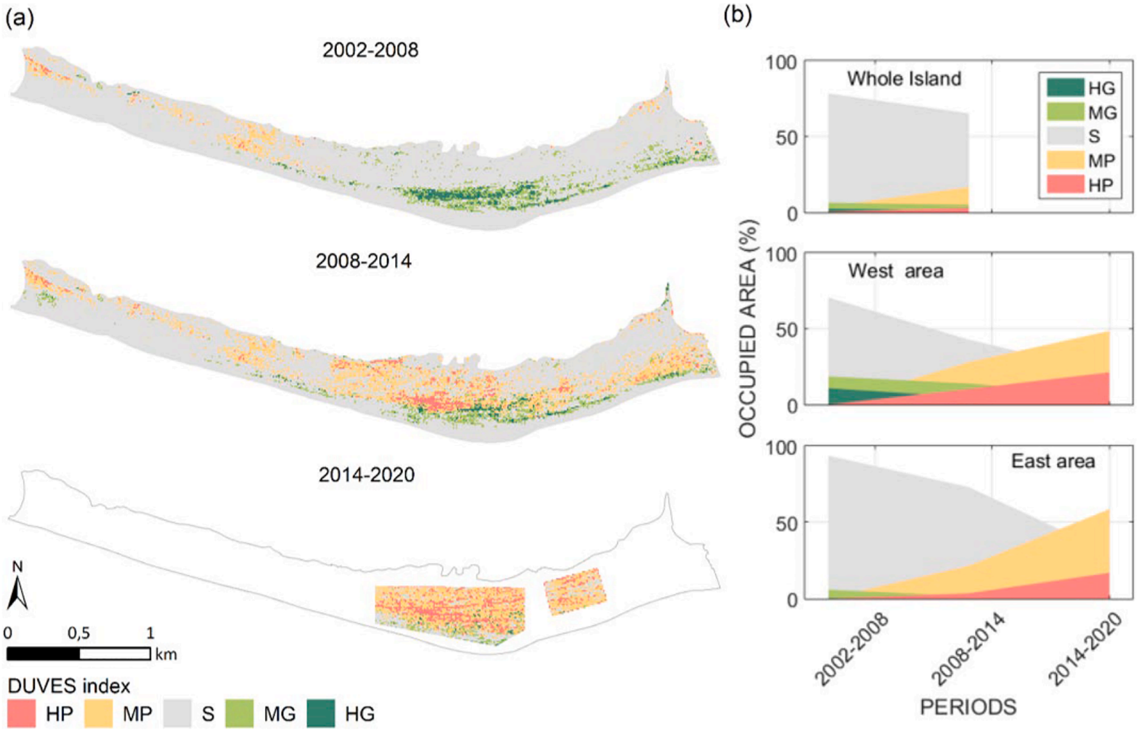

Fig. 6. (a) Dune vegetation state index maps showing the spatiotemporal evolution of the different dune vegetation states (S = Stable, MP = Moderately Perturbed; HP = Highly Perturbed; MG = Moderately Grown, HG = Highly Grown), (b) Areal occupation (%) of each dune vegetation state quantified for the whole island (upper panel) from 2002 to 2014, as well as for the western and eastern surveyed areas (mid and lower panel, respectively) from 2002 to 2020. Note that the index maps and areal occupation values show the dune vegetation states accumulated progressively over the different periods analysed.

foredunes (Fig. 5a and b). There were also relatively small and isolated areas under moderate and high vegetation perturbation, occupying 4% and 0.4% of the total island extension, respectively (see yellow and red in Fig. 6a and b).

In the next period (2008–2014), dune vegetation stability continued dominating across the island, although its extent decreased by around 15% compared to the previous period (Fig. 6a and b). This was due to the appearance of areas under moderate and high dune vegetation perturbation. The MP areas occupied 17% of the area and were mostly located in the central area of the island and along its eastern flank (see the yellow patches in the middle panels in Fig. 6a and b). The HP areas showed a moderate increase (from 0.4% in 2002–2008 to 3% in 2008–2014) and were localised in two specific regions nearby the highest dune ridge in the central grey dunes (see red patches in the middle panel of Fig. 6a and b). This revealed a significant expansion of dune perturbation, as the total extent of this dune vegetation state in Barreta Island increased to nearly 16%.

In the last analysed period (2014–2020), the perturbation experienced an expansion in both western and eastern areas. Note that the changes mentioned in the previous paragraphs referred to the entire island extent while the following ones refer solely to the western and eastern surveyed areas, and thus the values are not directly comparable. In the western area, the relative extent of the areas under moderate perturbation increased by 20% approximately (from 28% in the period 2008–2014 to 49% in 2014–2020) while the areas under high perturbation increased by 10% (from 10% in 2008–2014 to 21% in 2014–2020) (bottom panel in Fig. 6a and middle panel in Fig. 6b). Both perturbation states expanded towards the north and southeast directions, affecting an area 32% larger than in the previous period (relative extent increased from 38% to 70%) (bottom panel in Fig. 6a and middle panel in Fig. 6b). In the eastern area, both dune perturbation categories also expanded to the north and south directions, with areas under moderate and high perturbation increasing their relative extent by 37% and 14%, respectively (bottom panels in Fig. 6a and b). These values denote an important expansion of dune perturbation in both the western and eastern areas, affecting relative extents of 70% and 51%, respectively.

Despite the low quality of the Google Earth images (2011, 2013, and 2017), they showed clear signs of perturbation (documented by the lack of vegetation or the occurrence of different plants) that coincided in location with the western and eastern perturbed areas identified by DUVES (Fig. 7a and b), confirming the dune vegetation perturbation identified by DUVES. For instance, the 2011 and 2013 Google Earth images showed areas under a light purple colour (associated with ruderal vegetation) and less vegetation cover in the western and eastern degraded areas, respectively, coinciding in location with the perturbed areas identified by DUVES from 2008 to 2014 (Fig. 7a). Likewise, the larger grey dune areas under perturbation identified in 2020 were also observable in the Google Earth image of 2017 (Fig. 7b).

