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Disentangling the effect of coastal erosion and accretion on plant communities of Mediterranean dune ecosystems

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ABSTRACT

Coastal erosion, in combination with sea-level rise and extreme meteorological events, is globally threatening the biodiversity and functioning of dune ecosystems, along with the essential ecosystem services they provide. In this study, by quantifying the intensity of erosion and accretion processes occurred over two decades in a wide Mediterranean dune system, we explore the influence of sand processes on dune plant communities focusing on a large portion of the sea-inland gradient. In particular, using different regression techniques, we assess how erosion and accretion processes affect richness, cover and diversity of Mediterranean coastal dune plant communities. Results show that the influence of coastal erosion and accretion varies along the sea-inland gradient, with foreseeable consequences on the integrity of dune systems. The negative effect of erosion seems to be particularly marked on foredunes, which play a key role in dune formation, while decreasing in landward communities. On the other hand, accretion features an opposite trend, unexpectedly influencing only Mediterranean shrubs. We highlight the importance of monitoring the effects of erosion and accretion processes on coastal vegetation in order to support the conservation of dune habitats and preserve the associated ecosystem services, especially in the context of climate and human-induced changes.

1. Introduction

In the coming decades coastal areas will be globally threatened by increasing levels of erosion and flooding (Neumann et al., 2015), likely causing severe damages to human settlements and reductions in the provision of fundamental ecosystem services (Adger et al., 2005) including coastal defense (McLachlan and Defeo, 2017), groundwater storage (Rhymes et al., 2015) and climate mitigation (Drius et al., 2016; Carranza et al., 2018). Indeed, several reports on global climate change (Church et al., 2013; Spanger-Siegfried et al., 2014) alerted countries about the risk induced by sea-level rise and extreme events with strong consequences for the functioning of coastal environments (Schlacher et al., 2007), especially when in combination with anthropogenic coastal subsidence (Anzidei et al., 2016; Antonioli et al., 2017).

Such damages are expected to be particularly severe in the Mediterranean Basin, where more than a third of the total population lives in coastal administrative entities (UNEP, 2017). Antonioli et al. (2017) predicted that the relative sea-level rise expected in Italy by 2100 will change dramatically the present-day morphology, potentially flooding up about 5500 km^2 of coastal plains at elevations close to present-day sea level.

Along with the risk induced by the predicted sea-level rise, in the Mediterranean basin coastal erosion driven by anthropogenic activities (e.g. construction of harbors, groins and dams), has represented one of the main threats affecting the integrity of dune ecosystems in the last decades (Eurosion, 2004).

Comprehensive and comparable information on the extent of coastal erosion and its causes is unfortunately scarce or unavailable for the whole Mediterranean basin, nevertheless it is known that more than 25% of the beaches along the Mediterranean coasts of Europe are

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affected by erosion (Eurosion, 2004). In Italy alone, the Ministry of the Environment and Protection of Land and Sea recently estimated that, between 1960 and 2012, about 23% of the peninsular sandy coast experienced erosion, for an overall land loss of ca. 35.5 km^2 (MATTM, 2017).

To limit the loss of the related ecosystem services and cope with the above mentioned hazards driven by sea-level rise and anthropogenic coastal erosion, timely research should focus on the effects and the drivers of such changes to eventually accelerate the efforts to stabilize and protect coastal areas.

So far, stabilizing measures have relied upon the construction of structures such as jetties and levees, groins and breakwaters, but also revetments and seawalls, often resulting in an even worse loss of coastal ecosystems and related ecosystem services (Jackson et al., 2013; Pranzini et al., 2015).

Conversely, it is widely acknowledged that the stability of coastal areas and the provision of most of the aforementioned ecosystem services is guaranteed by the integrity of ecomorphodynamic interactions between *psammophilous* plants encountered along the sea-inland gradient and sand (Stallins and Parker, 2003; Durán and Moore, 2013; Aucelli et al., 2018); therefore, stabilizing measures should focus on preserving and investigating such interaction in relation to erosion and accretion processes. On one hand, dune vegetation depends on a number of different abiotic factors such as salinity, wind exposure, flooding (Ciccarelli, 2014; Ruocco et al., 2014; Bazzichetto et al., 2016; Sperandii et al., 2019a). On the other hand, being adapted to sand burial, *psammophilous* plant communities can retain sediment by affecting its movement, therefore determining dune morphology and stabilization over time (Maun, 2008).

