Unmanned aerial systems-based monitoring of the eco-geomorphology of coastal dunes through spectral Rao's Q

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Title:

UAS-based monitoring of coastal dunes eco-geomorphology through spectral Rao's Q

Running title: Drones for coastal integrity

Marco Malavasi[1], Manuele Bazzichetto[2], Jan Komarek[1], Vítězslav Moudry[1], Duccio Rocchini [1,3], Simonetta Bagella[4], Alicia T.R. Acosta[5], Maria L. Carranza[6]

ORCID

Marco Malavasi: 0000-0002-9639-1784;

Manuele Bazzichetto: 0000-0002-9874-5064

Jan Komarek: 0000-0002-3505-6755;

Vítězslav Moudry: 0000-0002-3194-451X

Duccio Rocchini: 0000-0003-0087-0594

Alicia T.R Acosta: 0000-0001-6572-3187

Maria Laura Carranza: 0000-0001-5753-890X

AFFILIATIONS

[1] Department of Applied Geoinformatics and Spatial Planning, Faculty of Environmental Sciences, Czech University of Life Sciences Prague, Kamycka 129, Praha – Suchdol, Czech Republic.

[2] Université de Rennes, CNRS, EcoBio (Ecosystèmes, biodiversité, évolution) - UMR 6553, F-35000 Rennes, France.

[3] Alma Mater Studiorum University of Bologna, Department of Biological, Geological and Environmental Sciences, via Irnerio 42, 40126, Bologna, Italy.

[4] Department of Chemistry and Pharmacy, University of Sassari, Via Piandanna 4, I07100 Sassari, Italy. ORCID Simonetta Bagella: 0000-0002-8519-2675

[5] Departiment ofi Sciences, University of Rome 3, V.le Marconi 446, 00146 Rome, Italy.

[6] EnviX-Lab, Dipartimento di Bioscienze e Territorio, Università Degli Studi del Molise, C.da Fonte Lappone, 86090 Pesche, IS, Italy.

Correspondence: M. Laura Carranza, EnviX-Lab, Dipartimento di Bioscienze e Territorio, Università Degli Studi del Molise.

ORCID Maria Laura Carranza: 0000-0001-5753-890X; Email: carranza@unimol.it

Abstract

Question: Does spectral diversity captured by Unmanned Aerial Systems (UAS) provide reliable information for monitoring the eco-geomorphological integrity of Mediterranean coastal dune ecosystems? Can this information discriminate between two coastal areas with low (LP) and high (HP) human pressure?

Location: Tyrrhenian coast, Central Italy

Methods: By processing UAS images, we derived NDVI and topographic variables at high spatial resolution (0.5 m) for 150 m wide strips starting from the coastline inland on two representative coastal tracts under low and high human pressure. We mapped the sea-inland heterogeneity applying Rao's Q index to the plant biomass (NDVI) and geomorphology variables (elevation and slope). Since Rao's Q index can be calculated in a multidimensional space, we summarized the variability of these three variables into a single eco-geomorphological layer. We then inspected and compared how the plant biomass, geomorphology and eco-geomorphology Rao's Q index values change as a function of the distance from the sea between the two coastal sites.

Results: Rao's Q heterogeneity values vary along the sea-inland gradient of well-preserved sites (LP). The maximum eco-geomorphological heterogeneity was found at intermediate distances from the sea and decreased towards the inner sector where the dune geomorphology was more stable and vegetation more homogeneously distributed. Instead, Rao's Q heterogeneity values featured constant low values along the gradient on the HP site, highlighting a simplified eco-geomorphological gradient related to the high human pressure.

Conclusions: Using UAS, the eco-geomorphological gradient of coastal dunes can be quantified at a very fine spatial resolution over management-relevant extents. Rao's Q index applied to sensing imagery successfully captured the differences in the eco-geomorphological heterogeneity along the sea-inland dune gradient and among sites with different levels of anthropic pressure. This approach supports frequent surveys and is particularly suitable for spatial monitoring of key coastal functions and services.

Keywords: coastal dunes, eco-geomorphology, dune elevation, habitat monitoring, human pressure, NDVI, dune slope, Rao's Q index, spectral diversity UAS

1. Introduction

Coastal dunes ecosystems are crucial for human health, delivering a wide range of essential services to society including coastal defense, groundwater storage and water purification, or tourism and recreation (Mendoza-González et al. 2012; Drius et al. 2013; Liquete, Piroddi, et al. 2013; Drius, Bongiorni, et al. 2019; Drius, Jones, et al. 2019). Nonetheless, in Mediterranean areas, the loss and degradation of littoral landscapes and the associated services has been particularly severe in the last decades (Malavasi et al. 2013; Carranza et al. 2020; Prisco et al. 2020). For instance, results from the 4th Monitoring Report (European Habitats Directive 92/43/EEC, hereafter HD) depicted a dramatically impaired conservation status of Italian natural coasts with 88% of the dune habitats being in a bad conservation status and the remaining 12% inadequately protected (for details, see Prisco *et* *al*. 2020). According to the HD, the preservation, continuous monitoring, and reporting of the coastal ecosystems is currently a priority at both the national and European levels (Janssens *et al*. 2009; Gigante *et al*. 2018). The introduction of new practices facilitating recurrent and effective monitoring on a wide spatial extent is crucial for meeting HD goals.

It is now acknowledged that the stability of coastal dunes and the provision of most of the aforementioned ecosystem services is assured by the integrity of ecomorphodynamic interactions (hereafter eco-geomorphological integrity) between *psammophilous* plants encountered along the sea-inland gradient and geomorphology (Baas 1997; Sperandii et al. 2019; Bazzichetto et al. 2020). Thus, on the one hand, vegetation distribution and biomass depend on many geomorphology-related factors (e.g. wind and marine aerosol exposure, wave energy, flooding); in turn, vegetation exerts major control on the development of the topographic features (e.g. substrate fixation, erosion prevention), mediating the very same abiotic governing factors (Bazzichetto *et al*. 2016; Yousefi Lalimi *et al*. 2017). Accordingly, an accurate monitoring approach should be able to capture such type of eco-geomorphological integrity.

Nevertheless, standard monitoring procedures have mostly been performed either through ground surveys (Stanisci *et al*. 2014; Prisco *et al*. 2016; Sperandii *et al*. 2018) or through habitat mapping, integrating the photointerpretation of aerial imagery or classification of remotely sensed imagery with floristic data (Acosta et al. 2009b; Malavasi et al. 2013; Rapinel et al. 2014; Carranza et al. 2018; Marzialetti et al. 2019; Marzialetti et al. 2020). However, ground approaches are laborious, limited by the lack of standardized procedures for reproducible data gathering (Rocchini *et al*. 2017), and may fail in reporting the state of the ecosystem on a wide range of scales in a consistent, borderless and repeatable manner. Likewise, habitat mapping procedures are limited by the expensive high-resolution data required to map the heterogeneous and fine-grain habitat mosaics such as those encountered in Mediterranean coastal ecosystems (Zhang & Baas 2012; Rapinel et al. 2014). Besides, habitat mapping, relying on classification techniques, inevitably leads to the degradation of continuous information stored in remotely sensed data (Foody 2002; Palmer et al. 2002; Rocchini et al. 2017).

Unmanned Aerial Systems (UASs) and their use are among the most dynamically developing fields of remote sensing (RS), representing a suitable source of data for environmental analyses. UASs, besides collecting multispectral images usable to capture vegetation patterns and distribution, represent an emerging, relatively low-cost, alternative to the traditional photogrammetry or active sensor technologies (e.g. LIDAR) for generating high-resolution topographic reconstruction (Whitehead & Hugenholtz 2014). Photo-reconstruction algorithms based on the structure-from motion (SfM) and multi-view-stereo analysis (MVS) algorithms (James & Robson 2012) enable the generation of reliable 3D point clouds from large sets of multi-angle images. In this sense, UASs have the potential to overcome the standard monitoring procedures, simultaneously delivering all information required to report about the eco-geomorphological integrity of coastal dune ecosystems (Valentini *et al*. 2020).

In this study, we aim to determine to what extent can a combination of *in situ* sensing data on vegetation and geomorphological variables captured from a UAS deliver valuable information about the eco-geomorphological integrity of Mediterranean coastal dune ecosystems. More specifically, we compared the eco-geomorphological pattern along the sea-inland gradient of two different beaches in Central Italy, one with high (HP) and the other with low (LP) human pressure, to explore the potential of UAS-derived eco-geomorphological data for capturing the spatial heterogeneity of coastal dunes. Such heterogeneity will be quantified employing the recently proposed Rao's Q diversity index applied to spectral data (Rocchini *et al.* 2017). As opposed to other diversity metrics applied to remotely sensed data that rely on Shannon's entropy theory and summarize the relative abundances of reflectance values, (Shannon 1948), Rao's Q index takes into account both the proportion of cells assuming different spectral values and their spectral distance (Rocchini *et al.* 2017). The analysis of images by Rao's Q could adequately describe highly heterogeneous landscapes and fine-scale environmental gradients, preserving most of the spectral variability which could be lost if processed though commonly used habitat classification approaches (Palmer *et al.* 2002). Likewise, as Rao's Q can be calculated in a multidimensional space (multi-layers), it is potentially a good parameter capable of combining the ecological and geomorphological aspects of the dune at the same time.

In this context, we expect a different behavior of the Rao's Q index according to the conservation status of the coastal areas. In particular, an intact eco-geomorphological arrangement of dune ecosystems in well-preserved coasts should correspond to a high spectral diversity with maximum Rao's Q values at intermediate distances from the seashore where tiny habitat mosaics occur (Acosta et al. 2009a; Bazzichetto et al. 2016). On the other hand, in highly disturbed coastal areas, the simplification and integrity loss of the dune ecosystems (Malavasi, Santoro, et al. 2016) should result in flat spectral diversity profiles maintaining low values at all seashore distances.

2. Material and Methods

2.1 Study area

The study area includes representative tracts of Mediterranean coastal dunes located on the Tyrrhenian coast of central Italy (Latium region). In natural conditions (i.e. integrity of the eco-geomorphological dynamics), recent dunes (Holocene) generally occupy a narrow strip along the seashore. They are not very high (usually less than 8–10 m) and are relatively simple in structure, with beaches of varying width from a few meters to around 40 m, low embryo-dunes, generally consisting of only one mobile dune ridge, dune slacks, and stabilized dunes (Acosta et al. 2003b; Bazzichetto et al. 2016). Vegetation zonation follows the sea-inland ecological gradient, ranging from annual communities on the strandline zone of the beach to patchy Mediterranean Macchia on the inland stabilized dunes (Acosta, Stanisci, et al. 2003; Carranza et al. 2008) (for a description of the habitat types along the zonation as detailed in the Habitat Directive 92/43/EEC, see Fig 1). Most of those plant communities are of conservation concern in Europe (Janssens *et al.* 2009). Nonetheless, along several tracts of the study area, human pressure (i.e. seaside tourism and urban expansion) has severely transformed coastal dune ecosystems and altered their eco-geomorphological integrity. In particular, human trampling and mechanical cleaning on the strandline zone of the beach are depleting plant communities and, in turn, their stabilizing effect on the substrate (Santoro et al. 2012; Battisti et al. 2016). Likewise, human infrastructure (e.g. bathhouses, roads) keeps gaining new space at the expense of the inland stabilized dunes, which often results in the removal of woody vegetation (Malavasi et al. 2013).

On the basis of the incidence of the human settlements and the population density (Italian Institute of Statistics, available at http://www.istat.it) used as a proxy of human pressure (Carboni et al. 2010;

Malavasi, Santoro, et al. 2016), we selected two different beaches (LP and HP) in two larger areas with low and high human pressure (WGS84 UTM N33: 213583E, 4694824N, and 262637E, 4644756N, respectively). The environmental conditions at both LP and HP sites are comparable in terms of climate, potential vegetation, geographical position, sediment type, and aspect (Carranza et al. 2008). The LP beach is located in an area characterized by a reduced presence of infrastructure and buildings (artificial surfaces constitute less than 10% of the area), with a population density of about 76.6 habitants per km^2. These conditions favor the development of natural dunes characterized by well-structured vegetation (Malavasi, Santoro, et al. 2016; Malavasi et al. 2018) and geomorphological pattern (Bazzichetto *et al*. 2016). On the other hand, HP beach is located in an area characterized by widespread tourism infrastructure, summer houses, and other artificial surfaces (more than 35% of the total area), with the population density of about 683.3 habitants per km^2. These conditions have restrained the coastal vegetation to small areas distributed in tiny patches and fragmented pattern (Malavasi et al. 2013). Given that in central Italy, the dune ridges are generally very narrow, we focused the analysis on an approximately 150 m wide strip starting from the coastline inland. Specifically, we analyzed 3 km of the coast, i.e, approx. 50 ha, for each site (HP and LP).

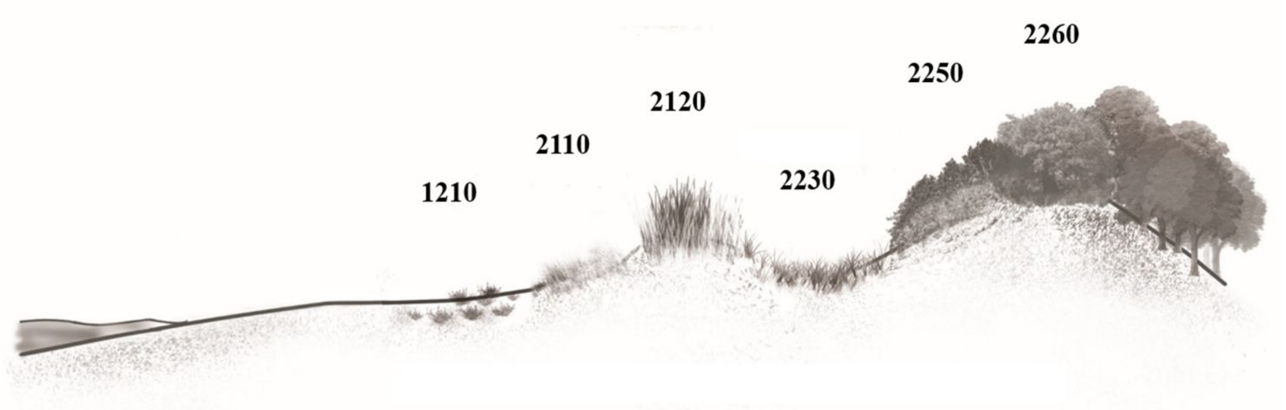

Fig 1. A typical sequence of the EC Habitat types (Habitat Directive 92/43/EEC) along the sea-inland vegetation zonation: 1210 Annual vegetation of drift line, 2110 Embryonic shifting dunes, 2120 Shifting dunes along the shoreline with *Ammophila arenaria*, 2230 *Malcolmietalia* dune grasslands, 2250* Coastal dunes with *Juniperus* spp., 2260 *Cisto-Lavanduletalia* dune sclerophyllous scrubs.