4.4. Human occupation

The distribution of buildings and wooden paths did not change significantly during the period of analysis, except the fishermen warehouses located in the north-west of the island (Fig. 8), which were removed in the late 2014 or early 2015, and the relocation of the restaurant a hundred of meters to the south (2007). Most of the trampling paths appeared in the surroundings of the fishermen warehouses and near the restaurant (see the 2014 and 2017 maps in Fig. 8a). They were probably formed by frequent and routine activities. Similarly, there were also signs of trampling from the main wooden path of the island to the lagoon beaches (see small black lines in Fig. 8), as this specific area experiences high human pressure during the summer season due to the significant affluence of tourists and locals. No trampling signs were found connecting the main wooden path that crosses the island with the eastern and western perturbed areas identified by DUVES

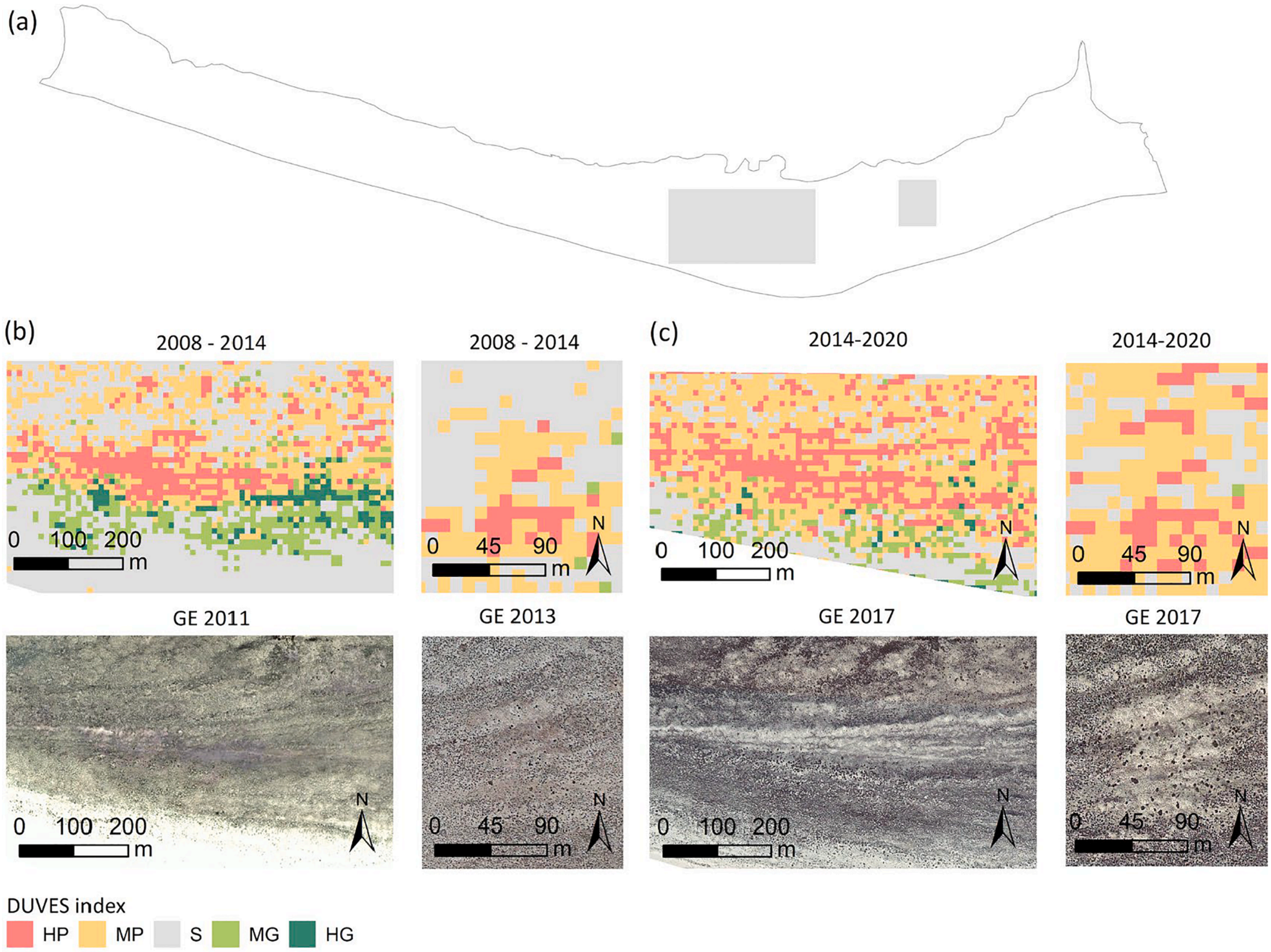

Fig. 7. (a) Location map showing the western and eastern areas in which the dune vegetation index maps have been compared to the Google Earth images (b) Dune vegetation state index maps (S = Stable, MP = Moderately Perturbed; HP = Highly Perturbed; MG = Moderately Grown, HG = Highly Grown) showing dune perturbation in the western and eastern area (2008–2014) coinciding with evidences of perturbation observable in the 2011 (western area) and 2013 (eastern area) Google Earth images, and (c) Dune vegetation state index maps showing large areas under dune perturbation in the western and eastern area (2014–2020) coinciding with evidence of perturbation observable in the 2017 Google Earth image. Note that the extent of the perturbed areas shown in the Google Earth imagery could differ from the ones shown in the index maps due to the time lag between images.

(Fig. 8). Areas under different degrees of vegetation perturbation appeared close to the human-derived activities and occupation in Barreta Island, especially close to the buildings and trampling paths, but they were small and localised areas.

4.5. *Gull occupation*

The main distribution areas of YLG and AG along Barreta Island changed over time but were mostly located at the central part of the island (see the black and blue circles, respectively; Fig. 9a). YLG mostly occupied two regions on the dune crests and surrounding areas (between 2014 and 2019) and an additional low elevation area on the western part of the island from 2015, approximately. AG was found mostly close to the YLG population located in the central west part of Barreta Island, but occupying the lower areas to the north and south of the highest dune ridge crest (2014–2020) or lateral areas (2020; Fig. 9a). From the 2014–2019 surveys, it was observable that apart from some displacements of the populations of gulls, the most relevant trend was the increase in the occupied area by both species. Regarding the population size of both colonies, AG was clearly superior to YLG during the whole period of analysis and the difference increased with time. Moreover, its population density was higher than YLG since they occupy areas of a smaller extent within the island. Both populations have gradually increased from 2014 to 2020, reaching their peaks and apparent stability after 2018 (Fig. 9b).

5. Discussion

5.1. *DUVES performance and methodological considerations*

DUVES proved to be an effective tool to identify, assess and monitor the state of the vegetation cover of relatively large dune areas, providing a categorisation that depends on the trend of the observed changes: vegetation stability, perturbation and growth, at medium time scales (years). Moreover, it is relatively simple to apply, requiring the use of a GIS platform and RGB imagery as inputs, which are often easily accessible and of free availability. This makes DUVES a reliable tool that is potentially applicable to a wide range of temporal and spatial scales as well as transferable to other worldwide areas, especially in the light of the intensification of disturbances linked to agriculture, urbanisation or tourism, among others, which have already threatened 85% of the European coastal dunes (Heslenfeld et al., 2008).