Few studies have explored the effects of erosion and accretion on coastal dune habitats (but see Bitton and Hesp, 2013; Miller, 2015; Ciccarelli et al., 2017), and even less accounted for their concurrent influence along the entire sea-inland gradient, thus considering all the plant communities occurring along the typical coastal zonation (Acosta et al., 2003). Moreover, most of these studies focused on Oceanic dunes, while, up to our knowledge, the influence of erosion and accretion phenomena on Mediterranean coastal dune systems remains mostly uncharted. As such, these studies may do not apply to the Mediterranean Basin which differs from Oceanic systems in a number of features: higher water temperature and salinity, lower intensity of marine and meteorological processes (tides, waves and storms), dune structures that are less complex (e.g. limited width of the dune system, presence of limited number of dune cordons) and, finally, a longer disturbance history (see Fenu et al., 2013 and references therein).

Additionally, as opposed to coastal erosion, the influence of coastal accretion on dune vegetation has been rarely addressed in a targeted manner (but see Bitton and Hesp, 2013 and Miller, 2015). Indeed, its effect has been mainly studied on single coastal plant species (Maun, 2009; Wilson and Sykes, 1999; Konlechner et al., 2019), while it is still not clear how dune plant communities respond to accretion as a whole.

Understanding how erosion and accretion affect plant communities is crucial for preserving the functioning of coastal dunes and their associated ecosystem services (Schlacher et al., 2007), and it becomes especially important in the Mediterranean area, given the severity of the impacts that global changes are likely to cause (Antonioli et al., 2017). In this context, the present study aims at providing the first quantification of the effect of erosion and accretion processes on Mediterranean coastal dune plant communities, focusing on a wide portion of the sea-inland gradient and including several EU Habitats (*sensu* 92/43/EEC) of conservation concern (Acosta et al., 2005; Prisco et al., 2012). Moreover, by using a widely adopted and standard system of vegetation classification, we aim at supplying EU Habitat-specific insights that can help in the development of conservation and management strategies.

In particular, the influence of increasing erosion and accretion is assessed at the habitat level by analyzing species richness, vegetation cover, diversity and evenness of the investigated plant communities, and at the species level by exploring the specific response of a set of diagnostic (i.e. focal) species.

To achieve these aims, we applied a shape index commonly used in landscape ecology to georeferenced polygons (derived from freely available remotely sensed data) representing the overall change in the shoreline position occurred over ca. twenty years to summarize the magnitude of shoreline dynamics (intensity of coastal erosion and accretion) occurred along a wide Mediterranean dune system.

2. Materials and methods

2.1. Study area

The study focuses on the Tyrrhenian coast of Central Italy (Lazio region) and is characterized by an interchange of areas undergoing both erosion and accretion processes (MATTM-Regioni, 2017) (a map of the study area is reported in Appendix A). In general, the Lazio coast features a Mediterranean climate (Pesaresi et al., 2017) and is dominated by detrital sedimentation with a relatively low tidal range for the whole Tyrrhenian Sea, equal to 0.45 m (Ferrarin et al., 2013). Although weather conditions may vary, the whole area is influenced by dominant winds coming from W, W–S, S and S–W. (http://www.cmgizc.info). In the study area, holocenic dune systems (altogether 96 km long) occupy a narrow strip along the seashore (<500 m), are low (<10 m in height) and relatively simple in structure. In well-preserved coastal dunes, vegetation is typically structured in a sequence of plant communities (i.e. coastal zonation, see Fig. 1) strongly associated to sea distance (Bazzichetto et al., 2016), which in this case includes pioneer communities of the upper beach followed by a section of low embryo dunes, usually a single ridge of shifting dunes, coastal dune grasslands and, finally, Mediterranean coastal shrubs (Acosta et al., 2003; Carranza et al., 2008). However, in this area, as well as in most of Mediterranean coastal systems, a long history of human activity can be traced, which substantially influenced and modified natural vegetation. For this reason, vegetation in our study area could be considered representative of the typical Mediterranean coastal zonation alongside human disturbance.