2.2 UAS flight and image acquisition

The low altitude aerial survey was performed across the LP and HP sites using a light fixed-wing Unmanned Aerial Vehicle eBee Cassic (senseFly, Switzerland). The UAS with a maximum take-off weight of 0.8 kg was mounted with a multispectral camera multiSPEC 4C (Airinov, France) (Komárek *et al*. 2018). The sensor acquires pictures in green (G: 530-570 nm), red (R: 640-680 nm), red-edge (RE: 730-740 nm), and near infra-red (NIR: 770-810 nm) bands each, with an image resolution of 1.23 MPx. Flight missions, performed in eMotion 2 ground control software, were planned parallel to the seashore with 80% overlaps of flight lines. Flights were conducted at 90 m above ground level with UAS airspeed of 10–11 m.s^{-1}. Conditions for the flight were convenient, ceiling and visibility were OK, i.e. no cloud below 1,500 m or the highest minimum sector altitude and no cumulonimbus or towering cumulus at any level, a visibility of 10 km or more and no significant weather change; the weather was sunny with low cloud cover (1/8), temperature of 20 °C, side-stable light breeze of 2–3 m.s^{-1}. In total, four individual flights were realized on May 03, 2017 across the LP site where 1751 perpendicular images were acquired, and two flights on May 04, 2017 at the HP site with 896 images. Acquired imagery was processed using SfM–MVS photo-reconstruction algorithms in Pix4DMapper 3.1.23 (Pix4D S.A., Switzerland) image-matching software. To improve the reconstruction accuracy due to a large portion of water in the images, manual tie points using a lidar-based elevation model (RNDT, cnipa.gov.it) were spatially dislocated across the sites. To gain precise values of surface reflectance, acquired mosaics were calibrated using Sun irradiance and Sun angle values from the camera sensor and albedo values from the reflectance panel. Both orthorectified mosaics representing values of surface reflectance together with Digital Surface Models (DSM) were built with a strong model geometry and exported with a pixel size of 10 cm in WGS84 UTM N33 projections (for a visual inspection of RGN false-color images of the compared areas, see Appendix S1).

In order to acquire topographic data, DSM point clouds were classified using fully automatic custom machine learning algorithms into a Digital Terrain Model (DTM) (Villanueva et al. 2019) with a 50 cm pixel size, from which the slope was also derived. The pixel size was reduced to 50 cm due to the smoothing nature of the DTM generation algorithm, where results are better when the DTM resolution is slightly lower than the resolution of the project (for details see “Pix4D support”). A sea distance layer was also computed in a GIS Environment (ArcGIS 10.4.1), calculating the straight-line Euclidean distance between each cell (the center) and the shoreline, manually derived through photointerpretation of the UAS image visualized in false colors (band composition: NIR-R-G). Finally, to indicate geomorphological variables, elevation (m asl), slope (degree), and sea distance (m) were selected (see Table 1) as proved reliable measures of dune topography for vegetation distribution (Bazzichetto *et al.* 2016).

Table 1: UAS original data and derived data used to compute the heterogeneity Rao’s Q index along the sea-inland gradient (sea distance) for vegetation, geomorphology, and dune eco-geomorphology. [RGN false-color images of the compared areas, along with the raster outputs of the Rao’s Q Heterogeneity Index calculation for plant biomass ($Q_{p\text{-}biom}$), surface geomorphology (Q_{geo}), and Eco-geomorphology ($Q_{eco\text{-}geo}$) are reported on Appendix S1].

UAS data	**UAS derived data**	**Rao’s Q Heterogeneity Index**	
Surface reflectance	NDVI	Plant biomass ($Q_{p\text{-}biom}$)	Eco-geomorphology ($Q_{eco\text{-}geo}$)
DTM (Digital Terrain Model) False color (NIR-R-G)	Elevation (m.asl) Slope (degr.) Sea distance (m)	Geomorphology (Q_{geo})	

To indicate plant biomass, the Normalized Difference Vegetation Index (NDVI) was calculated using the map algebra following the equation below (Tucker 1979): $NDVI = NIR - R / NIR + R$.

NDVI has been widely shown to be a representative proxy for green biomass and photosynthetic activity (Bermúdez & Retuerto 2013). Moreover, it has been successfully applied to dune vegetation as a proxy of plant biomass (Castanho et al. 2015; Yousefi Lalimi et al. 2017; Marzialetti et al. 2019). All layers were rescaled to 50 cm in order to reduce the random noise and to better match the scale of the eco-geomorphological processes (Moudrý *et al.* 2019). Then, all the raster values of each layer were rescaled from 0 to 10 (linear function in ArcGIS 10.4.1) to apply the multidimensional Rao’s Q heterogeneity index.

2.3 Rao’s Q Heterogeneity index

Recently, the Rao’s Q index has been proposed as an innovative spectral heterogeneity measure in the field of remote sensing (Rocchini *et al.* 2017), with a high degree of accuracy compared to the metrics built on the Shannon’s entropy theory (Khare et al. 2019; Torresani et al. 2019). To capture and summarize the complex spatial eco-geomorphological heterogeneity of coastal dunes, Rao’s Q index was applied to different sets of UAS derived data (Table 1). The proposed application of Rao's Q index considers both the relative abundances of pixel values in the selected image and the distances among pixel' numerical values. Besides, since Rao's Q index can be calculated in a multidimensional space (multi-layers), the variability of more than one layer can be considered at a time, and it is calculated as follows:

$$Q_{rs} = \sum_{i=1}^{F-1} \sum_{j=i+1}^{F} d_{ij} * p_i * p_j$$

where

Q_{rs} = Rao's Q applied to remote sensing

p = relative abundance of a pixel value in a selected plot image (e.g. moving window)

d_{ij} = spectral distance between the i-th and j-th pixel value ($d_{ij} = d_{ji}$ and $d_{ii} = 0$)

i = pixel i

j = pixel j

The distance matrix where the d_{ij} is computed was built in different dimensions, thus allowing to consider more than one layer at a time (in our case, plant biomass and geomorphology variables).

In order to explore the potential of Q_{rs} for summarizing the plant biomass and the geomorphological aspects into a single eco-geomorphological index, a first output ($Q_{eco\text{-}geo}$) was produced considering NDVI, elevation, and slope at a time. For capturing the plant domain of the eco-geomorphological pattern, only the NDVI layer was considered ($Q_{p\text{-}biom}$) while for the geomorphological domain, elevation and slope were considered together (Q_{geo}). We calculated the Q_{rs} in a single or multi-dimensional environment using the R function "spectralrao" (Rocchini *et al*. 2017), obtaining three different rasters ($Q_{eco\text{-}geo}$, $Q_{p\text{-}biom}$ and Q_{geo}). Q_{rs} was calculated using a moving window device of 3x3 pixels (1.5 x 1.5 m). The selection of the window sizes conforms to the previous studies (Bazzichetto *et al*. 2016; Malavasi *et al*. 2018) that found such scales to be effective for describing the dune mosaic patterns in the Mediterranean coastal tracts under different disturbance regimes. (Raster outputs of the Rao's Q Heterogeneity Index calculation for plant biomass ($Q_{p\text{-}biom}$), surface geomorphology (Q_{geo}), and Eco-geomorphology ($Q_{eco\text{-}geo}$) are reported in Appendix S1).

2.4 Data analyses

In order to display and compare Rao's Q Heterogeneity values along the sea-inland gradient for both LP and HP sites, we sampled the Rao's Q index value at 750 randomly generated locations throughout each site, (approximately 15 random points per hectare). Specifically, we extracted the Rao's Q values $Q_{eco\text{-}geo}$ (NDVI, elevation, slope), $Q_{p\text{-}biom}$ (plant biomass), and Q_{geo} (elevation, slope) at each location. The random locations were then classified into 6 sequential sectors based on their distance to sea. Profile sectors where identified every 25 m, since the change of dune types and related plant communities in the analyzed area occurs on average every 25 m (Acosta et al. 2003b; Bazzichetto et al. 2016). Random locations were sampled only within natural and vegetated areas, urbanized ones were disregarded. Box and whiskers plots were produced for HP and LH to display and compare their Rao's Q values along the sea-inland gradient. Finally, to assess the difference of the Rao's Q values for each sector between LP and HP, a Welch's t-test was computed, and p-values were adjusted according to Holm correction (Holm 1979).

3. Results

The Rao's Q index values at LP and HP sites featured distinct trends for eco-geomorphology, plant biomass, and geomorphology (Table 2; Fig 2, 3 and 4), especially when considering different sectors of the sea-inland gradient: $Q_{eco-geo}$ showed different values for the LP and HP site along all the sectors of the sea-inland gradient, Q_{p-biom} in the foredune sectors (from 0 to 50 m from the seashore) and in the more inland sectors (from 75 to 125 m from the seashore), while Q_{geo} differed only in the inland sector (from 100 to 125 m from the seashore).

Specifically, compared to HP, LP showed more dispersed $Q_{eco-geo}$ values (wider boxes and longer whiskers) all along the sea-inland gradient (Fig 2), with pronounced differences in the two first sectors (0 to 50 m from the seashore) (Table 2). That is, the LP site showed higher eco-geomorphological diversity values in these foredune sectors. In general, $Q_{eco-geo}$ values for LP presented a slight peak in the second sector (25 to 50 m from the seashore) that tended to decrease in the last inland sectors, depicting more homogeneous ecological and morphological characteristics (Fig 2). On the contrary, HP did not show any peak, featuring a flatter but increasing trend all along the gradient.
As regards plant biomass, LP again showed more dispersed Q_{p-biom} values all along the gradient, except for the second sector (25 to 50 m from the seashore) (Fig 3). In general, both LP and HP sites showed very low, although different, values (Table 2) in the very first sector (0 to 25 m). As for $Q_{eco-geo}$ but slightly more pronounced, Q_{p-biom} values showed a peak for the LP site in the second sector (25 to 50 m) that subsequently decreased again, presenting a flatter but increasing trend in the last inland sectors (Fig 3). HP did not show any peak in the Q_{p-biom} values, featuring a flatter but increasing trend all along the gradient.

Table 1. Welch's t-test results comparing $Q_{eco-geo}$, Q_{p-biom} and Q_{geo} values for each sector between LP and HP ('***' $p < 0.001$; '**' $p < 0.01$; '*' $p < 0.05$; '.' $p < 0.1$).

	$Q_{eco-geo}$			Q_{p-biom}			Q_{geo}		
Sector	**T**	**Df**	**p**	**T**	**Df**	**p**	**T**	**Df**	**p**
25	6.431	99.369	***	2.675	138.038	*	0.304	137.393	
50	7.737	174.820	***	4.791	174.134	***	-0.087	169.630	
75	2.184	144.428	*	0.481	129.509		-0.597	163.507	
100	3.306	119.424	**	3.124	106.960	**	-0.426	146.126	
125	3.311	160.001	**	3.504	159.585	**	-5.041	117.867	***
150	2.513	155.262	*	1.474	156.924		0.309	147.383	

Finally, Q_{geo} featured equally dispersed values (similar sizes of the boxes and whiskers) all along the gradient with high and similar values in the foredune sectors (0 to 75 m from the seashore) (Fig 4) and lower in the inner sectors. A marked difference in the last sectors (100 to 150 m) between LP and HP can be observed, where LP presented a lower geomorphology diversity.

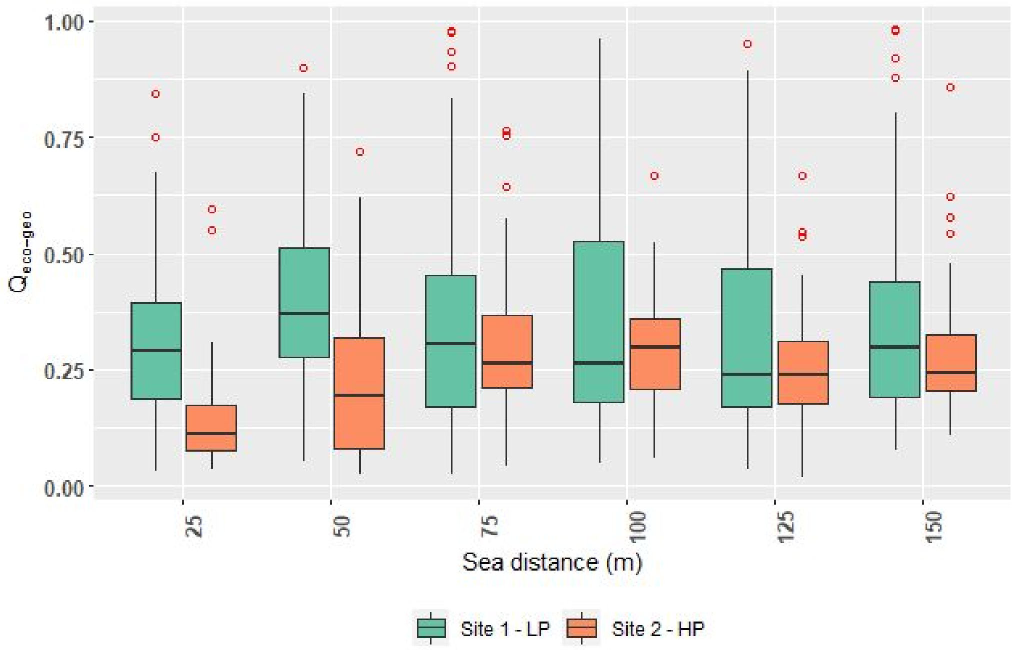

Fig. 2 Box plots of the $Q_{eco\text{-}geo}$ values (NDVI, elevation, slope) along the sea-inland gradient for the LP (green) and HP (orange) sites.