DUVES is an index devoted to characterise the state (or health) of dune vegetation using as an indicator the magnitude of the cover changes obtained from a coarse classification of shrubs and sand. The focus of the classification can be easily adapted depending on the type of

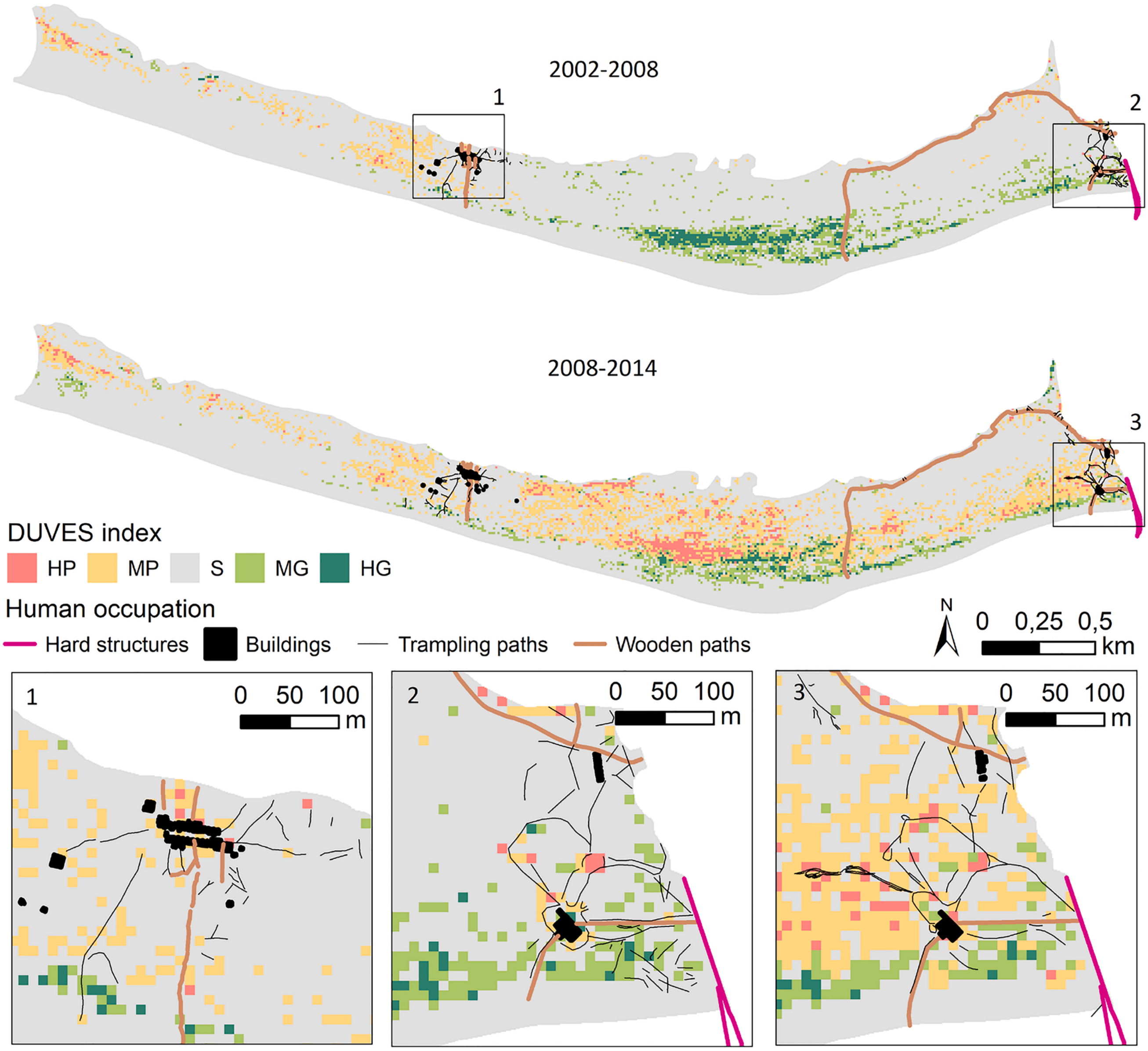

Fig. 8. Dune vegetation state index map from 2002 to 2008 and human occupation in 2008 (upper panel), and dune vegetation state index map from 2008 to 2014 and human occupation in 2014 (middle panel). The lower panel shows insight on the areas nearby human occupation (see location and timeframe at the upper and middle panels).

plant community in the explored habitats. Other indexes, such as those developed by Delgado-Fernandez et al. (2019) and Laporte-Fauret et al. (2020), also required classification methods able to differentiate vegetation from sand cover for their computation. Delgado-Fernandez et al. (2019) used an approach similar to DUVES to identify dune vegetation disturbance, relying on the manual classification of both vegetation and sand cover using different RGB orthophotos, a technique that leads to accurate results, being however more tedious and time-consuming. Besides, it also differs from DUVES by the fact that uses theoretical dune mobility functions to estimate the relative amount of vegetation cover that could be expected due to climatic controls on coastal dune field dynamics (wind, temperature, precipitation and evapotranspiration), and dune disturbance was understood as changes to vegetation cover not explained by these climatic controls. DUVES assesses the overall variability (natural or anthropic) of the system under analysis based on quantitative changes in vegetation cover occurring during a baseline period representative of the intrinsic natural variability of the system when absent of high magnitude and/or persistent perturbations. The index developed by Laporte-Fauret et al. (2020) to identify coastal stability patterns, is somehow similar to DUVES as it relays on vegetation types too. However, the index used a robust two-step classification approach based on the NDVI and Random Forest classifier to identify a total of 11 vegetation and sand cover types. It uses UAS and both airborne and ground hyperspectral vegetation data, which for this particular study would not be necessary, since it would increase the complexity of the approach, making it time-consuming, data demanding, and costly. In addition, this work provided a spatially variable stability gradient, without considering temporal changes. Alternatively, a faster way to differentiate vegetation from sand and avoid the disadvantages inherent to the different image classification methods mentioned above, would be to apply remote sensing indexes (e.g. NDVI; Difference Vegetation Index; Grey Index; among others), as done by Chen et al. (2021). These authors used the previous indexes derived from Landsat images to indicate the abundance of vegetation or sand and estimated the vegetation cover applying a dimidiate pixel model. The approach used by the authors could be fast. However, the obtained