2.2. Vegetation and floristic data

Vegetation and floristic data was extracted from ‘‘RanVegDunes’’ (Sperandii et al., 2017), a database including georeferenced 4-m^2 plots randomly located along coastal dunes of Central Italy. For each vegetation plot, a list of vascular plant species recorded following the “shoot presence” criterion (Cancellieri et al., 2017) is available, together with relative cover values measured on a percentage scale. Additionally, each plot is assigned to a level-3 EUNIS category according to the EUNIS habitat classification system (Davies et al., 2004). For this study, we selected 534 plots sampled between 2005 and 2015 and belonging to four EUNIS categories: sand beach drift lines (B1.1), shifting coastal dunes (B1.3), coastal stable dune grassland (B1.4) and coastal dune

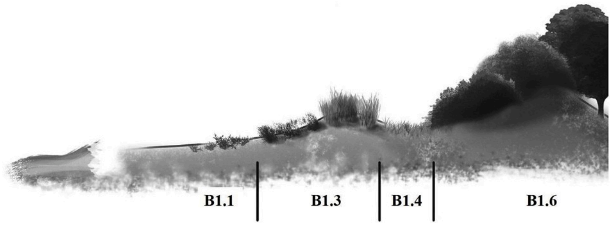

Fig. 1. Coastal dune zonation along with EUNIS codes associated to the following habitat types: sand beach drift lines (B1.1); shifting coastal dunes (B1.3); coastal stable dune grassland (B1.4); coastal dune scrub (B1.6). See Table 1 for a detailed description. Picture drawn by Federico Romiti.

Table 1
Description of the communities, along with their diagnostic species. For each community, the number of observations used for the analyses is reported in brackets. Nomenclature follows Conti et al. (2005). Diagnostic species tested for the effect of erosion and accretion processes are highlighted in bold (see section 2.4.3).

Level 3-EUNIS type (number of observations)	Description and correspondence with EU habitats (ex Annex I 92/43/EEC)	Diagnostic species
B1.1 Sand beach drift lines (N = 73)	Pioneer annual formations characterizing the strandline zone of the beach (EU hab 1210 - Annual vegetation of drift lines)	***Cakile maritima* Scop. subsp. *maritima*** ***Chamaesyce peplis* (L.) Prokh.** ***Polygonum maritimum* L.** ***Salsola kali* L.**
B1.3 Shifting coastal dunes (N = 203)	Mobile coastal sand ridges which include embryonic dunes characterized by *Elymus farctus* (EU hab 2110 - Embryonic shifting dunes) and semi-permanent dune systems dominated by *Ammophila arenaria subsp. Australis* (EU hab 2120 - Shifting dunes along the shoreline with *Ammophila arenaria*)	***Ammophila arenaria* (L.) Link subsp. *australis* (Mabille) Laínz** ***Anthemis maritima* L.** *Calystegia soldanella* (L.) Roem. & Schult. ***Cyperus capitatus* Vand.** *Echinophora spinosa* L. ***Elymus farctus* (Viv.) Runemark ex Melderis subsp. *farctus*** *Eryngium maritimum* L. *Euphorbia paralias* L. *Lotus cytisoides* L. ***Medicago marina* L.** *Otanthus maritimus* (L.) Hoffmanns. & Link subsp. *maritimus* ***Pancratium maritimum* L.** *Sporobolus virginicus* Kunth
B1.4 Coastal stable dune grassland (N = 116)	Stable dune grasslands including chamaephytic communities of the inland dunes dominated by *Crucianella maritima* (EU hab 2210 - *Crucianellion maritimae* fixed beach dunes) and annual, species-rich communities colonizing dry interdunal depressions (EU hab 2230 - *Malcolmietalia* dune grasslands)	*Bromus diandrus* Roth subsp. *maximus* (Desf.) Soó *Crucianella maritima* L. *Cutandia maritima* (L.) Barbey *Lagurus ovatus* L. *Medicago littoralis* Loisel. *Ononis variegata* L. *Phleum arenarium* L. subsp. *caesium* H. Scholz *Pseudorlaya pumila* (L.) Grande *Pycnocomon rutifolium* (Vahl) Hoffmanns & Link *Silene canescens* Ten. *Sixalix atropurpurea* (L.) Greuter & Burdet *Vulpia fasciculata* (Forssk.) Fritsch
B1.6 Coastal dune scrub (N = 142)	Shrub communities including formations dominated by *Juniperus* spp. and formations dominated by sclerophyllous shrubs	***Juniperus oxycedrus* L. subsp. *macrocarpa* (Sibth. & Sm.) Neilr.** ***Lonicera implexa* Aiton subsp. *implexa*** ***Phillyrea angustifolia* L.** ***Pistacia lentiscus* L.**