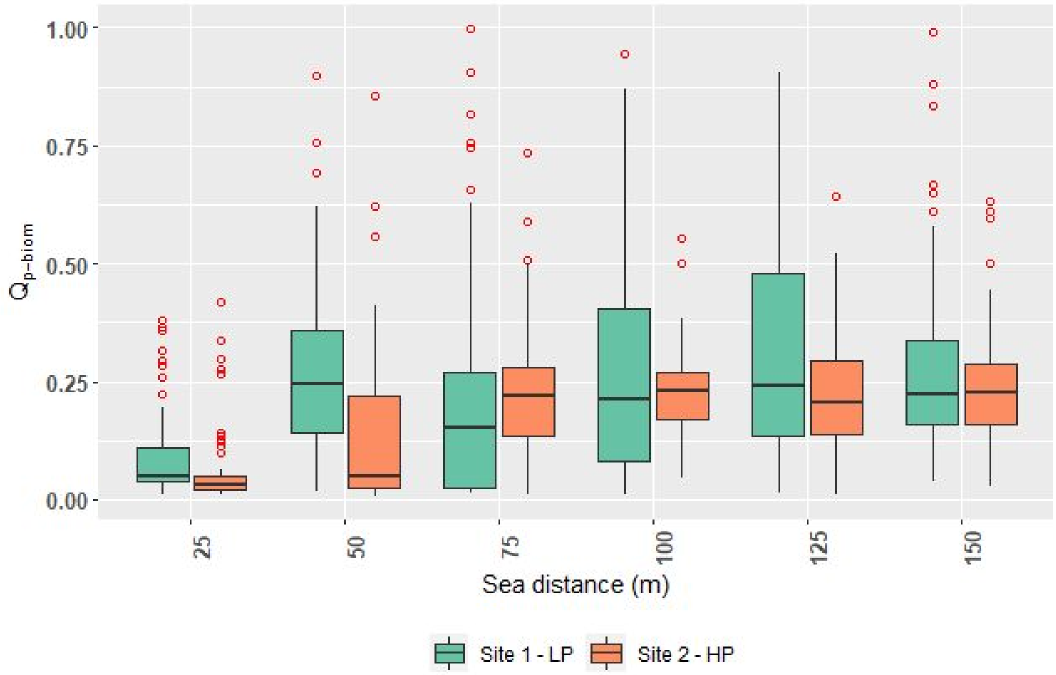

Fig. 3 Box plots of the $Q_{p\text{-}biom}$ values (NDVI) along the sea-inland gradient for the LP (green) and HP (orange) sites.

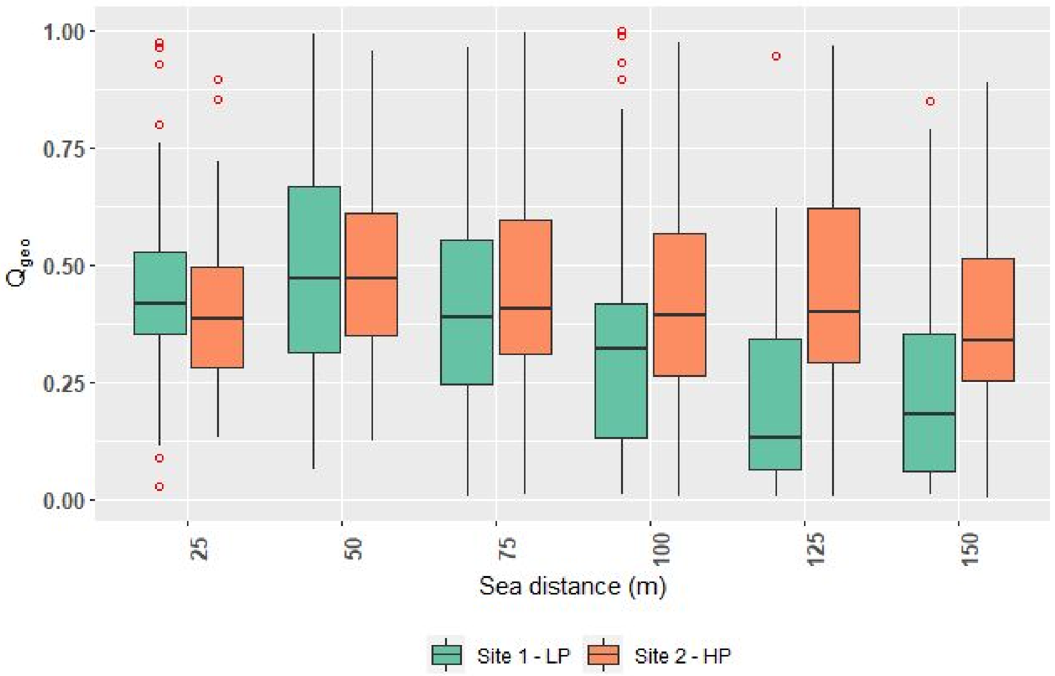

Fig. 4 Box plots of the Q_{geo} values (elevation and slope) along the sea-inland gradient for the LP (green) and HP (orange) sites .

4. Discussion

In this paper, we tested the potential of fine-scale UAS data to describe the eco-geomorphological pattern of coastal dunes by comparing such pattern along the sea-inland gradient of two different beaches in Central Italy with low (LP site) and high (HP site) human pressure. Concurrently, we tested the recently proposed Rao's Q diversity index applied to the UAS-derived spectral information (Q_{rs}) for describing the dune eco-geomorphological integrity as an supplement to the habitats classification approaches commonly relied upon for describing and reporting the state of conservation of littoral landscapes.

In this sense, the Rao's Q index successfully discriminated between the sites with high and low human pressure, reporting different patterns for the two sites, especially when observing individual sectors of the sea-inland gradient. Such differences were better explained when considering all the separate components of eco-geomorphology, i.e. plant biomass and geomorphology.

Specifically, if compared to the LP site, the HP site features a lower eco-geomorphological heterogeneity within all the sectors of the sea-inland gradient. Besides, as opposed to LP, HP did not present a distinctive peak value of Rao's Q in the second sector of the gradient (25 to 50 m from the seashore), which is typical of well-conserved dune systems where a patchy mosaic of several plant communities occurs along with a complex geomorphological profile. These findings confirm previous observations from highly urbanized coasts in the Mediterranean (Drius et al. 2013; Malavasi et al. 2013) where a high level of human pressure leads to the homogenization of the littoral landscape and thus to a simplification of the typical spatial pattern of well-preserved dune mosaics (Acosta *et al*. 2003a; Carboni *et al*. 2009), both in biomass and geomorphology. Such a process of trivialization has been also linked with a consistent decline of biodiversity values (Malavasi *et al*. 2018) and ecosystem integrity loss (Drius et al. 2013; Drius, Jones, et al. 2019).

However, these trends are more clearly explained when looking in detail at the plant biomass and geomorphology heterogeneity values. In both LP and HP sites, very low values of plant biomass diversity ($Q_{p\text{-}biom}$) at the very beginning of the zonation (0 to 25 m from the seashore) were related to the presence of large surfaces of bare sand and sparse annual plant communities (i.e. communities related to the EC habitat type 1210 - Annual vegetation of drift lines) with a low photosynthetic surface. Indeed, these environments are characterized by high salinity and exposure to salt spray, continuous wind abrasion, and sand burial (Bazzichetto et al. 2016; Malavasi, Conti, et al. 2016). Concurrently, if compared to LP, the lower plant biomass diversity for HP in this foredune sector and, especially, in the following one (25 to 50 m) is probably caused by the intense beach cleaning activities, often (and increasingly on highly visited beaches) carried out using mechanical equipment that may cause the depletion of plant communities through their direct removal and alteration of beach functionality (e.g., the nutrient cycle or food chain) (Dugan & Hubbard 2010).

Conversely, in the same sector (25 to 50 m), the LP site featured a peak in the biomass diversity indicating the beginning of the typical patchy mosaic of plant communities that contribute to the dune formation by acting as initial wind blocks. Here, the "Embryonic shifting dunes" (habitat type 2110), representing the first stages of dune construction, show a vegetation structure similar to that found in the habitat type 2120 "Shifting dunes along the shoreline with *Ammophila arenaria* (white dunes)" because of the dominance of tall perennial grasses (i.e. *Ammophila arenaria* and *Elymus farctus*). Both habitats present a naturally discontinuous cover, the gaps in which are colonized by annual vegetation very different in composition and structure (i.e. habitat 2230-*Malcolmietalia* dune grasslands) (Pisanu *et al*. 2014). In this sector, the high level of plant biomass diversity ($Q_{p\text{-}biom}$) confirms once again that in a well-preserved dune ecosystem, there is no abrupt zonation with a clear delineation of habitats along the sea-inland gradient but in most cases, plant communities are patchy and gradually transitional (Acosta *et al*. 2003a; Acosta *et al*. 2003b; Biondi, 2007; Carboni *et al*. 2009). Finally, plant biomass diversity ($Q_{p\text{-}biom}$) differed between LP and HP also in the inland sectors; in the LP area, we observed more dispersed values already indicating the presence of the first patchy woody formations of the habitat type "2250-Coastal dunes with *Juniperus* spp.(juniper scrub)" and "2260-*Cisto-Lavanduletalia* dune sclerophyllous scrubs".

Finally, the geomorphology patterns appeared similar for the first three sectors closest to the shoreline (0 to 75 m) in both LP and HP sites, with the high values indicating unstable substrate, which is subject to the constant influence of the sea with consistent changes in elevation and slope within relatively small areas. On the contrary, in the more inland sectors of the gradient, the geomorphological diversity started to decrease for the LP area, indicating the beginning of a more stable substrate and more sheltered conditions of the dune system, creating a sector with plant species growing in more stable and richer soils with lower salinity (Acosta et al. 2009a; Santoro et al. 2011). In these inland sectors, the root structure of the dune habitats vegetation provides a soil retention function contributing to substrate stabilization and, therefore, playing an important role in regulating coastal erosion (Barbier *et al*. 2011; Bazzichetto *et al*. 2020). The presence of the embryo, mobile, and fixed dunes is also important for protecting the inner coastal sectors from the wind, aerosol, and storms (Feagin *et al*. 2015; Bazzichetto *et al*. 2016). On the other hand, the higher geomorphological diversity of the HP area reaching up to the farthest inland sectors illustrates the presence of incoherent substrate with tiny and sparse psammophilous species. Indeed, the anthropogenic disruption of the fixed and patchy woody vegetation driven by the efforts to create new infrastructure (e.g. roads, access to the beach, houses, beach resorts) (Malavasi et al. 2013) prevents the protection of the inner and back dune sectors from aerosol, wind and storms (Barbier et al. 2011; Liquete, Zulian, et al. 2013). Therefore, in the HP area, we observed an unstable substrate still subject to the influence of the sea with consistent changes in elevation and slope within relatively small areas (which is normally typical of the sectors closest to the sea) even in the last sectors.

5. Conclusion

Rao's Q enabled us to generate a synthetic eco-geomorphological dune profile directly showing the status of coastal landscapes. Nonetheless, in order to gain greater insight into the state of the sea-inland gradient, we stress the importance of independently considering the plant biomass and geomorphology aspects forming a basis for the individual aspects of which the eco-geomorphology is composed. Through a UAS-based approach, we described and summarized essential aspects of the dune ecology and functionality previously described separately and with instruments constrained either by a coarser scale (e.g. dune biomass using SENTINEL 2 NDVI values, see Marzialetti *et al.* 2019 and Marzialetti *et al.* 2020) or implementation costs (e.g. dune morphology using airborne LiDAR images; Bazzichetto *et al.* 2016). Indeed, the monitoring of the Mediterranean coastal ecosystems cannot entirely rely on satellite-borne or air-borne data. Freely available data (e.g. Landsat, Sentinel, or MODIS for land cover) cannot provide the high spatial resolution required to capture the heterogeneous and fine-grain habitat mosaic, while finer resolution data can be prohibitively costly (e.g. QuickBird, IKONOS for land cover, LiDAR, TanDEM-X DEM for topography). Besides, the monitoring of such ever-changing ecosystems requires high temporal resolution data (e.g. seasonal) which is often unaffordable or unavailable (e.g. LiDAR, ALOS World 3D, or TanDEM-X DEM) for topographical data. Nonetheless, even if our approach is cost-effective and capable of providing high spatial and temporal resolution data, it is so far eligible only when relatively small areas are at stake. Therefore, further efforts should be devoted both to investigating the scale and spatial resolution dependence of Rao's Q index on remote sensing-derived spectral heterogeneity information and to harmonizing UAS high-resolution data covering small extents with coarser-scale data covering wider areas. Such efforts would allow upscaling similar information from local to regional and national scales. Finally, our attempt of linking spectral information with dune integrity can contribute to defining more effective tools for monitoring and prioritizing conservation actions in these fragile and highly vulnerable ecosystems.

6. Acknowledgments

This study was carried out with the partial support of the bilateral program Italy-Israel DRESEMII (Developing state-of-the-art remote sensing tools for monitoring the impact of invasive plant species in coastal ecosystems in Israel and Italy) and the Interreg Italia-Croazia CASCADE (CoAStal and marine waters integrated monitoring systems for ecosystems proteCtion AnD managemEnt). The authors acknowledge the editor and the anonymous reviewers for their comments that helped us to improve the manuscript.

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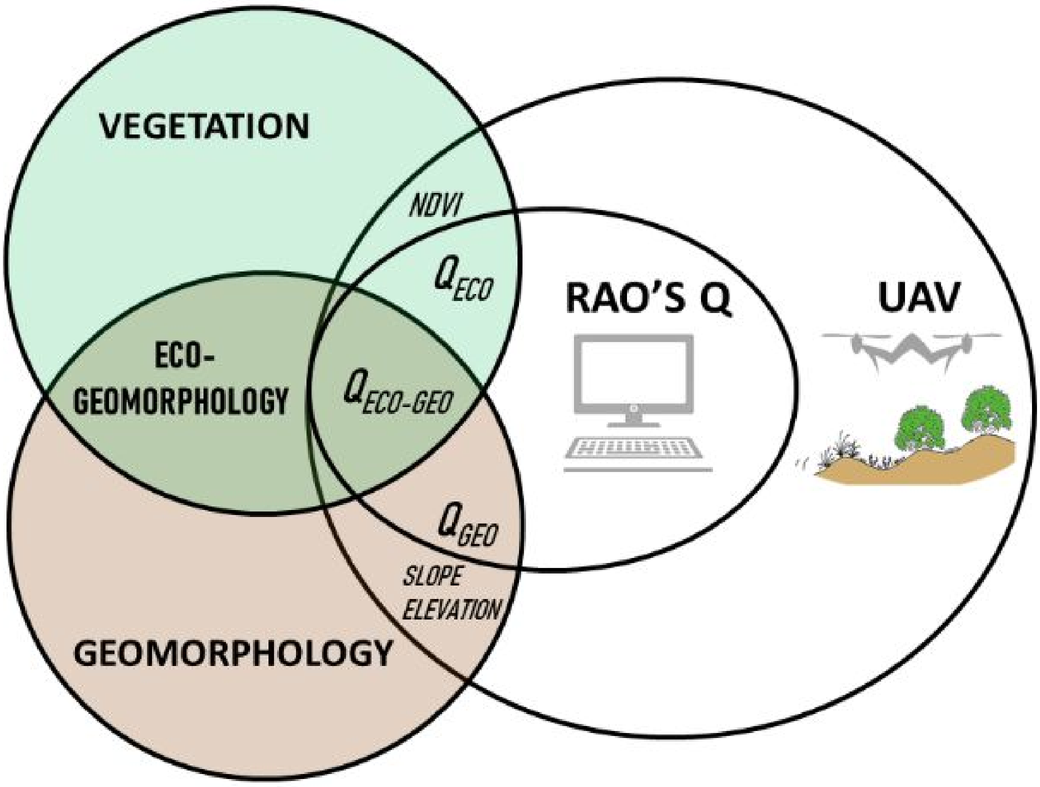
Graphical Table of Contents



Appendix S1.