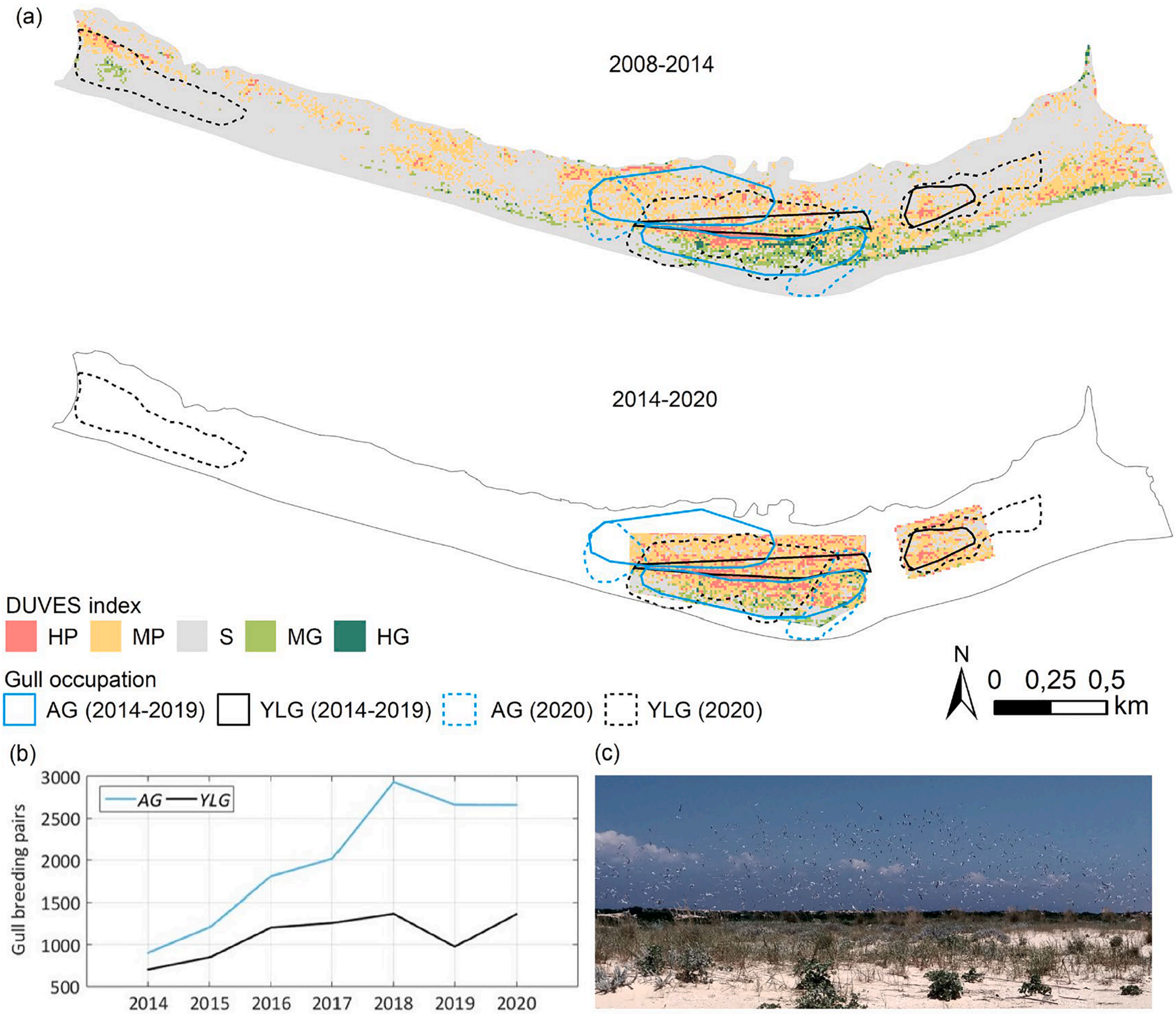

Fig. 9. (a) Gull distribution areas in Barreta Island (2014–2020) overlying the vegetation index maps of 2008–2014 (upper panel) and 2014–2020 (bottom panel), (b) gull breeding pairs as obtained from censuses performed by the University of Coimbra (2014–2019) and SPEA (2020), and (c) photograph showing some AG flying over their southeast distribution area in 2020.

vegetation cover would need to be verified using visually classified drone imagery and field observations.

Despite being cost-effective, quick, relatively user-friendly and potentially transferable, DUVES also has limitations. Disadvantages inherent to the adopted approach could be related to the quality and seasonality of the available RGB imagery, which may influence the unsupervised image classification accuracy as previously pointed out (Delgado-Fernandez et al., 2019), interfering in the estimate of vegetation cover changes and ultimately altering the definition of the dune vegetation states over the years. A way to minimise this limitation would be to use RGB imagery captured during the same season. In addition, the resolution used to estimate the shrubs and sand cover changes and to compute the dune index maps (100 m^2 in this case) can affect the distribution configurations by masking unexpected patterns or distortions in their shape, and this would influence the definition of the dune state thresholds too. However, using smaller areas would hamper the identification of trends on the dune vegetation state at the landscape level, which was the goal of this study. Nevertheless, the selection of the spatial resolution of analysis can be adapted, and it is recommended to qualitatively compare the DUVES outputs with other images *or in situ* observations, as done in this work. Another possible source of uncertainty is the selection of the baseline period to define the expected vegetation cover variability of the system, which affects the values of the percentiles used to define the dune vegetation states for the upcoming periods. For instance, in the study case of this work, the baseline period chosen was characterised by significant growth of shrubs (class 1) (Fig. 6). Therefore, each user should analyse carefully the observed trends identified by DUVES, without forgetting the existing cover change distributions in the chosen baseline period. Thus, defining the expected variability of vegetation cover on such dynamic dune systems is challenging. According to Landres et al. (1999), no a priori time period or spatial extent can be used in defining natural variability. Instead, the selection of the relevant period and spatial extent must rely on specific goals and explicitly stated values. In the study case, the selection of the baseline period (2002–2008) was determined by the image availability, and also represents reasonably well the expected natural variability of the dune vegetation cover before any significant and persistent perturbation. Extending further backwards the temporal scale would not solve this issue (threshold improvement) as the progradation of dune ridges and the subsequent vegetation zonation in the island would still be ongoing. This would hamper again an accurate definition of the expected natural vegetation cover variability and bias the definition of the dune vegetation states. It is, therefore, important to emphasize that this work provides a general workflow to compute a dune state index in which the different steps shown (e.g. selection of a number of classes used in the classification, the spatiotemporal resolution used to estimate cover changes, selection of the baseline period) are customisable and adaptable from user to user (Fig. 2). That adaptation depends on the characteristics of each particular study site, the purpose of each work, and the availability and quality of images. Even with the mentioned inconveniences, DUVES can quickly and easily inform decision-makers about the state (or health) of the vegetation on coastal dunes, allowing also to communicate information about habitat changes and trends, and helping to identify possible sources of disturbance.

5.2. Causes and consequences of dune vegetation perturbation in Barreta Island

The application of DUVES in Barreta Island allowed to understand the evolution of the dune vegetation perturbation at the area but also the associated causes when compared to possible disturbance sources (human interferences and gull pressure). Dune vegetation under perturbation associated with human occupation and activities seemed to be localised and with a relatively small expression when compared to the overall island dimension. Human occupied areas do not correspond to the main perturbed areas identified by DUVES (western and eastern areas represented in Fig. 7). The gull colonies seemed to contribute to most of the dune vegetation perturbation in Barreta Island. The perturbed western and eastern areas identified from applying DUVES largely coincided with the distribution areas of YLG and AG (see the blue and black polygons representing gull occupation areas over the red patches representing vegetation perturbation in Fig. 9a). In Barreta Island, both gull colonies are known to breed in sympatry from mid-April to mid-July (Matos et al., 2018) and seem to exist on the island at least since 2008, based on the testimony of the only inhabitant of the island. In addition, the first censuses performed in 2010 (AG) and 2011 (YLG) showed that there were already 399 and 250 breeding pairs, respectively (Instituto da Conservação da Natureza e das Florestas, ICNF; personal communication).