scrub (B1.6). The selected EUNIS categories represent most common habitat types found in the Mediterranean coastal zonation (Janssen et al., 2016; see Fig. 1 and Table 1). We decided to use the level 3-EUNIS classification as it represents the standard classification for European habitats, and at the same time it adopts a commonly accepted nomenclature, therefore allowing easier comparisons of the results between European countries (Medvecká et al., 2014). Additionally, as level 3-EUNIS categories hold a precise correspondence to European Habitats *sensu* 92/43/EEC, results of this study can provide support in the development of habitat-specific monitoring and management strategies.

For each plot we extracted values of species richness and vegetation cover. In particular, species richness was calculated as the total number of species recorded in each plot (hereafter, species richness), while vegetation cover was computed by summing up the percentage cover of each species recorded in a given plot (hereafter, vegetation cover). It should be noticed that, since this value can exceed 100% ground cover, for each EUNIS category we rescaled cover values between 0 and 1. To this aim, we divided the value of vegetation cover recorded in each plot by the maximum value measured in its corresponding EUNIS category.

To explore the response of a set of diagnostic species (i.e. focal species) to coastal erosion/accretion processes, for each analyzed community (i.e. EUNIS category) we identified diagnostic species following the Italian Interpretation Manual of the Habitats Directive (Biondi et al., 2009) (see Table 1). The use of diagnostic species in ecological research has been increasingly implemented to detect habitat modifications, due to these species being particularly sensitive to environmental changes (Santoro et al., 2012; Del Vecchio et al., 2016; Angiolini et al., 2018).

2.3. Coastal erosion and accretion data

Data describing coastal erosion and accretion conditions were downloaded from the Italian "*Geoportale Nazionale*" (http://www.pcn.minambiente.it/mattm/en/wfs-service/) and imported in an ArcGIS environment (ArcGIS 10.1; ESRI, 2011). Specifically, data consists of a vector layer of georeferenced polygons representing the net change in coastal extent occurred from 1994 to 2012 due to the retreating or progradation of the shoreline. These polygons resulted out of the intersection of the shorelines obtained by digitalizing high-resolution aerial orthophotos at the two time-points (1994 and 2012; for metadata and details on the procedure see http://www.pcn.minambiente.it/mattm/en/project-coasts/). Although we are aware that coastal erosion and accretion phenomena can be the result of different processes, to distinguish among them is not the intention of this paper, which instead only aims at assessing how different intensities of such phenomena affect coastal dune habitats. In this sense, we refer to erosion and accretion as to the visually quantifiable extent of dune area lost or

Table 2
Model outcomes reporting the effect of coastal erosion on species richness of coastal dune habitats (identified through EUNIS categories). P/QP: Poisson/QuasiPoisson model. Values of the z-test and *t*-test are reported in case of Poisson and QuasiPoisson models, respectively. The superscript^2 identifies the quadratic term for SI_{change}, included in the model through the R function "poly()", which fits orthogonal polynomials for reducing collinearity with the lower order term.

EUNIS	P/QP	Formula	Estimate	Std. Error	*t*/*z*-value	Pr(>$\lvert t/z \rvert$)
B1.1 Sand beach drift lines	QP	Sp. Rich. ~ SI_{change}	−0.0591	0.02528	−2.338	0.0245
B1.3 Shifting coastal dunes	P	Sp. Rich. ~ SI_{change}	−0.0325	0.0146	−2.218	0.0265
B1.4 Coastal stable dune grassland	P	Sp. Rich. ~ SI_{change}	−0.4693	0.3364	1.395	0.1629
		$(SI_{change})^2$	−0.9272	0.3489	−2.658	0.0079
B1.6 Coastal dune scrub	QP	Sp. Rich. ~ SI_{change}	0.0133	0.0244	0.544	0.589

gained due to shoreline dynamism.