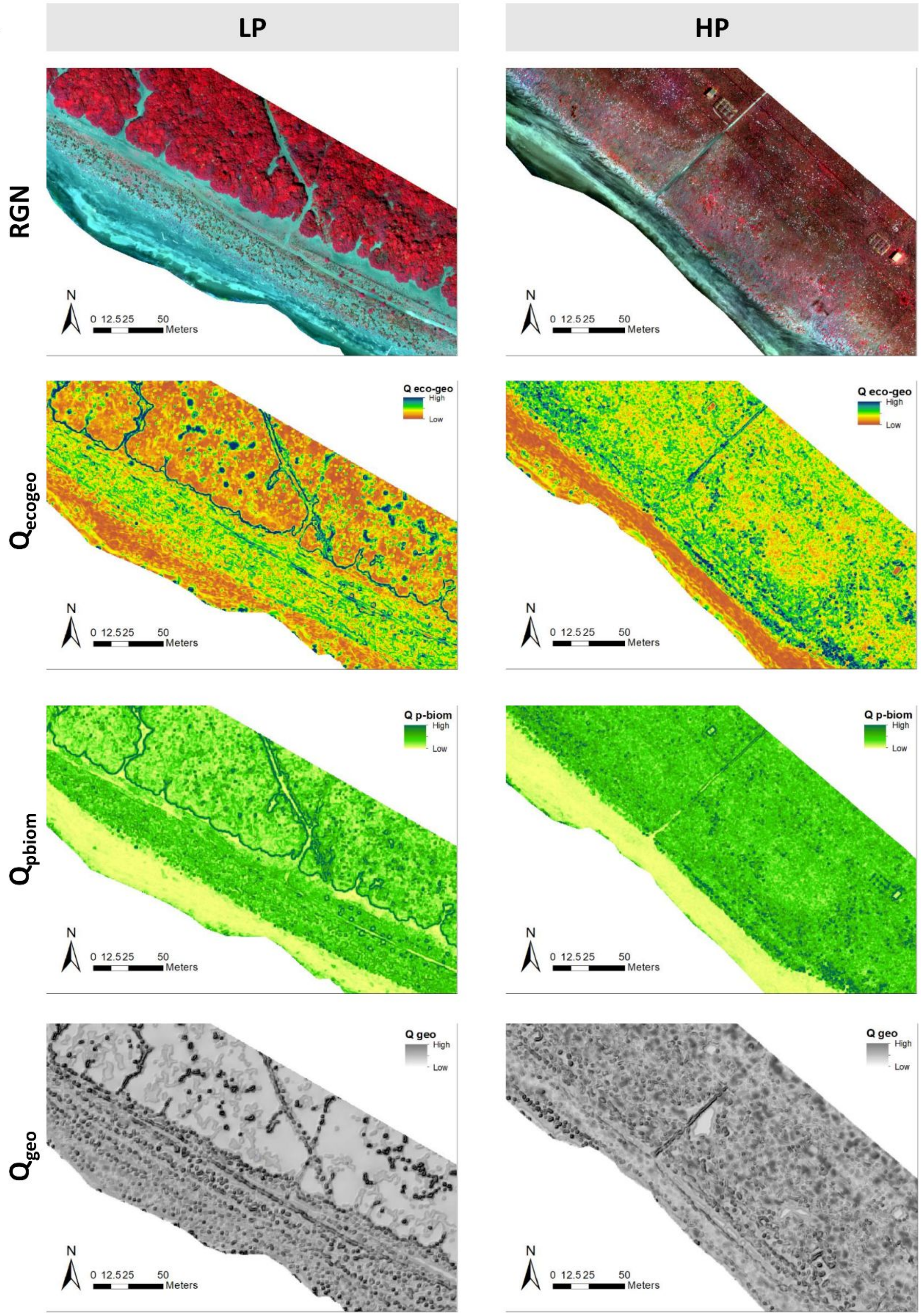
RGN false color images of the compared areas, along with the raster outputs of the Rao's Q Heterogeneity Index calculation for plant biomass (Qp-biom), surface geomorphology (Qgeo), and Eco-geomorphology (Qeco-geo).

Supporting information to the paper

Malavasi et al. UAS -based monitoring of coastal dunes eco-geomorphology through spectral Rao's Q. *Applied Vegetation Science.*

Appendix S1.

RGN false color images of the compared areas, along with the raster outputs of the Rao's Q Heterogeneity Index calculation for plant biomass (Qp-biom), surface geomorphology (Qgeo), and Eco-geomorphology (Qeco-geo).



To the kind attention of the Co-ordinating Editor, Applied Vegetation Science
Hannes Feilhauer

Subject: *Submission of the revised version of the manuscript AVS-RA-02674*

Dear Editor,

Please find enclosed the revised version of the manuscript AVS-RA-02674: "Drones for Mediterranean coastal vegetation integrity: yes, we can" (by Marco Malavasi, Manuele Bazzichetto, Jan Komarek, Vítězslav Moudry, Duccio Rocchini, Simonetta Bagella, Alicia T.R. Acosta) accepted with revisions to be published in the special feature "Remote sensing for Vegetation Science", led by Duccio Rocchini, Jana Müllerová, Sebastian Schmidtlein and Hannes Feilhauer.

First of all, we would like to thank the anonymous reviewers for all helpful suggestions on our manuscript. The comments were very useful in improving the original version of the manuscript. We have followed all indications which led us to modify the original title as follows: "UAS -based monitoring of coastal dunes eco-geomorphology through spectral Rao's Q"

As suggested, we improved the methodology section. As requested by Rev 1, we improved the description of the analysed eco-morphological gradient, included extra information concerning Q Rao index and modified the study area figure including the requested details. According to Rev 1's and Rev 2's indications, we better defined the existing human pressure impinging the analyzed coasts and we emphasized, where possible, the applied vegetation aspects.

The "study area" section has been significantly improved. A new supplementary material was included, reporting RGN images of the compared areas along with the respective raster outputs of the Rao index calculations (Qeco-geo, Qp-biom and Qgeo). We have also improved the discussion following Rev 1 and 2 comments.

All changes made on the manuscript are highlighted through the track-changes feature of Microsoft Word. Please find enclosed below the replies to each point raised in the review process.

Thank you for Your consideration,

Sincerely, and on behalf of all other co-authors, Reviewer(s)' Comments to Author:

Referee 1:

Thank you for the opportunity to review the submitted manuscript entitled “Drones for Mediterranean coastal vegetation integrity: yes, we can.” This research article examines the potential to remotely monitor the eco-geomorphological integrity of Mediterranean coastal dune ecosystems using high-resolution imagery acquired with a small fixed-wing UAV. The authors are focusing in their image analysis on the use of the Rao´s Q index, which can be applied in a multidimensional space. Overall the article is well written and coherently structured. The research idea is interesting and has a relevance for monitoring ecosystems with the use of drone based remote sensing.

Authors: Thank you for your appreciation. We have included all the comments you and rev 2 have made, which helped us to improve the original version of the manuscript.

Referee 1:
At this point, however, I cannot recommend your manuscript for direct publication in Applied Vegetation Science because some issues need to be resolved. One of the main problems I have caught during reading is that is not always transparent how the data was analyzed and interpreted. Moreover, it is not really clear what is meant by the term eco-geomorphological integrity. The study is very interesting as a “case study”, but perhaps better published in a remote sensing journal.

Authors: Thank you for your valuable comments that allowed us to improve the MS. Relying on your suggestions, we made data analysis and interpretation more transparent. We also specified in the Introduction the meaning of “eco-geomorphological integrity”. Accordingly, in the Study area section, we described the vegetation and geomorphological pattern of a costal dune area when the eco-geomorphological processes are intact.

The strong remote sensing background of this MS is due to the fact that it was submitted as a contribution to the AVS special feature “Remote sensing for Vegetation Science”, led by Duccio Rocchini, Jana Müllerová, Sebastian Schmidtlein and Hannes Feilhauer.

Referee 1:
In my opinion, the article "Mapping Coastal Dune Landscape through Spectral Rao’s Q Temporal Diversity" published by the co-authors in MDPI Remote Sensing Journal must also be clearly stated and the connection to the submitted manuscript must be indicated. Please describe the existing research gap resulting from the previously published article.
Authors: The mentioned article published MDPI Remote Sensing Journal deals with land cover classification and mapping based on multi-temporal SENTINEL2 data, which is summarized using Rao’s Q framework. The present research is neither focused on

multi-temporal satellite data analysis nor on land cover classification. Here, we have used Rao’s Q for exploring the sea-inland eco-geomorphological gradient on coastal dunes using high resolution UAS images collected on a single date.
We can certainly say that our MS does not push forward what already investigated in the paper "Mapping Coastal Dune Landscape through Spectral Rao’s Q Temporal Diversity", but rather answer to additional research questions using another approach and data. Nonetheless, the article is still cited in our MS.

Referee 1: Please also see my following specific comments:
Title: Please change the title. Especially the sentence "Yes, we can" sounds unscientific and inappropriate. Since the Rao's Q Index plays a central role in data analysis, it should also be mentioned in the title.
Authors: As suggested, we have modified the original title as follows
“UAS -based monitoring of coastal dunes eco-geomorphology through spectral Rao's Q”

R#1:
Page 3 | Line 51 – 55: Please introduce the topic differently. It is of course true that dune ecosystems are important for human health, but that should not be named in first place. The article is about negative human influence on the ecosystem, so the loss of ecosystem services and biodiversity should be emphasized.
Authors: In the revised version, we tried to emphasize the negative human influence on the ecosystem and biodiversity. We include a new dedicated paragraph describing the main ways of human pressure impinging coastal dunes in the Mediterranean (in Material and methods section).

R#1:
Page 3 | Line 60: Please give examples of other endangered ecosystems.
Authors: Thanks. We modified the sentence specifying that according the 4th Monitoring Report (European Habitats Directive 92/43/EEC), conservation status of Italian natural coasts is dramatically impaired with the 88% of the dune habitats in bad conservation status and the remaining 12% inadequately protected (for details, see Prisco et al. 2020). Good examples of such ecosystems impinged by human pressure are described in the study area section. Nonetheless, in order to avoid incoherent information, we prefer to not include examples of other ecosystems, different from coastal dunes.

R#1:
Page 4 | Line 7 – 8: The expression "jeopardized management actions" must be explained. What do the authors mean in this context?
Authors: We agree that such sentence can be rather confusing, so we changed it into “…is crucial to meet the HD goals”

R#1:
Page 4 | Line 38 – 41: What is meant by the subjective tasks in using classification techniques? Is your approach more objective? If so, why?
Authors: Foody et al, 2002, explains how many of the processes involved in land

classification are too often subjectively performed (e.g. accuracy assessment). Nonetheless, we prefer to delete this sentence since its full explanation would take more than just a few words and would be probably unnecessary for this paper.

R#1:
Page 4 | Line 43: I would rather suggest using the term Unmanned Aerial System (UAS) in the entire manuscript as a UAS consists of an aerial platform, associated sensors and control equipment.
Authors: Thank you, although both terms are eligible in this context, we have modified the text using the term Unmanned Aerial System (UAS)

R#1:
Page 5 | Line 6 – 26: Rao´s Q Index: It is necessary to show more clearly what the differences are to the commonly used indices. In particular, what are the differences to e.g. the Shannon's H Index, which can be used as a measure of biodiversity.
Authors: As requested, some details about the Rao's Q index as opposed to common metrics applied to remote sensed data and relying on Shannon's entropy theory has been included. Accordingly, two more experimental papers have been cited in the section "2.3 Rao's Q Heterogeneity index" to report the high accuracy of Rao's Q if compared to the Shannon's H Index (Khare et al 2019 and Torresani et al 2019).

R#1:
Page 5 | 2.1 Study area: Please provide a map of the study area. In addition, the resulting aerial orthomosaics should be shown, including the 750 randomly distributed points.
Authors: As also requested by Reviewer#2, we are providing a set of images of a selected portion of our LP and HP sites. We have created a new supplementary material (S1) reporting the RGN image (derived from UAS) of the LP and HP site, along with the raster outputs of the Rao index calculations (Qeco-geo, Qp-biom and Qgeo). We believe this to be the best way how to display the study area and help the reader to understand the coastal ecosystem. The visual representation of the random points results in a very confusing and difficult-to-read image so we prefer to leave the clean version of the figure (see supplementary material S1)

R#1:
Page 5 – 8: I am missing detailed information about the conducted ground truth data collection. Or was no data recorded in the field? Please provide further information here. If no ground truthing has been carried out, how possible subjective processing steps (e.g. visual image interpretation) were avoided?
Authors: The only ground data indirectly used in this MS are those derived from vegetation field sampling already published in previous articles cited in the text, which also allowed us to distinguish between HP and LP. Dedicated ground truth data were not collected for this research in relation to our UAS images and analysis. Notice that our research does not include visual image interpretation or any other process to be considered strictly subjective.

R#1:
Page 8 | Line 28: "…that is a good spatial resolution" Please rephrase. Why did you choose the 25m spatial resolution? Please justify.
Authors: Thank you, we took your comment into account and rephrased the sentence. We now clarified that such interval of 25 m was chosen since the turnover of dunes and related plant communities in the analyzed area averagely occurs every 25 m. This information is supported both by Bazzichetto et 2016 and Acosta et al 2003 (both cited in the MS).