Gulls are often beneficial to flora, small fauna (Olafson, 1981) and other organisms such as bacteria and the invertebrate community that feeds on these (Petersen, 2009) due to different behavioural reasons: transport of nutrients and salt from the ocean onto land in the form of food remains that they accumulate during nesting, regurgitation and defecation. Gull faecal material, known as ‘guano’, contains a high proportion of micro and macronutrients, although it can become highly concentrated and unfavourable or even toxic to plants at high deposition rates (Sanchez-Pinero and Polis, 2000). Studies specifically focused on the impacts of the AG on vegetation were not found, as this gull species has a limited spatial distribution. However, several studies have been specifically devoted to investigate the YLG impacts on vegetation in different habitats (De La Peña-Lastra et al., 2021; Ghermaoui et al., 2016; Otero et al., 2015; Serra et al., 2016; Vidal et al., 1998). This is probably attributed to the greater abundances of YLG, which has undergone a widespread demographic increase in the Mediterranean basin in the last decades (Vidal et al., 1998), and had often been considered as a pest. Serra et al (2016) warned that the settlement of dense colonies of YLG on vegetated grounds for several years could affect significantly the habitat. Minor impacts on vegetation caused by gulls (or other seabirds) in general and the YLG, in particular, include plant physical disturbance as well as activities that directly damage plant tissues (e.g. uprooting, burrowing, leaf pulling) (Ellis, 2005; Kolb et al., 2011; Otero et al., 2018), seed dispersal of non-indigenous plants, and even erosion due to plant disappearance following chemical soil alteration (Serra et al., 2016). Major impacts include plant desiccation nearby nests, changes in the physiognomy and composition of plant communities due to stamping, and an increase in nutrients (N and P) that may alter the chemical composition of soils (Otero et al., 2015; Serra et al., 2016; Vidal et al., 2000). Moreover, chemical soil alterations can be especially aggravated in dense colonies settled in arid areas with low precipitation and high-temperature conditions where the dilution of nutrients is low and there are high rates of soil evaporation (Ellis, 2005; Sanchez-Pinero and Polis, 2000). Nevertheless, the same areas in wet years could benefit from the presence of gulls and other seabirds and experience a significant increase in biomass and annual cover of plants (Anderson and Polis, 1999; Polis et al., 1997).

Soil excessive nutrient accumulation and physical disturbance in dense gull colonies may change the performance of plants and the competitive interactions between them, favouring short-lived (annual and/or biennial) nutrient-demanding species and the ruderalisation of vegetation and habitats (García et al., 2002; Kolb et al., 2011; Otero et al., 2018; Serra et al., 2016; Vidal et al., 2000). This may lead to the loss of biodiversity (Bou et al., 2021) and even the irreversible soil and vegetation transformation towards a new environmental system (De La Peña-Lastra et al., 2021). Signs of habitat ruderalisation have been observed in Barreta Island, associated with the areas that DUVES characterised as exhibiting moderately or highly perturbed dune vegetation. The growth of *Malcolmia Littorea,* grasses and other graminoid plant species such as *Vulpia alopecuros* (Table S1) seemed to be solely restricted to the perturbed areas occupied by gulls and identified by DUVES (Fig. 10). The previous plant association, in these particular areas, is probably related to their adaptation to elevated nutrient inputs and gull physical disturbance and had likely replaced previous plant species intolerant to those conditions (Kolb et al., 2011). This, caused a bifurcation event towards a change of the plant community and thus of the habitat (or state) and the fragmentation of the grey dune habitat in Barreta Island.

Even though the major dune vegetation perturbation identified in Barreta Island was caused directly by gull pressure and into much minor extent human interference, it must be highlighted that anthropogenic activities are the main cause of demographic increase and geographic expansion of gulls (Mendes et al., 2018). Activities such as intense fishing, fishery discards, and also the presence of terrestrial landfills in the surroundings of the gull breeding sites can influence the foraging behaviour of gulls, as they provide food resources (Calado et al., 2018). This is especially relevant for the YLG breeding in Barreta Island, which has been found to use landfills and fishing harbours in the surrounding area as forage destinations while the AG has a high use of the marine habitat, showing almost no venture to terrestrial habitats (Calado et al., 2018). Besides, both species were found to be synchronized with fishing activities in the area and their population dynamics will likely be influenced by the European fishery discard ban policy, which is expected to cause a decline in their populations and an increase in the use of land resources, especially for the YLG (Calado et al., 2018; Matos et al., 2018).

5.3. Management implications for dune conservation

As management tools, environmental indicators may provide awareness over conservation problems that may arise and the eventual need for actions (Espejel et al., 2008). DUVES can serve as a management tool to implement funded and informed coastal management decisions on the preservation of grey dune areas. For instance, at the study site, the results obtained from testing DUVES will serve as the starting point to the implementation of several conservation measures for dune habitat protection, namely the main walkway restoration and its relocation at some points along the island and signposting, which are aimed at minimizing dune human trampling and alterations in the dune vegetation habitat. Gull control measures (namely trough feeding) are also being analysed as a possibility to minimise the impact of gulls at the area (see LIFE Ilhas Barreira, www.lifeilhasbarreira.pt). Likewise, DUVES can also be used to monitor dune vegetation recovery after the

Fig. 10. Drone photo showing the spread of *Malcolmia Littorea* in the western and eastern perturbed dune areas occupied by gulls (upper panel) (Note that the purple colour displayed is similar to the one observed in the 2011 Google Earth image of Fig. 7a), and some ground photos showing *Malcolmia Littorea*, graminoid plants, and grasses solely found in the perturbed areas (from left to right).

implementation of conservation measures, which is also of interest worldwide as it is a way of testing the effectiveness of such measures at places where interventions have been or will be implemented.

6. Conclusions

In this work, an effective index to identify, assess, and monitor dune vegetation stability, perturbation and growth was developed using as indicators the per cent cover changes of shrubs and sand estimated from classifying easily accessible true colour imagery. DUVES has allowed the characterisation of the conservation status of the dune vegetation in Barreta Island from 2002 to 2020, and the identification of hotspots of dune vegetation perturbation that were linked, to a small extent, to human-related activities and more importantly to the demographic increase and expansion of two gull breeding colonies. Habitat perturbation derived from gull disturbance had led to a ruderalisation process in the areas occupied by the gulls in the island, which favoured annual and/or biennial plant species that substituted the original plant communities. There was a gull-driven bifurcation event or ecological shift towards a new plant composition in the grey dune habitat present in Barreta Island induced by the positive feedback established between gulls and vegetation.