In order to synthetically quantify the intensity of erosion and accretion processes occurred between 1994 and 2012 in the study area, we used a compactness index commonly employed in landscape ecology (Farina, 2008) that we will name, for simplicity, shape index (hereafter, SI_{change}). The index, which provides an intuitive measure of the overall intensity of erosion/accretion, is computed as:

$$SI_{change} = A_{polygon}/Per_{polygon}$$

where $A_{polygon}$ is the area of the coastal polygon (associated to erosion or accretion), while $Per_{polygon}$ represents its perimeter. Being affected by both shape and size of the polygons, this index features the desirable property of averaging the intensity of erosion/accretion processes over the extent of the affected coastal stretch (see also Appendix B). Indeed, we assume that the intensity of erosion or accretion (and its subsequent influence on plant communities) is given not only by the width, but also by the length of the affected portion of the shoreline. Therefore, coastal stretches that experienced low intensity of erosion/accretion (summarized by thin polygons deployed parallel to the coastline and representing a small change in the shoreline position occurred over time) will result in low values of SI_{change}. On the other hand, wide coastal sectors that experienced high erosion/accretion intensity (represented by thick and compact polygons deployed parallel to the coastline) will result in high values of SI_{change}. In between these two cases, the index will assume increasing values with increasing intensity of the phenomenon.

In order to analyze the effects of erosion and accretion intensity on coastal dune vegetation, each sampled plot was spatially matched to a unique polygon by its proximity. Given that low-lying sandy beaches of the Lazio system underwent, to some degree, either erosion or accretion processes during the analyzed period, it was possible to associate all the vegetation plots to one of the former processes.

2.4. Statistical analyses

Statistical analyses were conducted separately in erosion and accretion sectors to independently highlight the effect of each process on the dune vegetation characterizing the selected EUNIS categories (Table 1).

2.4.1. Analysis of the effect of coastal erosion/accretion processes on species richness and cover

The influence of erosion and accretion on coastal dune plant communities was assessed by modelling their plant species richness and vegetation cover as a function of SI_{change} using different regression techniques.

For each EUNIS category, Generalized Linear Models (GLMs) were implemented for exploring the change in species richness due to the aforementioned coastal processes, setting species richness as response variable and SI_{change} as predictor. Models were fitted assuming a Poisson distribution of the response conditional on the predictor and using a log link. Since standard error of the estimates can be biased in Poisson models due to over- or underdispersed data, we estimated the dispersion parameter for each Poisson fitted model. In case of significant over-/underdispersion being detected (function dispersiontest, "AER" R package; Kleiber and Zeileis, 2008), a QuasiPoisson model was fitted.

For each EUNIS category, Linear Models (LMs) were used to assess the influence of coastal erosion and accretion on vegetation cover, setting vegetation cover as response variable and SI_{change} as predictor. Standardized vegetation cover values were transformed on a logit scale to match the assumptions required by LMs.

In both GLMs and LMs, we accounted for nonlinear relationships between response variables and SI_{change} by including the latter as quadratic term in the models and testing whether its inclusion significantly increased the model fit.

Table 3
Model outcomes representing the effect of coastal erosion on vegetation cover of coastal dune habitats (identified through EUNIS categories). Vegetation cover values were standardized and logit-transformed.

EUNIS	Formula	Estimate	Std. Error	*t*-value	Pr(>$\lvert t \rvert$)
B1.1 Sand beach drift lines	H. Cov. ~ SI_{change}	−0.2666	0.0788	−3.384	0.0016
B1.3 Shifting coastal dunes	H. Cov. ~ SI_{change}	−0.0280	0.0359	−0.780	0.4374
B1.4 Coastal stable dune grassland	H. Cov. ~ SI_{change}	−0.0787	0.0614	−1.282	0.205
B1.6 Coastal dune scrub	H. Cov. ~ SI_{change}	0.0258	0.0364	0.709	0.481