R#1:
Page 10 – 12: Discussion: Please discuss in detail what the pro and cons of the used approach are, especially: what are the limitations of the Rao´s Q Index in the context of such a dune ecosystem monitoring? Moreover, what are the advantages and disadvantages compared to regularly used indices?
Authors: As requested, we have included more details about the Rao'Q index and its possible advantages compared to common metrics applied to remote sensed data and relying on Shannon's entropy theory. Two recent experimental papers have been cited in section "2.3 Rao's Q Heterogeneity index" to report the high accuracy of Rao's Q compared to Shannon's H Index (Khare et al 2019 and Torresani et al 2019). Nonetheless, a comparison of the selected approach and other indices should entail further comparative and dedicated analyses which are beyond the paper aims.

R#1:
From the user perspective: What do the results mean for dune monitoring and management, especially regarding future perspectives? How could a real applicability look like, especially due to the existing limitations: e.g. UAS imagery can only cover small areas, so shouldn't satellite data be used for monitoring? As you submitted your manuscript to Applied Vegetation Science, you should discuss more the further application of the presented remote sensing technique.
Authors: Thank you for your comment. We better explained in the conclusion that using a UAS-based approach, we were able to describe and summarize essential aspects of dune ecology and functionality previously described separately and with instruments constrained either by a coarser scale (e.g. dune biomass using SENTINEL 2 NDVI values, see Marzialetti et al. 2019 and Marzialetti et al. 2020) or implementation costs (e.g. dune morphology using airborne LiDAR images; Bazzichetto et al. 2016). We also clarified that even if cost-effective and very promising, our approach is so far eligible only when relatively small areas are analyzed. Nonetheless, the monitoring of Mediterranean coastal ecosystems cannot entirely rely on satellite-borne or air-borne data. Freely available data (e.g. Landsat, Sentinel and MODIS for land cover) cannot provide the high spatial resolution required to capture the heterogeneous and fine grained habitat mosaic, while other sub-meter resolution data can be prohibitively costly (e.g. QuickBird, IKONOS for land cover; ALOS World 3D and TanDEM-X DEM for topography). Furthermore the ever-changing nature of such ecosystems requires high temporal resolution data (e.g. seasonal) which is unaffordable or unavailable (e.g. LiDAR, ALOS World 3D and TanDEM-X DEM) for topographical data. It follows that our

approach can be eligible for local institutions or stakeholders to monitor relatively small areas.

R#1:
Khare et al. 2019 (Forest beta-diversity analysis by remote sensing: How scale and sensors affect the Rao's Q index) indicated a strong scale and spatial resolution dependence of Rao's Q index on remote sensing-derived spectral heterogeneity information. How does the scale and spatial resolution affect your data analysis and results?
Authors: Thanks for indicating this significant contribution in the field. The paper has now been cited to support the good performance of Rao's Q index when compared to Shannon's H. As regards the scale issue, so far, we limited our analyses to the spatial scale indicated by previous studies at which ecological and geomorphological investigated processes of coastal ecosystems are known to occur. Nonetheless, the indicated paper may be an inspiration to compute further analyses to test how the selected scale and spatial resolution may affect coastal dune monitoring through Rao's Q index. The need for such analyses has now been stated in the conclusion.

Referee 2:

Dear author,
thank you for your valuable and interesting contribution. I really like the idea to present a gradient based process understanding of human impact on coastal dune ecosystems. The UAV data used in connection with the approach of Rao's Q for assessing eco-geomorphological gradients present a novel approach. The study needs a better clarification of the term "human pressure" and further needs to elaborate more on representability of the chosen metrics and test sites. How stable and transferable are your results under varying dune conditions? Please find my specific comments below.

Authors: Thanks for your valuable comments, which have been carefully addressed. The meaning of the term "human pressure" was articulated as the choice for metrics and test sites.

Referee 2: General comments:
There is one crucial question: Why did you chose to sample transects within these particular distance classes?
Authors: As requested, we justified the chosen sampling distance step in the text. We sampled transects within 25 m distance classes since in the analyzed area, the turnover of dunes and related plant communities occurs on average every 25 m (Bazzichetto et 2016, Acosta et al 2003).

Referee 2: Are both gradients comparable? Can you present a map of low and high human pressure (a figure of your drone imagery as RGB composite)? In these drone figures the transect area should be marked. What is the difference between both areas and is this difference representative for all eco-geomorphological gradients of the dune

ecosystem? I ask myself how comparable are your chosen distance classes, if you would just take another HP area. Sometimes high human pressure may even lead to more diverse structures due to human influence. In summary, the author need to elaborate more on the representability of this study and present the drone imagery as figure.
On the other hand, I even do not understand what is meant with “human pressure”. Is it land use of dune ecosystems? Or is it settlement?

Authors:
Thanks for your comments that helped us to improve the study area section (text and figures). It has been significantly improved in order to present Mediterranean coastal dunes ecology to a wide public not familiar with these environments. A new paragraph in the study area section describing the characteristics of human pressure (mainly related to tourism and recreational activities) and its consequences in the analyzed coasts, was provided. Concerning your doubt on the consistency of the compared gradients, please note that the environmental conditions in the two sites (HP and LP) are very similar in terms of climate, potential vegetation, geographical position, sediment type and aspects (see Carranza et al 2008) and are potentially impinged by the same threats (Malavasi et al. 2013).
Besides, although the nature and magnitude of human disturbance acting on coastal dunes is variable (note that we have chosen two areas that still host coastal dunes), such human-driven disturbance is generally very similar in the Mediterranean basin, characterized by trampling and beach cleaning due to the high summer tourism, erosion and by the disruption of the Mediterraean macchia in the inner zone to gain space for infrastructure, such as roads, beach access, bath houses... For all these reasons, the Tyrrhenian coast could be considered as representative of typical Mediterranean vegetation zonation alongside human disturbance (Malavasi et al 2018)
As requested, an RGN image of a small sector of the HP and LP site is provided and we agree that this new figure helps the reader to better understand the considered areas and data.

Referee 2: Here again I would imagine that the NDVI variability crucially depends on the type of human pressure. If for example new species are introduce and buildings are built I would expect an increase in NDVI variability. Or is the Rao’s Q index more than just NDVI and topographic index variability?
Authors:
On the analyzed area, as on several coastal tracts of the Mediterranean basin, human pressure is mainly related to seaside tourism that, during the last 50 years, severely transformed dune ecosystems and altered their integrity (Drius et al 2013). In particular, human trampling and mechanical cleaning acting on the strandline zone of the beach are depleting plant communities and thus prevent their stabilizing effect on the substrate (Santoro et al. 2012; Battisti et al 2016). Likewise, human infrastructure (e.g. bath houses, roads) requires new space, which is acquired at the expenses of the inland stabilized dunes, which often results in the removal of woody vegetation (Malavasi et al. 2013).

Concerning artificial surfaces (built up areas), we remember that we have focused the analysis on natural and vegetated areas excluding urbanized ones, so we are not detecting this spectral information. We may have detected some coastal dune invasive species, but it is worth to say that coastal dunes are a very constraining environments where only pre-adapted species can survive.

Referee 2:
Can you please, provide a map of Rao's Q for both test sites? It would help the reader to better interpret or understand the distribution of your diversity metric. I want to see the gradient on a map to evaluate the variance that is probably hidden behind figure 2.
Authors: As also requested by Reviewer#1, we are providing a set of images of a selected portion of our LP and HP sites. We have created a new supplementary material (S1) with an RGN image (derived from UAS) of the LP and HP sites, along with the raster outputs of the Rao index calculations (Qeco-geo, Qp-biom and Qgeo). We believe this to be the best way of displaying the study area, helping the reader to understand the coastal ecosystem.

Referee 2: A language editing is recommended. There are a number of sentences that do not fulfill the requirements for scientific writing e.g. "Besides, thanks to the multidimensional meaning of the Rao's Q index,…", "Conditions for flight were convenient, ceiling and visibility were OK" or "…UAV technology is steel modest."
Authors: The paper was submitted to an English proofreader. The sentences you indicated were also modified as requested. Nonetheless, we understand you found the sentence "ceiling and visibility were OK" too trivial, but it is an international METAR codes for pilots. METAR is a format for reporting weather information. The proper code would be CAVOK, which stand for **C**eiling **A**nd **V**isibility **OK**, indicating no cloud below 1,500 m or the highest minimum sector altitude and no cumulonimbus or towering cumulus at any level, a visibility of 10 km or more and no significant weather change. Therefore, we prefer to keep this sentence followed by the above description.

Referee 2: Detailed comments:
P3 L. 57-60 Please specify the type of report. From the literature I can see that it is probably a Natura 2000 assessment of conservation status. That way the reader can get an idea about the meaning of a "bad" conservation status (do you mean unfavorable status C?) Reading the following lines means that after the "report" the habitat directive was adopted. However, the report is already a result from the application of the habitat directive. Please re-structure this part.
Authors: As requested, we specified that we refer to the 4th Monitoring Report for Italian coasts. The used terms conform to the HD code Unfavorable-Inadequate (U1) and Unfavorable-Bad (U2). This sentence was included simply to shed light on the continuous degradation of coastal habitats, so we now state in the text "see Prisco et al., 2020, for details". The modified text clarify what we mean.

R#2:

P6 L. 39-40 “Conditions for flight were convenient, ceiling and visibility were OK” This statement is too trivial. Either remove or explain what OK means. Also “…low cloud cover…” if this is important (irradiance sensor), write which cloud type and what percentage of cover.
Authors: See above.
By writing “ceiling and visibility were OK“ we are respecting the international METAR codes for pilots. As we are submitting this paper to a special feature on Remote sensing for vegetation, we prefer to keep some technical terms for pilots. We keep the sentence in the original form followed by a brief description of its meaning.

R#2:
P6 L. 50-57: For orthorectified imagery the term “pixel size” is used. GSD is the resolution of a scanner that in your case does not fit since you probably use a full frame camera.
Authors: Thank you. We changed the term GSD to “pixel size”.
Why is the pixel size decreased to 50cm after DTM calculation?
Authors: We followed the guidelines provided by the Pix4D website: “Due to the smoothing nature of the DTM generation algorithm, results are better when the DTM resolution is moderately lower than the resolution of the project. By default, the resolution of the DTM is set to 5x GSD of the project.” For details see https://support.pix4d.com/hc/en-us/articles/202560579-How-to-automatically-generate-a-Digital-Terrain-Model-DTM

R#2:
How do you “classify” a DTM from a DSM? This is not a trivial step and crucially influence your further analyses.
Authors: Thank you for your comment. We used Pix4D Mapper image-matching SW. We specified it in the revised version of the manuscript and we have included the relative references (Pix4D SA Pix4Dmapper 4.1 USER MANUAL; Pix4D SA: Lausanne, Switzerland, 2017). In this approach, terrain extraction and DEM generation is based on fully automatic, custom machine learning algorithms that classify the dense point cloud generated in typical semantic class labels, e.g., bare earth, buildings, vegetation and roads. The user has no prior control in the training of the classification algorithms. For details see Pix4D SA Pix4Dmapper 4.1 USER MANUAL; Pix4D SA: Lausanne, Switzerland, 2017. And *Sensors* **2019**, *19*(14), 3205; **https://doi.org/10.3390/s19143205**

R#2:
Can you provide accuracy metrics for DTM derivation?
Authors: Following your suggestion, we performed an accuracy analysis using the only available and reliable dataset of the area (LiDAR, 2008). Using 1000 randomly distributed points across our beaches, we calculated the mean absolute error (MAE) for DSM and DTM. For LP, MAE-DSM = 0.432m and MAE-DTM = 0,420m, while for HP, MAE-DSM = 0.899m and MAE-DTM = 0,896m.
Still, we prefer not to include this information in the main text because we are not confident in validating actual DTM with the old lidar data (LiDAR, 2008). Moreover, the dynamic nature of coastal dune topography would make the results of such type of validation unreliable anyway.

R#2:
P8 L. 8 The author writes “vegetation biomass” however it was never shown how this variable is calculated. The NDVI itself is a spectral index. It is not recommended to just replace it with the term “biomass” since there are different empirical relationships that translate NDVI to biomass. If not done so, please use NDVI as term.
Authors: We changed the term “vegetation biomass” into “plant biomass” in order to be consistent across the text. However, plant biomass (in the old MS: vegetation biomass) was calculated through NDVI, which is a spectral index acknowledged to be a good proxy for plant biomass (Bermúdez & Retuerto 2013), and, in particular, for dune vegetation (Castanho et al. 2015; Yousefi Lalimi et al. 2017; Marzialetti et al. 2019). These references are included in Section 2.2 “UAS Flight and image production”

R#2:
P8 L. 25 Why was the Rao’s Q index sampled?
Authors: We specified the reason for such sampling using an introductory sentence and modified the order of the section to better clarify what we have extracted for each random location.

R#2:
P12 L. 17-22: How can you “see” substrate properties when the inland sector is stabilized by vegetation? How accurate is the DTM extraction for this area since you may have a dense vegetation canopy (see figure 1)? Please, explain which type of human pressure leads to high geomorphological diversity (tree removal because of what?)
Authors: In case of a full-grown forest (dense vegetation), the DTM extraction could be problematic for ground filtering. Nonetheless, in the analyzed area where the woody vegetation occurs, we can define such vegetation as a patchy Mediterranean Macchia, allowing a more accurate ground filtering.

Concerning the question on human pressure, we know that here, woody vegetation removal is often carried out to gain space for different human-built infrastructures (e.g. roads, accesses to the beach, houses, beach resorts) and in this work, we focused on natural and vegetated areas. On disturbed non-built-up inner sectors, we observed unstable substrate still subject to the influence of the sea with consistent changes in elevation and slope within relatively small areas, just like in the sectors closest to the shoreline.

Title:

UAS-based monitoring of coastal dunes eco-geomorphology through spectral Rao's Q

Running title: Drones for coastal integrity

Marco Malavasi[1], Manuele Bazzichetto[2], Jan Komarek[1], Vítězslav Moudry[1], Duccio Rocchini [1,3], Simonetta Bagella[4], Alicia T.R. Acosta[5], Maria L. Carranza[6]

ORCID

Marco Malavasi: 0000-0002-9639-1784;

Manuele Bazzichetto: 0000-0002-9874-5064

Jan Komarek: 0000-0002-3505-6755;

Vítězslav Moudry: 0000-0002-3194-451X

Duccio Rocchini: 0000-0003-0087-0594

Alicia T.R Acosta: 0000-0001-6572-3187

Maria Laura Carranza: 0000-0001-5753-890X

AFFILIATIONS

[1] Department of Applied Geoinformatics and Spatial Planning, Faculty of Environmental Sciences, Czech University of Life Sciences Prague, Kamycka 129, Praha – Suchdol, Czech Republic.