When applying DUVES, it is recommended to carefully consider the quality and seasonality of the RGB imagery, to properly select of the baseline period determining the expected variability of the vegetation cover changes within the evaluated system, and to define the resolution used to estimate those cover changes. The previous aspects affect the selection of cover change thresholds that ultimately define the different dune vegetation states. The latter can be improved, although not solved completely, by using RGB imagery captured at the same seasons.

DUVES can quickly and easily inform decision-makers worldwide about the state (or health) of dune vegetation. When used for monitoring purposes, it can inform about dune habitat changes and trends, as well as help to identify natural or anthropogenic sources of dune vegetation disturbance. As a management tool, DUVES may provide awareness over conservation problems that may arise in dune habitats and actions needed, as well as help to prove their effectiveness once interventions are carried out.

CRediT authorship contribution statement

Lara Talavera: Conceptualization, Methodology, Validation, Formal analysis, Investigation, Data curation, Writing – original draft, Writing – review & editing, Visualization. **Susana Costas:** Conceptualization, Methodology, Resources, Writing – review & editing, Supervision, Funding acquisition. **Óscar Ferreira:** Conceptualization, Resources, Writing – review & editing, Supervision, Project administration, Funding acquisition.

Declaration of Competing Interest

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

Acknowledgments

Special thanks go to Animaris for the logistical support to conduct this work at Barreta Island, to the University of Coimbra team and SPEA for sharing the gull data as well as the DGT (Direção-Geral do Território) for providing the orthophotos. We would also like to thank the different institutions that granted the permits needed to perform the UAS surveys in this area of Ria Formosa: ANAC (Autoridade Nacional da Aviação Civil), ANN (Autoridade Aeronáutica Nacional), ICNF (Instituto da Conservação da Natureza e das Florestas), and the Capitania Marítima do Porto de Faro. We also acknowledge the field assistance of Luísa Bon de Sousa, Rita Carrasco, and Margarida Ramires. Lastly, we thank the anonymous reviewers for their careful reading of our manuscript and their insightful comments and suggestions.

Funding

This work is funded by the project LIFE18 NAT/PT/000927 - LIFE Ilhas Barreira “Conserving the Barrier Islands in Algarve to protect priority species and habitats”, and by the Portuguese Foundation of Science and Technology (FCT) to CIMA through UID/0350/2020.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.ecolind.2022.108770.

References

Almeida, L.P., Ferreira, Ó., Vousdoukas, M.I., Dodet, G., 2011. Historical variation and trends in storminess along the Portuguese South Coast. Nat. Hazards Earth Syst. Sci. 11, 2407–2417. https://doi.org/10.5194/nhess-11-2407-2011.

Anderson, W.B., Polis, G.A., 1999. Nutrient fluxes from water to land: Seabirds affect plant nutrient status on Gulf of California islands. Oecologia 118, 324–332. https://doi.org/10.1007/s004420050733.

Andrade, C., 1990. O Ambiente de barreira da Ria Formosa (Algarve, Portugal). PhD Thesis. University of Lisbon, Portugal, p. 636.

Bazzichetto, M., Malavasi, M., Acosta, A.T.R., Carranza, M.L., 2016. How does dune morphology shape coastal EC habitats occurrence? A remote sensing approach using airborne LiDAR on the Mediterranean coast. Ecol. Indic. 71, 618–626. https://doi.org/10.1016/j.ecolind.2016.07.044.

Bou, J., Vilar, L., Carreras, J., 2021. Habitat changes over 45 years on the small Mediterranean archipelago of the Medes Islands (Catalonia, NE Spain). Plant Biosyst. 155, 914–924. https://doi.org/10.1080/11263504.2020.1810806.

Calado, J.G., Matos, D.M., Ramos, J.A., Moniz, F., Ceia, F.R., Granadeiro, J.P., Paiva, V.H., 2018. Seasonal and annual differences in the foraging ecology of two gull species breeding in sympatry and their use of fishery discards. J. Avian Biol. 49 https://doi.org/10.1111/jav.01463.

Chen, Y., Yizhaq, H., Mason, J.A., Zhang, X., Xu, Z., 2021. Dune bistability identified by remote sensing in a semi-arid dune field of northern China. Aeolian Res. 53, 100751 https://doi.org/10.1016/j.aeolia.2021.100751.

Cohen, J., 1960. A coefficient of agreement for nominal scales. Educ. Psychol. Meas. 20, 37–46. https://doi.org/10.1177/001316446002000104.

Costa, M., Silva, R., Vitorino, J., 2001. Contribuição para o estudo do clima de agitação marítima na costa portuguesa. 2ª Jornadas Port. Eng. Costeira e Portuária 20, 20 pp.

De Giglio, M., Greggio, N., Goffo, F., Merloni, N., Dubbini, M., Barbarella, M., 2019. Comparison of pixel- and object-based classification methods of unmanned aerial vehicle data applied to coastal dune vegetation communities: Casal borsetti case study. Remote Sens. 11, 1416. https://doi.org/10.3390/rs11121416.

De La Peña-Lastra, S., Gómez-Rodríguez, C., Pérez-Alberti, A., Torre, F., Otero, X.L., 2021. Effects of a yellow legged gull (Larus michahellis) colony on soils and cliff vegetation in the Atlantic Islands of Galicia National Park (NW Spain). Catena 199, 105115. https://doi.org/10.1016/j.catena.2020.105115.

Delgado-Fernandez, I., O’Keeffe, N., Davidson-Arnott, R.G.D., 2019. Natural and human controls on dune vegetation cover and disturbance. Sci. Total Environ. 672, 643–656. https://doi.org/10.1016/j.scitotenv.2019.03.494.

Dias, A.J.M., Neal, W.J., 1992. Sea cliff retreat in southern Portugal: profiles, processes, and problems. J. Coast. Res. 8, 641–654.

Ellis, J.C., 2005. Marine birds on land: A review of plant biomass, species richness, and community composition in seabird colonies. Plant Ecol. 181, 227–241. https://doi.org/10.1007/s11258-005-7147-y.

Espejel, I., Ahumada, B., Cruz, Y., Heredia, A., 2008. Coastal Vegetation as Indicators for Conservation, in: Coastal Dunes. Springer, pp. 297–318. https://doi.org/10.1007/978-3-540-74002-5_18.

Fleiss, J.L., Levin, B., Paik, M.C., 2013. Statistical methods for rates and proportions. John Wiley & Sons.

Fraterrigo, J.M., Rusak, J.A., 2008. Disturbance-driven changes in the variability of ecological patterns and processes. Ecol. Lett. 11, 756–770. https://doi.org/10.1111/j.1461-0248.2008.01191.x.