[2] Université de Rennes, CNRS, EcoBio (Ecosystèmes, biodiversité, évolution) - UMR 6553, F-35000 Rennes, France.

[3] Alma Mater Studiorum University of Bologna, Department of Biological, Geological and Environmental Sciences, via Irnerio 42, 40126, Bologna, Italy.

[4] Department of Chemistry and Pharmacy, University of Sassari, Via Piandanna 4, I07100 Sassari, Italy. ORCID Simonetta Bagella: 0000-0002-8519-2675

[5] Departiment ofi Sciences, University of Rome 3, V.le Marconi 446, 00146 Rome, Italy.

[6] EnviX-Lab, Dipartimento di Bioscienze e Territorio, Università Degli Studi del Molise, C.da Fonte Lappone, 86090 Pesche, IS, Italy.

Correspondence: M. Laura Carranza, EnviX-Lab, Dipartimento di Bioscienze e Territorio, Università Degli Studi del Molise.

ORCID Maria Laura Carranza: 0000-0001-5753-890X; Email: carranza@unimol.it

Abstract

Question: Does spectral diversity captured by Unmanned Aerial Systems (UAS) provide reliable information for monitoring the eco-geomorphological integrity of Mediterranean coastal dune ecosystems? Can this information discriminate between two coastal areas with low (LP) and high (HP) human pressure?

Location: Tyrrhenian coast, Central Italy

Methods: By processing UAS images, we derived NDVI and topographic variables at high spatial resolution (0.5 m) for 150 m wide strips starting from the coastline inland on two representative coastal tracts under low and high human pressure. We mapped the sea-inland heterogeneity applying Rao's Q index to the plant biomass (NDVI) and geomorphology variables (elevation and slope). Since Rao's Q index can be calculated in a multidimensional space, we summarized the variability of these three variables into a single eco-geomorphological layer. We then inspected and compared how the plant biomass, geomorphology and eco-geomorphology Rao's Q index values change as a function of the distance from the sea between the two coastal sites.

Results: Rao's Q heterogeneity values vary along the sea-inland gradient of well-preserved sites (LP). The maximum eco-geomorphological heterogeneity was found at intermediate distances from the sea and decreased towards the inner sector where the dune geomorphology was more stable and vegetation more homogeneously distributed. Instead, Rao's Q heterogeneity values featured constant low values along the gradient on the HP site, highlighting a simplified eco-geomorphological gradient related to the high human pressure.

Conclusions: Using UAS, the eco-geomorphological gradient of coastal dunes can be quantified at a very fine spatial resolution over management-relevant extents. Rao's Q index applied to sensing imagery successfully captured the differences in the eco-geomorphological heterogeneity along the sea-inland dune gradient and among sites with different levels of anthropic pressure. This approach supports frequent surveys and is particularly suitable for spatial monitoring of key coastal functions and services.

Keywords: coastal dunes, eco-geomorphology, dune elevation, habitat monitoring, human pressure, NDVI, dune slope, Rao's Q index, spectral diversity UAS

1. Introduction

Coastal dunes ecosystems are crucial for human health, delivering a wide range of essential services to society including coastal defense, groundwater storage and water purification, or tourism and recreation (Mendoza-González et al. 2012; Drius et al. 2013; Liquete, Piroddi, et al. 2013; Drius, Bongiorni, et al. 2019; Drius, Jones, et al. 2019). Nonetheless, in Mediterranean areas, the loss and degradation of littoral landscapes and the associated services has been particularly severe in the last decades (Malavasi et al. 2013; Carranza et al. 2020; Prisco et al. 2020). For instance, results from the 4th Monitoring Report (European Habitats Directive 92/43/EEC, hereafter HD) depicted a dramatically impaired conservation status of Italian natural coasts with 88% of the dune habitats being in a bad conservation status and the remaining 12% inadequately protected (for details, see Prisco *et* *al*. 2020). According to the HD, the preservation, continuous monitoring, and reporting of the coastal ecosystems is currently a priority at both the national and European levels (Janssens *et al*. 2009; Gigante *et al*. 2018). The introduction of new practices facilitating recurrent and effective monitoring on a wide spatial extent is crucial for meeting HD goals.

It is now acknowledged that the stability of coastal dunes and the provision of most of the aforementioned ecosystem services is assured by the integrity of ecomorphodynamic interactions (hereafter eco-geomorphological integrity) between *psammophilous* plants encountered along the sea-inland gradient and geomorphology (Baas 1997; Sperandii et al. 2019; Bazzichetto et al. 2020). Thus, on the one hand, vegetation distribution and biomass depend on many geomorphology-related factors (e.g. wind and marine aerosol exposure, wave energy, flooding); in turn, vegetation exerts major control on the development of the topographic features (e.g. substrate fixation, erosion prevention), mediating the very same abiotic governing factors (Bazzichetto *et al*. 2016; Yousefi Lalimi *et al*. 2017). Accordingly, an accurate monitoring approach should be able to capture such type of eco-geomorphological integrity.

Nevertheless, standard monitoring procedures have mostly been performed either through ground surveys (Stanisci *et al*. 2014; Prisco *et al*. 2016; Sperandii *et al*. 2018) or through habitat mapping, integrating the photointerpretation of aerial imagery or classification of remotely sensed imagery with floristic data (Acosta et al. 2009b; Malavasi et al. 2013; Rapinel et al. 2014; Carranza et al. 2018; Marzialetti et al. 2019; Marzialetti et al. 2020). However, ground approaches are laborious, limited by the lack of standardized procedures for reproducible data gathering (Rocchini *et al*. 2017), and may fail in reporting the state of the ecosystem on a wide range of scales in a consistent, borderless and repeatable manner. Likewise, habitat mapping procedures are limited by the expensive high-resolution data required to map the heterogeneous and fine-grain habitat mosaics such as those encountered in Mediterranean coastal ecosystems (Zhang & Baas 2012; Rapinel et al. 2014). Besides, habitat mapping, relying on classification techniques, inevitably leads to the degradation of continuous information stored in remotely sensed data (Foody 2002; Palmer et al. 2002; Rocchini et al. 2017).

Unmanned Aerial Systems (UASs) and their use are among the most dynamically developing fields of remote sensing (RS), representing a suitable source of data for environmental analyses. UASs, besides collecting multispectral images usable to capture vegetation patterns and distribution, represent an emerging, relatively low-cost, alternative to the traditional photogrammetry or active sensor technologies (e.g. LIDAR) for generating high-resolution topographic reconstruction (Whitehead & Hugenholtz 2014). Photo-reconstruction algorithms based on the structure-from motion (SfM) and multi-view-stereo analysis (MVS) algorithms (James & Robson 2012) enable the generation of reliable 3D point clouds from large sets of multi-angle images. In this sense, UASs have the potential to overcome the standard monitoring procedures, simultaneously delivering all information required to report about the eco-geomorphological integrity of coastal dune ecosystems (Valentini *et al*. 2020).

In this study, we aim to determine to what extent can a combination of *in situ* sensing data on vegetation and geomorphological variables captured from a UAS deliver valuable information about the eco-geomorphological integrity of Mediterranean coastal dune ecosystems. More specifically, we compared the eco-geomorphological pattern along the sea-inland gradient of two different beaches in Central Italy, one with high (HP) and the other with low (LP) human pressure, to explore the potential of UAS-derived eco-geomorphological data for capturing the spatial heterogeneity of coastal dunes. Such heterogeneity will be quantified employing the recently proposed Rao's Q diversity index applied to spectral data (Rocchini *et al*. 2017). As opposed to other diversity metrics applied to remotely sensed data that rely on Shannon's entropy theory and summarize the relative abundances of reflectance values, (Shannon 1948), Rao's Q index takes into account both the proportion of cells assuming different spectral values and their spectral distance (Rocchini *et al*. 2017). The analysis of images by Rao's Q could adequately describe highly heterogeneous landscapes and fine-scale environmental gradients, preserving most of the spectral variability which could be lost if processed though commonly used habitat classification approaches (Palmer *et al*. 2002). Likewise, as Rao's Q can be calculated in a multidimensional space (multi-layers), it is potentially a good parameter capable of combining the ecological and geomorphological aspects of the dune at the same time.

In this context, we expect a different behavior of the Rao's Q index according to the conservation status of the coastal areas. In particular, an intact eco-geomorphological arrangement of dune ecosystems in well-preserved coasts should correspond to a high spectral diversity with maximum Rao's Q values at intermediate distances from the seashore where tiny habitat mosaics occur (Acosta et al. 2009a; Bazzichetto et al. 2016). On the other hand, in highly disturbed coastal areas, the simplification and integrity loss of the dune ecosystems (Malavasi, Santoro, et al. 2016) should result in flat spectral diversity profiles maintaining low values at all seashore distances.

2. Material and Methods

2.1 Study area

The study area includes representative tracts of Mediterranean coastal dunes located on the Tyrrhenian coast of central Italy (Latium region). In natural conditions (i.e. integrity of the eco-geomorphological dynamics), recent dunes (Holocene) generally occupy a narrow strip along the seashore. They are not very high (usually less than 8–10 m) and are relatively simple in structure, with beaches of varying width from a few meters to around 40 m, low embryo-dunes, generally consisting of only one mobile dune ridge, dune slacks, and stabilized dunes (Acosta et al. 2003b; Bazzichetto et al. 2016). Vegetation zonation follows the sea-inland ecological gradient, ranging from annual communities on the strandline zone of the beach to patchy Mediterranean Macchia on the inland stabilized dunes (Acosta, Stanisci, et al. 2003; Carranza et al. 2008) (for a description of the habitat types along the zonation as detailed in the Habitat Directive 92/43/EEC, see Fig 1). Most of those plant communities are of conservation concern in Europe (Janssens *et al*. 2009). Nonetheless, along several tracts of the study area, human pressure (i.e. seaside tourism and urban expansion) has severely transformed coastal dune ecosystems and altered their eco-geomorphological integrity. In particular, human trampling and mechanical cleaning on the strandline zone of the beach are depleting plant communities and, in turn, their stabilizing effect on the substrate (Santoro et al. 2012; Battisti et al. 2016). Likewise, human infrastructure (e.g. bathhouses, roads) keeps gaining new space at the expense of the inland stabilized dunes, which often results in the removal of woody vegetation (Malavasi et al. 2013).

On the basis of the incidence of the human settlements and the population density (Italian Institute of Statistics, available at http://www.istat.it) used as a proxy of human pressure (Carboni et al. 2010;

Malavasi, Santoro, et al. 2016), we selected two different beaches (LP and HP) in two larger areas with low and high human pressure (WGS84 UTM N33: 213583E, 4694824N, and 262637E, 4644756N, respectively). The environmental conditions at both LP and HP sites are comparable in terms of climate, potential vegetation, geographical position, sediment type, and aspect (Carranza et al. 2008). The LP beach is located in an area characterized by a reduced presence of infrastructure and buildings (artificial surfaces constitute less than 10% of the area), with a population density of about 76.6 habitants per km^2. These conditions favor the development of natural dunes characterized by well-structured vegetation (Malavasi, Santoro, et al. 2016; Malavasi et al. 2018) and geomorphological pattern (Bazzichetto *et al*. 2016). On the other hand, HP beach is located in an area characterized by widespread tourism infrastructure, summer houses, and other artificial surfaces (more than 35% of the total area), with the population density of about 683.3 habitants per km^2. These conditions have restrained the coastal vegetation to small areas distributed in tiny patches and fragmented pattern (Malavasi et al. 2013). Given that in central Italy, the dune ridges are generally very narrow, we focused the analysis on an approximately 150 m wide strip starting from the coastline inland. Specifically, we analyzed 3 km of the coast, i.e, approx. 50 ha, for each site (HP and LP).

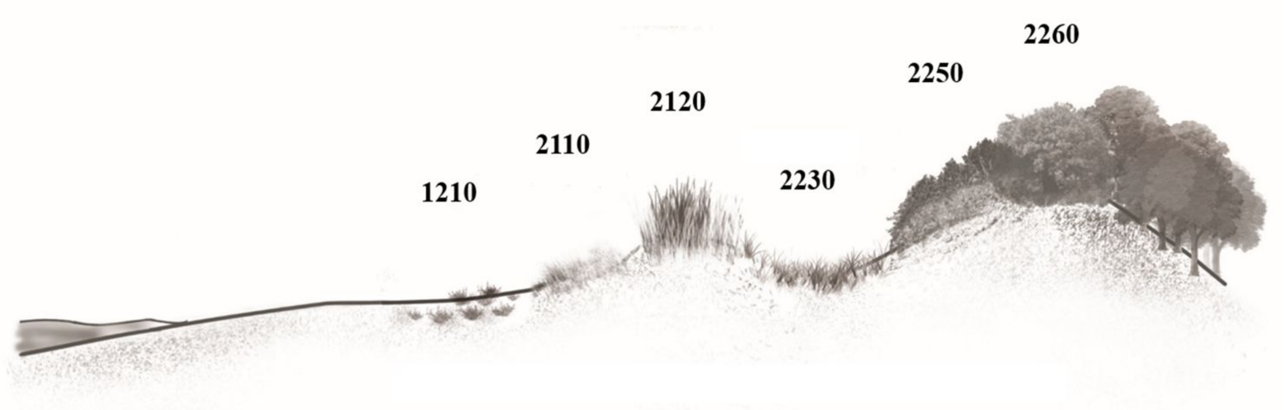


Fig 1. A typical sequence of the EC Habitat types (Habitat Directive 92/43/EEC) along the sea-inland vegetation zonation: 1210 Annual vegetation of drift line, 2110 Embryonic shifting dunes, 2120 Shifting dunes along the shoreline with *Ammophila arenaria*, 2230 *Malcolmietalia* dune grasslands, 2250* Coastal dunes with *Juniperus* spp., 2260 *Cisto-Lavanduletalia* dune sclerophyllous scrubs.