García-Novo, F., Barradas, M.C.D., Zunzunegui, M., Mora, R.G., Fernández, J.B.G., et al., 2004. Plant Functional Types in Coastal Dune Habitats. Ecological Studies: Coastal Dunes, Ecology and Conservation, 171. Springer, Verlag, pp. 155–169.

García-Romero, L., Delgado-Fernández, I., Hesp, P.A., Hernández-Calvento, L., Hernández-Cordero, A.I., Viera-Pérez, M., 2019. Biogeomorphological processes in an arid transgressive dunefield as indicators of human impact by urbanization. Sci. Total Environ. 650, 73–86. https://doi.org/10.1016/j.scitotenv.2018.08.429.

García, L.V., Marañón, T., Ojeda, F., Clemente, L., Redondo, R., 2002. Seagull influence on soil properties, chenopod shrub distribution, and leaf nutrient status in semi-arid Mediterranean islands. Oikos 98, 75–86. https://doi.org/10.1034/j.1600-0706.2002.980108.x.

Ghermaoui, M., Hassaine, K., Moulaï, R., 2016. Influence du Goéland leucophée Larus michahellis sur les formations végétales ouvertes du littoral de Rachgoun (Ouest Oranie, Algérie). Rev. d’écologie 71 (3): 250-265. http://hdl.handle.net/2042/60686.

Hague, B., 2016. The Use of Remote Sensing to Map and Monitor Coastal Dune Vegetation Change at Southampton, Ontario, Canada. Master thesis. Brock University, St. Catharines, Ontario, Canada.

Herrero, X., Costas, S., Kombiadou, K., 2020. Coastal ridge constructive processes at a multi-decadal scale in Barreta Island (southern Portugal). Earth Surf. Process. Landforms 45, 411–423. https://doi.org/10.1002/esp.4742.

Heslenfeld, P., Jungerius, P.D., Klijn, J.A., 2008. European Coastal Dunes: Ecological Values, Threats, Opportunities and Policy Development, in: Coastal Dunes. Springer, pp. 335–351. https://doi.org/10.1007/978-3-540-74002-5_20.

Hesp, P.A., 1991. Ecological processes and plant adaptations on coastal dunes. J. Arid Environ 21, 165–191. https://doi.org/10.1016/s0140-1963(18)30681-5.

Hesp, P., 2011. 3.08–Dune Coasts. Treatise Estuar. Coast. Sci. Acad. Press, Waltham, pp. 193–221.

Hesp, P.A., 2008. Coastal Dunes in the Tropics and Temperate Regions: Location, Formation, Morphology and Vegetation Processes. pp. 29–49. https://doi.org/10.1007/978-3-540-74002-5_3.

Hesp, P.A., da Silva, G.M., 2016. Secondary dune, in: Kennish, M.J. (Ed.), Encyclopedia of Earth Sciences Series. Springer Netherlands, Dordrecht, pp. 549–550. https://doi.org/10.1007/978-94-017-8801-4_280.

Hilgendorf, Z., Marvin, M.C., Turner, C.M., Walker, I.J., 2021. Assessing geomorphic change in restored coastal dune ecosystems using a multi-platform aerial approach. Remote Sens. 13, 1–34. https://doi.org/10.3390/rs13030354.

IPMA, I. P., 2019. Website of the Portuguese Institute for Sea and Atmosphere I.P., www.ipma.pt (accessed December 2019).

Jackson, D.W.T., Costas, S., González-Villanueva, R., Cooper, A., 2019. A global ‘greening’ of coastal dunes: An integrated consequence of climate change? Glob. Planet. Change 182, 103026. https://doi.org/10.1016/j.gloplacha.2019.103026.

Jensen, J.R., 1986. Introductory Digital Image Processing: A Remote Sensing Perspective. Univ. of South Carolina, Columbus.

Kolb, G.S., Young, H.S., Anderson, W.B., 2011. Effects of Seabirds on Island Consumers. In: Mulder, C.P.H., Anderson, W.B., Towns, D.R., Bellingham, P.J. (Eds.), Seabird Islands: Ecology, Invasion, and Restoration. Oxford University Press, pp. 212–241. https://doi.org/10.1093/acprof:osobl/9780199735693.003.0007.

Kombiadou, K., Matias, A., Ferreira, Ó., Carrasco, A.R., Costas, S., Plomaritis, T., 2019. Impacts of human interventions on the evolution of the Ria Formosa barrier island system (S. Portugal). Geomorphology 343, 129–144. https://doi.org/10.1016/j.geomorph.2019.07.006.

Landres, P.B., Morgan, P., Swanson, F.J., 1999. Overview of the use of natural variability concepts in managing ecological systems. Ecol. Appl. 9, 1179–1188. https://doi.org/10.1890/1051-0761(1999)009[1179:OOTUON]2.0.CO;2.

Laporte-Fauret, Q., Lubac, B., Castelle, B., Michalet, R., Marieu, V., Bombrun, L., Launeau, P., Giraud, M., Normandin, C., Rosebery, D., 2020. Classification of Atlantic coastal sand dune vegetation using in situ, UAV, and airborne hyperspectral data. Remote Sens. 12, 2222. https://doi.org/10.3390/rs12142222.

Martínez, M. L., Hesp, P.A., Gallego-Fernández, J.B., 2013. Coastal dunes: human impact and need for restoration, in: Martínez M.L, Gallego-Fernández J., Hesp P. (Eds.) Restoration of Coastal Dunes. Springer Series on Environmental Management. Springer, Berlin, Heidelberg, pp. 1–14. https://doi.org/10.1007/978-3-642-33445-0_1.

Martínez, M.L., Vázquez, G., Sánchez Colón, S., 2001. Spatial and temporal variability during primary succession on tropical coastal sand dunes. J. Veg. Sci. 12, 361–372. https://doi.org/10.2307/3236850.

Marzialetti, F., Giulio, S., Malavasi, M., Sperandii, M.G., Acosta, A.T.R., Carranza, M.L., 2019. Capturing coastal dune natural vegetation types using a phenology-based mapping approach: The potential of Sentinel-2. Remote Sens. 11, 1506. https://doi.org/10.3390/rs11121506.

Matias, A., Ferreira, Ó., Vila-Concejo, A., Garcia, T., Dias, J.A., 2008. Classification of washover dynamics in barrier islands. Geomorphology 97, 655–674. https://doi.org/10.1016/j.geomorph.2007.09.010.

Matos, D.M., Ramos, J.A., Calado, J.G., Ceia, F.R., Hey, J., Paiva, V.H., 2018. Erratum: How fishing intensity affects the spatial and trophic ecology of two gull species breeding in sympatry (ICES Journal of Marine Science (2018) DOI: 10.1093/icesjms/fsy096). ICES J. Mar. Sci. 75, 2288. https://doi.org/10.1093/icesjms/fsy137.

McLachlan, A., Defeo, O., 2018. Coastal Dune ecosystems and Dune–Beach interactions, in: McLachlan, A., Defeo, O.B.T.-T.E. of S.S. Third E. (Eds.), The Ecology of Sandy Shores. Academic Press, pp. 309–329. https://doi.org/10.1016/b978-0-12-809467-9.00013-8.

Mendes, R.F., Ramos, J.A., Paiva, V.H., Calado, J.G., Matos, D.M., Ceia, F.R., 2018. Foraging strategies of a generalist seabird species, the yellow-legged gull, from GPS tracking and stable isotope analyses. Mar. Biol. 165, 1–14. https://doi.org/10.1007/s00227-018-3421-0.

Miller, T.E., Gornish, E.S., Buckley, H.L., 2010. Climate and coastal dune vegetation: Disturbance, recovery, and succession. Plant Ecol. 206, 97–104. https://doi.org/10.1007/s11258-009-9626-z.

Moreno-Casasola, P., 2008. Dunes, in: Encyclopedia of Ecology, Five-Volume Set. Elsevier Inc., pp. 971–976. https://doi.org/10.1016/B978-008045405-4.00328-1.

Olafson, E., 1981. The status of the land-arthropod fauna on Surtsey, Iceland, in summer 1981. Surtsey Res. Progr. Rep. 9 (11), 68–71.

Otero, X.L., De La Peña-Lastra, S., Pérez-Alberti, A., Ferreira, T.O., Huerta-Diaz, M.A., 2018. Seabird colonies as important global drivers in the nitrogen and phosphorus cycles. Nat. Commun. 9 https://doi.org/10.1038/s41467-017-02446-8.

Otero, X.L., Tejada, O., Martín-Pastor, M., De La Peña, S., Ferreira, T.O., Pérez-Alberti, A., 2015. Phosphorus in seagull colonies and the effect on the habitats. The case of yellow-legged gulls (Larus michahellis) in the Atlantic Islands National Park (Galicia-NW Spain). Sci. Total Environ. 532, 383–397. https://doi.org/10.1016/j.scitotenv.2015.06.013.

Özdemir, I., Asan, Ü., Koch, B., Yeşil, A., Özkan, U.Y., Hemphill, S., 2005. Comparison of quickbird-2 and landsat-7 ETM+ data for mapping of vegetation cover in Fethiye-Kumluova coastal dune in the Mediterranean region of Turkey. Fresenius Environ. Bull. 14, 823–831.

Pacheco, A., Vila-Concejo, A., Ferreira, Ó., Dias, J.A., 2008. Assessment of tidal inlet evolution and stability using sediment budget computations and hydraulic parameter analysis. Mar. Geol. 247, 104–127. https://doi.org/10.1016/j.margeo.2007.07.003.

Petersen, A., 2009. Formation of A Bird Community on A New Island, Surtsey, Iceland. Surtsey Res. Prog. Rep. XII, pp. 133–148.

Polis, G.A., Anderson, W.B., Holt, R.D., 1997. Toward an integration of landscape and food web ecology: The dynamics of spatially subsidized food webs. Annu. Rev. Ecol. Syst. 28, 289–316. https://doi.org/10.1146/annurev.ecolsys.28.1.289.

Provoost, S., Jones, M.L.M., Edmondson, S.E., 2011. Changes in landscape and vegetation of coastal dunes in northwest Europe: A review. J. Coast. Conserv. 15, 207–226. https://doi.org/10.1007/s11852-009-0068-5.

Robin, N., Billy, J., Castelle, B., Hesp, P., Nicolae Lerma, A., Laporte-Fauret, Q., Marieu, V., Rosebery, D., Bujan, S., Destribats, B., Michalet, R., 2021. 150 Years of foredune initiation and evolution driven by human and natural processes. Geomorphology 374, 107516. https://doi.org/10.1016/j.geomorph.2020.107516.

Sanchez-Pinero, F., Polis, G.A., 2000. Bottom-up dynamics of allochthonous input: Direct and indirect effects of seabirds on islands. Ecology 81, 3117–3132. https://doi.org/10.1890/0012-9658(2000)081[3117:BUDOAI]2.0.CO;2.

Sen, P.K., 1968. Estimates of the regression coefficient based on Kendall's Tau. J. Am. Stat. Assoc. 63, 1379–1389. https://doi.org/10.1080/01621459.1968.10480934.

Serra, L., Andreotti, A., Kirov, D., Balkans, G., Nardelli, R., 2016. Guidelines for management of the breeding populations of the Yellow-legged Gull Larus michahellis in the saltpans and coastal wetlands of the Mediterranean (Linee guida per la gestione delle popolazioni nidificanti di Gabbiano reale Larus michahellis nelle saline e nelle zone umide costiere del Mediterraneo). Project LIFE10NAT/IT/000256. ISPRA, Serie Manuali e linee guida, 144/2016.

Shanmugam, S., Lucas, N., Phipps, P., Richards, A., Barnsley, M., 2003. Assessment of remote sensing techniques for habitat mapping in coastal dune ecosystems. J. Coast. Res. 19, 64–75. https://doi.org/https://www.jstor.org/stable/4299148.

Valentini, E., Taramelli, A., Cappucci, S., Filipponi, F., Xuan, A.N., 2020. Exploring the dunes: The correlations between vegetation cover pattern and morphology for sediment retention assessment using airborne multisensor acquisition. Remote Sens. 12, 1229. https://doi.org/10.3390/RS12081229.

Vidal, E., Medail, F., Tatoni, T., 1998. Is the yellow-legged gull a superabundant bird species in the Mediterranean? Impact on fauna and flora, conservation measures and research priorities. Biodivers. Conserv. 7, 1013–1026. https://doi.org/10.1023/A:1008805030578.

Vidal, E., Médail, F., Tatoni, T., Bonnet, V., 2000. Seabirds drive plant species turnover on small Mediterranean islands at the expense of native taxa. Oecologia 122, 427–434. https://doi.org/10.1007/s004420050049.

Vila-Concejo, A., Matias, A., Ferreira, O., Duarte, C., Dias, J.M.A., 2002. Recent evolution of the natural inlets of a barrier island system in Southern Portugal. J. Coast. Res. 36, 741–752. https://doi.org/10.2112/1551-5036-36.sp1.741.

Vinet, L., Zhedanov, A., 2011. A "missing" family of classical orthogonal polynomials. J. Phys. A Math. Theor. 44, 56. https://doi.org/10.1088/1751-8113/44/8/085201.

Xie, Y., Sha, Z., Yu, M., 2008. Remote sensing imagery in vegetation mapping: a review. J. Plant Ecol. 1, 9–23. https://doi.org/10.1093/jpe/rtm005.

Zhang, L., Baas, A.C.W., 2012. Mapping functional vegetation abundance in a coastal dune environment using a combination of LSMA and MLC: A case study at Kenfig NNR. Wales. Int. J. Remote Sens. 33, 5043–5071. https://doi.org/10.1080/01431161.2012.657369.