2.2 UAS flight and image acquisition

The low altitude aerial survey was performed across the LP and HP sites using a light fixed-wing Unmanned Aerial Vehicle eBee Cassic (senseFly, Switzerland). The UAS with a maximum take-off weight of 0.8 kg was mounted with a multispectral camera multiSPEC 4C (Airinov, France) (Komárek *et al*. 2018). The sensor acquires pictures in green (G: 530-570 nm), red (R: 640-680 nm), red-edge (RE: 730-740 nm), and near infra-red (NIR: 770-810 nm) bands each, with an image resolution of 1.23 MPx. Flight missions, performed in eMotion 2 ground control software, were planned parallel to the seashore with 80% overlaps of flight lines. Flights were conducted at 90 m above ground level with UAS airspeed of 10–11 m.s^{-1}. Conditions for the flight were convenient, ceiling and visibility were OK, i.e. no cloud below 1,500 m or the highest minimum sector altitude and no cumulonimbus or towering cumulus at any level, a visibility of 10 km or more and no significant weather change; the weather was sunny with low cloud cover (1/8), temperature of 20 °C, side-stable light breeze of 2–3 m.s^{-1}. In total, four individual flights were realized on May 03, 2017 across the LP site where 1751 perpendicular images were acquired, and two flights on May 04, 2017 at the HP site with 896 images. Acquired imagery was processed using SfM–MVS photo-reconstruction algorithms in Pix4DMapper 3.1.23 (Pix4D S.A., Switzerland) image-matching software. To improve the reconstruction accuracy due to a large portion of water in the images, manual tie points using a lidar-based elevation model (RNDT, cnipa.gov.it) were spatially dislocated across the sites. To gain precise values of surface reflectance, acquired mosaics were calibrated using Sun irradiance and Sun angle values from the camera sensor and albedo values from the reflectance panel. Both orthorectified mosaics representing values of surface reflectance together with Digital Surface Models (DSM) were built with a strong model geometry and exported with a pixel size of 10 cm in WGS84 UTM N33 projections (for a visual inspection of RGN false-color images of the compared areas, see Appendix S1).

In order to acquire topographic data, DSM point clouds were classified using fully automatic custom machine learning algorithms into a Digital Terrain Model (DTM) (Villanueva et al. 2019) with a 50 cm pixel size, from which the slope was also derived. The pixel size was reduced to 50 cm due to the smoothing nature of the DTM generation algorithm, where results are better when the DTM resolution is slightly lower than the resolution of the project (for details see “Pix4D support”). A sea distance layer was also computed in a GIS Environment (ArcGIS 10.4.1), calculating the straight-line Euclidean distance between each cell (the center) and the shoreline, manually derived through photointerpretation of the UAS image visualized in false colors (band composition: NIR-R-G). Finally, to indicate geomorphological variables, elevation (m asl), slope (degree), and sea distance (m) were selected (see Table 1) as proved reliable measures of dune topography for vegetation distribution (Bazzichetto *et al.* 2016).

Table 1: UAS original data and derived data used to compute the heterogeneity Rao’s Q index along the sea-inland gradient (sea distance) for vegetation, geomorphology, and dune eco-geomorphology. [RGN false-color images of the compared areas, along with the raster outputs of the Rao’s Q Heterogeneity Index calculation for plant biomass ($Q_{p\text{-}biom}$), surface geomorphology (Q_{geo}), and Eco-geomorphology ($Q_{eco\text{-}geo}$) are reported on Appendix S1].

UAS data	**UAS derived data**	**Rao’s Q Heterogeneity Index**	
Surface reflectance	NDVI	Plant biomass ($Q_{p\text{-}biom}$)	Eco-geomorphology ($Q_{eco\text{-}geo}$)
DTM (Digital Terrain Model)	Elevation (m.asl) Slope (degr.)	Geomorphology (Q_{geo})	
False color (NIR-R-G)	Sea distance (m)		

To indicate plant biomass, the Normalized Difference Vegetation Index (NDVI) was calculated using the map algebra following the equation below (Tucker 1979): $\text{NDVI} = \text{NIR} - \text{R} / \text{NIR} + \text{R}$.
NDVI has been widely shown to be a representative proxy for green biomass and photosynthetic activity (Bermúdez & Retuerto 2013). Moreover, it has been successfully applied to dune vegetation as a proxy of plant biomass (Castanho et al. 2015; Yousefi Lalimi et al. 2017; Marzialetti et al. 2019). All layers were rescaled to 50 cm in order to reduce the random noise and to better match the scale of the eco-geomorphological processes (Moudrý *et al.* 2019). Then, all the raster values of each layer were rescaled from 0 to 10 (linear function in ArcGIS 10.4.1) to apply the multidimensional Rao’s Q heterogeneity index.

2.3 Rao’s Q Heterogeneity index

Recently, the Rao’s Q index has been proposed as an innovative spectral heterogeneity measure in the field of remote sensing (Rocchini *et al.* 2017), with a high degree of accuracy compared to the metrics built on the Shannon’s entropy theory (Khare et al. 2019; Torresani et al. 2019). To capture and summarize the complex spatial eco-geomorphological heterogeneity of coastal dunes, Rao’s Q index was applied to different sets of UAS derived data (Table 1). The proposed application of Rao's Q index considers both the relative abundances of pixel values in the selected image and the distances among pixel' numerical values. Besides, since Rao's Q index can be calculated in a multidimensional space (multi-layers), the variability of more than one layer can be considered at a time, and it is calculated as follows:

$$Q_{rs} = \sum_{i=1}^{F-1} \sum_{j=i+1}^{F} d_{ij} * p_i * p_j$$

where

Q_{rs} = Rao's Q applied to remote sensing

p = relative abundance of a pixel value in a selected plot image (e.g. moving window)

d_{ij} = spectral distance between the i-th and j-th pixel value ($d_{ij} = d_{ji}$ and $d_{ii} = 0$)

i = pixel i

j = pixel j

The distance matrix where the d_{ij} is computed was built in different dimensions, thus allowing to consider more than one layer at a time (in our case, plant biomass and geomorphology variables).

In order to explore the potential of Q_{rs} for summarizing the plant biomass and the geomorphological aspects into a single eco-geomorphological index, a first output ($Q_{eco\text{-}geo}$) was produced considering NDVI, elevation, and slope at a time. For capturing the plant domain of the eco-geomorphological pattern, only the NDVI layer was considered ($Q_{p\text{-}biom}$) while for the geomorphological domain, elevation and slope were considered together (Q_{geo}). We calculated the Q_{rs} in a single or multi-dimensional environment using the R function "spectralrao" (Rocchini *et al.* 2017), obtaining three different rasters ($Q_{eco\text{-}geo}$, $Q_{p\text{-}biom}$ and Q_{geo}). Q_{rs} was calculated using a moving window device of 3x3 pixels (1.5 x 1.5 m). The selection of the window sizes conforms to the previous studies (Bazzichetto *et al.* 2016; Malavasi *et al.* 2018) that found such scales to be effective for describing the dune mosaic patterns in the Mediterranean coastal tracts under different disturbance regimes. (Raster outputs of the Rao's Q Heterogeneity Index calculation for plant biomass ($Q_{p\text{-}biom}$), surface geomorphology (Q_{geo}), and Eco-geomorphology ($Q_{eco\text{-}geo}$) are reported in Appendix S1).

2.4 Data analyses

In order to display and compare Rao's Q Heterogeneity values along the sea-inland gradient for both LP and HP sites, we sampled the Rao's Q index value at 750 randomly generated locations throughout each site, (approximately 15 random points per hectare). Specifically, we extracted the Rao's Q values $Q_{eco\text{-}geo}$ (NDVI, elevation, slope), $Q_{p\text{-}biom}$ (plant biomass), and Q_{geo} (elevation, slope) at each location. The random locations were then classified into 6 sequential sectors based on their distance to sea. Profile sectors where identified every 25 m, since the change of dune types and related plant communities in the analyzed area occurs on average every 25 m (Acosta et al. 2003b; Bazzichetto et al. 2016). Random locations were sampled only within natural and vegetated areas, urbanized ones were disregarded. Box and whiskers plots were produced for HP and LH to display and compare their Rao's Q values along the sea-inland gradient. Finally, to assess the difference of the Rao's Q values for each sector between LP and HP, a Welch's t-test was computed, and p-values were adjusted according to Holm correction (Holm 1979).

3. Results

The Rao's Q index values at LP and HP sites featured distinct trends for eco-geomorphology, plant biomass, and geomorphology (Table 2; Fig 2, 3 and 4), especially when considering different sectors of the sea-inland gradient: $Q_{eco\text{-}geo}$ showed different values for the LP and HP site along all the sectors of the sea-inland gradient, $Q_{p\text{-}biom}$ in the foredune sectors (from 0 to 50 m from the seashore) and in the more inland sectors (from 75 to 125 m from the seashore), while Q_{geo} differed only in the inland sector (from 100 to 125 m from the seashore).

Specifically, compared to HP, LP showed more dispersed $Q_{eco\text{-}geo}$ values (wider boxes and longer whiskers) all along the sea-inland gradient (Fig 2), with pronounced differences in the two first sectors (0 to 50 m from the seashore) (Table 2). That is, the LP site showed higher eco-geomorphological diversity values in these foredune sectors. In general, $Q_{eco\text{-}geo}$ values for LP presented a slight peak in the second sector (25 to 50 m from the seashore) that tended to decrease in the last inland sectors, depicting more homogeneous ecological and morphological characteristics (Fig 2). On the contrary, HP did not show any peak, featuring a flatter but increasing trend all along the gradient.
As regards plant biomass, LP again showed more dispersed $Q_{p\text{-}biom}$ values all along the gradient, except for the second sector (25 to 50 m from the seashore) (Fig 3). In general, both LP and HP sites showed very low, although different, values (Table 2) in the very first sector (0 to 25 m). As for $Q_{eco\text{-}geo}$ but slightly more pronounced, $Q_{p\text{-}biom}$ values showed a peak for the LP site in the second sector (25 to 50 m) that subsequently decreased again, presenting a flatter but increasing trend in the last inland sectors (Fig 3). HP did not show any peak in the $Q_{p\text{-}biom}$ values, featuring a flatter but increasing trend all along the gradient.

Table 1. Welch's t-test results comparing $Q_{eco\text{-}geo}$, $Q_{p\text{-}biom}$ and Q_{geo} values for each sector between LP and HP ('***' $p < 0.001$; '**' $p < 0.01$; '*' $p < 0.05$; '.' $p < 0.1$).

	$Q_{eco\text{-}geo}$			$Q_{p\text{-}biom}$			Q_{geo}		
Sector	**T**	**Df**	**p**	**T**	**Df**	**p**	**T**	**Df**	**p**
25	6.431	99.369	***	2.675	138.038	*	0.304	137.393	
50	7.737	174.820	***	4.791	174.134	***	-0.087	169.630	
75	2.184	144.428	*	0.481	129.509		-0.597	163.507	
100	3.306	119.424	**	3.124	106.960	**	-0.426	146.126	
125	3.311	160.001	**	3.504	159.585	**	-5.041	117.867	***
150	2.513	155.262	*	1.474	156.924		0.309	147.383	

Finally, Q_{geo} featured equally dispersed values (similar sizes of the boxes and whiskers) all along the gradient with high and similar values in the foredune sectors (0 to 75 m from the seashore) (Fig 4) and lower in the inner sectors. A marked difference in the last sectors (100 to 150 m) between LP and HP can be observed, where LP presented a lower geomorphology diversity.

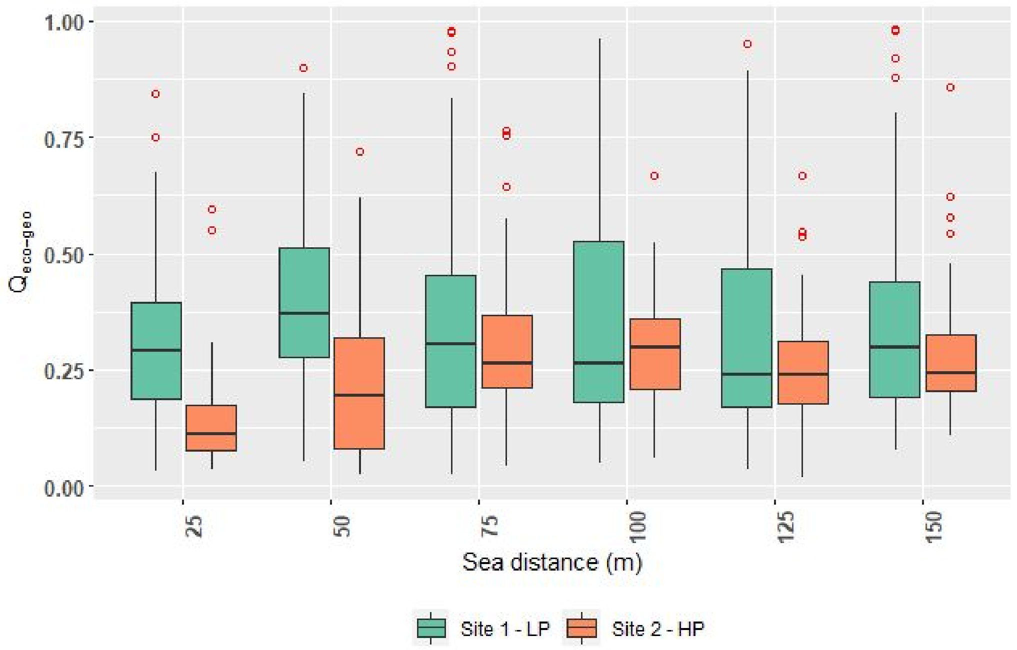


Fig. 2 Box plots of the $Q_{eco\text{-}geo}$ values (NDVI, elevation, slope) along the sea-inland gradient for the LP (green) and HP (orange) sites.

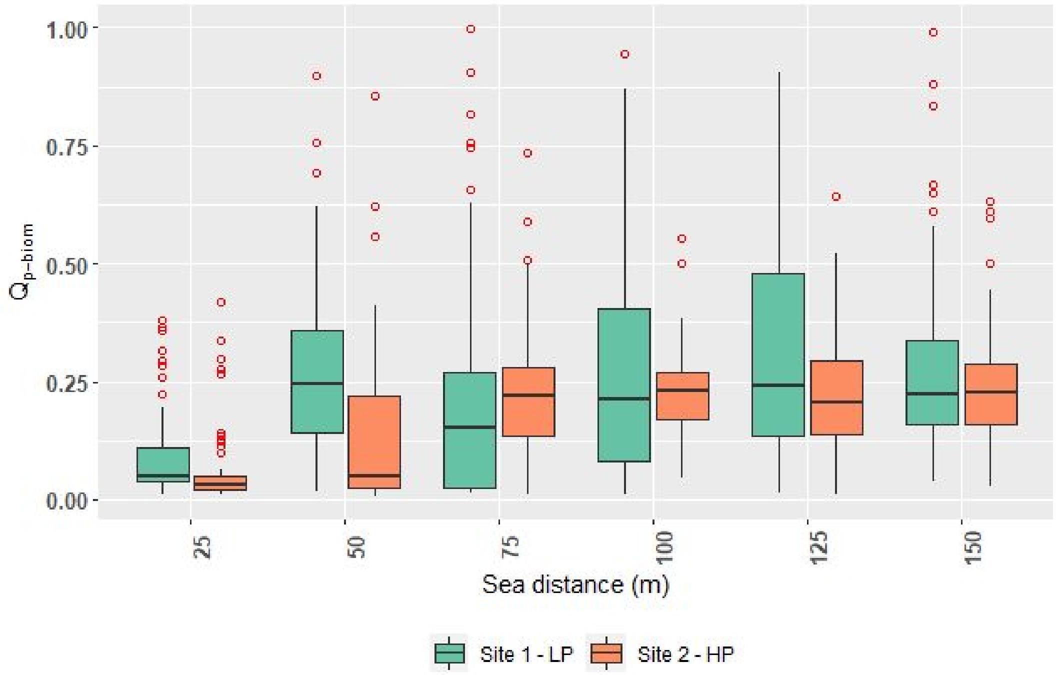


Fig. 3 Box plots of the $Q_{p\text{-}biom}$ values (NDVI) along the sea-inland gradient for the LP (green) and HP (orange) sites.

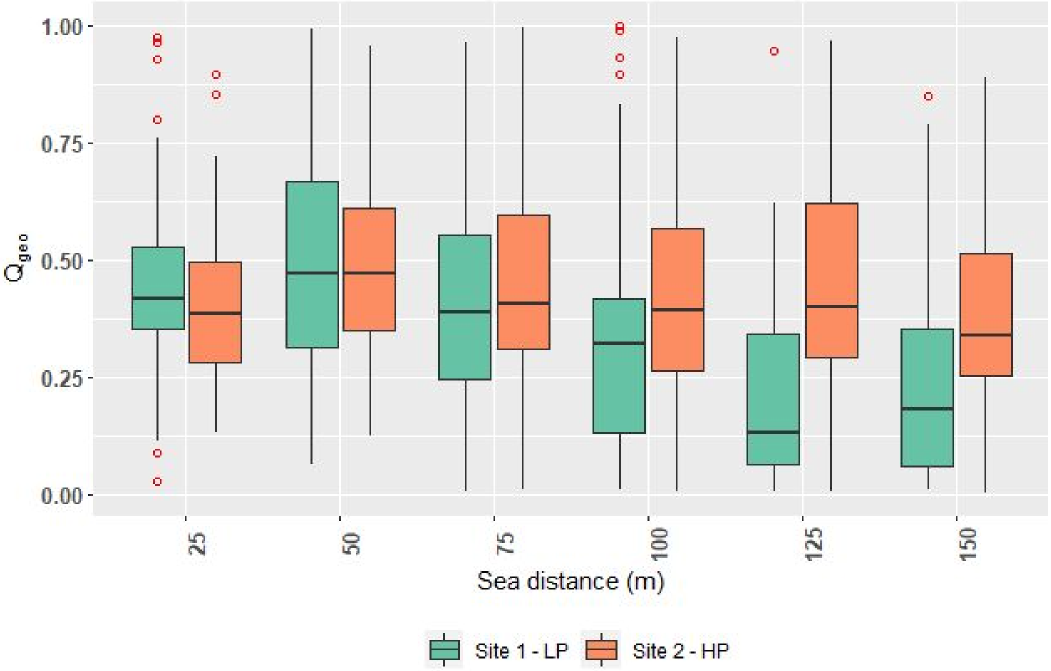


Fig. 4 Box plots of the Q_{geo} values (elevation and slope) along the sea-inland gradient for the LP (green) and HP (orange) sites .

4. Discussion

In this paper, we tested the potential of fine-scale UAS data to describe the eco-geomorphological pattern of coastal dunes by comparing such pattern along the sea-inland gradient of two different beaches in Central Italy with low (LP site) and high (HP site) human pressure. Concurrently, we tested the recently proposed Rao's Q diversity index applied to the UAS-derived spectral information (Q_{rs}) for describing the dune eco-geomorphological integrity as an supplement to the habitats classification approaches commonly relied upon for describing and reporting the state of conservation of littoral landscapes.

In this sense, the Rao's Q index successfully discriminated between the sites with high and low human pressure, reporting different patterns for the two sites, especially when observing individual sectors of the sea-inland gradient. Such differences were better explained when considering all the separate components of eco-geomorphology, i.e. plant biomass and geomorphology.

Specifically, if compared to the LP site, the HP site features a lower eco-geomorphological heterogeneity within all the sectors of the sea-inland gradient. Besides, as opposed to LP, HP did not present a distinctive peak value of Rao's Q in the second sector of the gradient (25 to 50 m from the seashore), which is typical of well-conserved dune systems where a patchy mosaic of several plant communities occurs along with a complex geomorphological profile. These findings confirm previous observations from highly urbanized coasts in the Mediterranean (Drius et al. 2013; Malavasi et al. 2013) where a high level of human pressure leads to the homogenization of the littoral landscape and thus to a simplification of the typical spatial pattern of well-preserved dune mosaics (Acosta *et al*. 2003a; Carboni *et al*. 2009), both in biomass and geomorphology. Such a process of trivialization has been also linked with a consistent decline of biodiversity values (Malavasi *et al*. 2018) and ecosystem integrity loss (Drius et al. 2013; Drius, Jones, et al. 2019).

However, these trends are more clearly explained when looking in detail at the plant biomass and geomorphology heterogeneity values. In both LP and HP sites, very low values of plant biomass diversity ($Q_{p\text{-}biom}$) at the very beginning of the zonation (0 to 25 m from the seashore) were related to the presence of large surfaces of bare sand and sparse annual plant communities (i.e. communities related to the EC habitat type 1210 - Annual vegetation of drift lines) with a low photosynthetic surface. Indeed, these environments are characterized by high salinity and exposure to salt spray, continuous wind abrasion, and sand burial (Bazzichetto et al. 2016; Malavasi, Conti, et al. 2016). Concurrently, if compared to LP, the lower plant biomass diversity for HP in this foredune sector and, especially, in the following one (25 to 50 m) is probably caused by the intense beach cleaning activities, often (and increasingly on highly visited beaches) carried out using mechanical equipment that may cause the depletion of plant communities through their direct removal and alteration of beach functionality (e.g., the nutrient cycle or food chain) (Dugan & Hubbard 2010).

Conversely, in the same sector (25 to 50 m), the LP site featured a peak in the biomass diversity indicating the beginning of the typical patchy mosaic of plant communities that contribute to the dune formation by acting as initial wind blocks. Here, the "Embryonic shifting dunes" (habitat type 2110), representing the first stages of dune construction, show a vegetation structure similar to that found in the habitat type 2120 "Shifting dunes along the shoreline with *Ammophila arenaria* (white dunes)" because of the dominance of tall perennial grasses (i.e. *Ammophila arenaria* and *Elymus farctus*). Both habitats present a naturally discontinuous cover, the gaps in which are colonized by annual vegetation very different in composition and structure (i.e. habitat 2230-*Malcolmietalia* dune grasslands) (Pisanu *et al*. 2014). In this sector, the high level of plant biomass diversity ($Q_{p\text{-}biom}$) confirms once again that in a well-preserved dune ecosystem, there is no abrupt zonation with a clear delineation of habitats along the sea-inland gradient but in most cases, plant communities are patchy and gradually transitional (Acosta *et al*. 2003a; Acosta *et al*. 2003b; Biondi, 2007; Carboni *et al*. 2009). Finally, plant biomass diversity ($Q_{p\text{-}biom}$) differed between LP and HP also in the inland sectors; in the LP area, we observed more dispersed values already indicating the presence of the first patchy woody formations of the habitat type "2250-Coastal dunes with *Juniperus* spp.(juniper scrub)" and "2260-*Cisto-Lavanduletalia* dune sclerophyllous scrubs".

Finally, the geomorphology patterns appeared similar for the first three sectors closest to the shoreline (0 to 75 m) in both LP and HP sites, with the high values indicating unstable substrate, which is subject to the constant influence of the sea with consistent changes in elevation and slope within relatively small areas. On the contrary, in the more inland sectors of the gradient, the geomorphological diversity started to decrease for the LP area, indicating the beginning of a more stable substrate and more sheltered conditions of the dune system, creating a sector with plant species growing in more stable and richer soils with lower salinity (Acosta et al. 2009a; Santoro et al. 2011). In these inland sectors, the root structure of the dune habitats vegetation provides a soil retention function contributing to substrate stabilization and, therefore, playing an important role in regulating coastal erosion (Barbier *et al*. 2011; Bazzichetto *et al*. 2020). The presence of the embryo, mobile, and fixed dunes is also important for protecting the inner coastal sectors from the wind, aerosol, and storms (Feagin *et al*. 2015; Bazzichetto *et al*. 2016). On the other hand, the higher geomorphological diversity of the HP area reaching up to the farthest inland sectors illustrates the presence of incoherent substrate with tiny and sparse psammophilous species. Indeed, the anthropogenic disruption of the fixed and patchy woody vegetation driven by the efforts to create new infrastructure (e.g. roads, access to the beach, houses, beach resorts) (Malavasi et al. 2013) prevents the protection of the inner and back dune sectors from aerosol, wind and storms (Barbier et al. 2011; Liquete, Zulian, et al. 2013). Therefore, in the HP area, we observed an unstable substrate still subject to the influence of the sea with consistent changes in elevation and slope within relatively small areas (which is normally typical of the sectors closest to the sea) even in the last sectors.

5. Conclusion

Rao's Q enabled us to generate a synthetic eco-geomorphological dune profile directly showing the status of coastal landscapes. Nonetheless, in order to gain greater insight into the state of the sea-inland gradient, we stress the importance of independently considering the plant biomass and geomorphology aspects forming a basis for the individual aspects of which the eco-geomorphology is composed. Through a UAS-based approach, we described and summarized essential aspects of the dune ecology and functionality previously described separately and with instruments constrained either by a coarser scale (e.g. dune biomass using SENTINEL 2 NDVI values, see Marzialetti *et al.* 2019 and Marzialetti *et al.* 2020) or implementation costs (e.g. dune morphology using airborne LiDAR images; Bazzichetto *et al.* 2016). Indeed, the monitoring of the Mediterranean coastal ecosystems cannot entirely rely on satellite-borne or air-borne data. Freely available data (e.g. Landsat, Sentinel, or MODIS for land cover) cannot provide the high spatial resolution required to capture the heterogeneous and fine-grain habitat mosaic, while finer resolution data can be prohibitively costly (e.g. QuickBird, IKONOS for land cover, LiDAR, TanDEM-X DEM for topography). Besides, the monitoring of such ever-changing ecosystems requires high temporal resolution data (e.g. seasonal) which is often unaffordable or unavailable (e.g. LiDAR, ALOS World 3D, or TanDEM-X DEM) for topographical data. Nonetheless, even if our approach is cost-effective and capable of providing high spatial and temporal resolution data, it is so far eligible only when relatively small areas are at stake. Therefore, further efforts should be devoted both to investigating the scale and spatial resolution dependence of Rao's Q index on remote sensing-derived spectral heterogeneity information and to harmonizing UAS high-resolution data covering small extents with coarser-scale data covering wider areas. Such efforts would allow upscaling similar information from local to regional and national scales. Finally, our attempt of linking spectral information with dune integrity can contribute to defining more effective tools for monitoring and prioritizing conservation actions in these fragile and highly vulnerable ecosystems.

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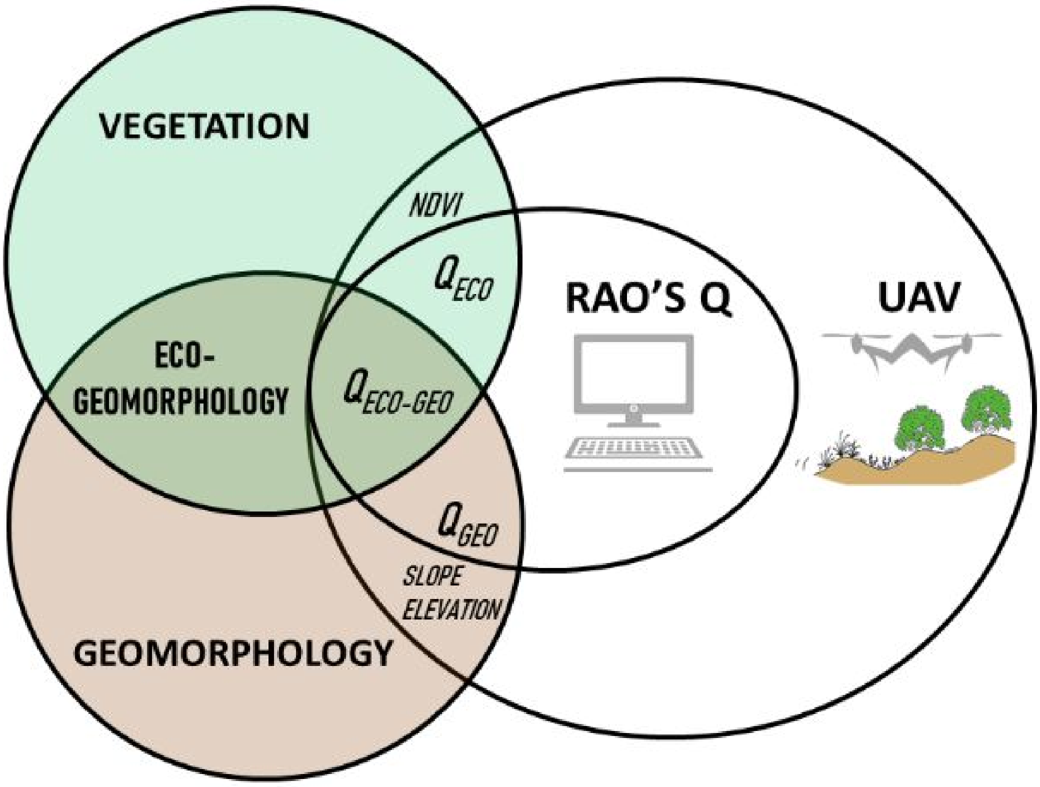
Graphical Table of Contents



Appendix S1.

RGN false color images of the compared areas, along with the raster outputs of the Rao's Q Heterogeneity Index calculation for plant biomass (Qp-biom), surface geomorphology (Qgeo), and Eco-geomorphology (Qeco-geo).