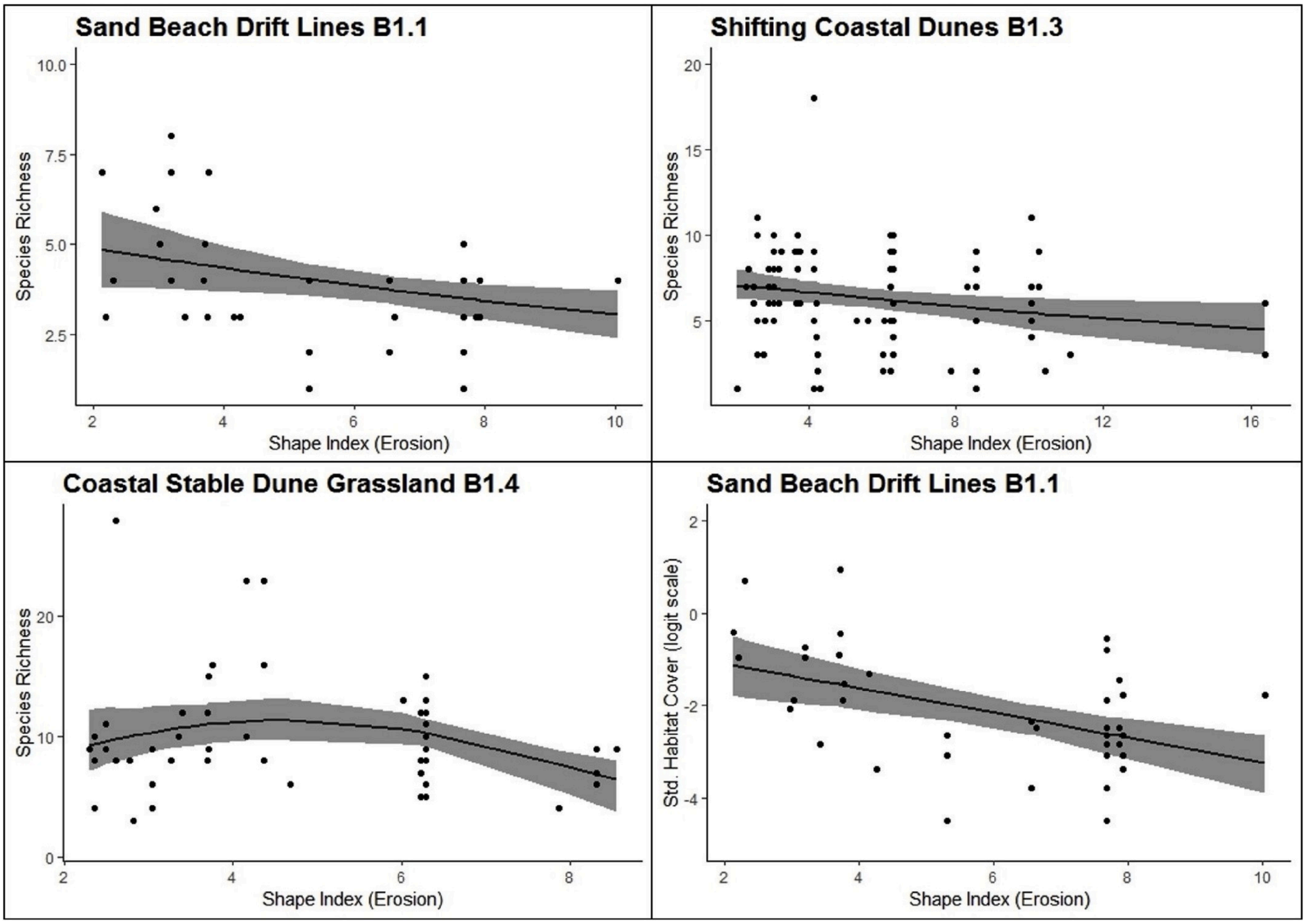

Fig. 2. Effect of coastal erosion on the species richness of sand beach drift lines (B1.1, top left), shifting coastal dunes (B1.3, top right) and coastal stable dune grasslands (B1.4, bottom left) and on vegetation cover (standardized and logit-transformed) of sand beach drift lines (B1.1, bottom right). Grey bands represent the 95% confidence intervals of the mean computed as 0.025 and 0.975 quantiles from 500 bootstrap samples.

2.4.2. Analysis of the effect of coastal erosion/accretion on communities' diversity and evenness

With the aim of further examining the effect of increasing intensity of erosion/accretion on coastal dune vegetation, regression trees based on conditional inference (function ctree, "party" R package; Hothorn et al., 2006) were implemented in those EUNIS categories highlighted by the models as significantly affected by coastal erosion/accretion. Specifically, we used regression trees to identify a threshold that, breaking the continuous range of SI_{change} (for both species richness and vegetation cover), would divide plots in statistically different groups (high erosion/accretion *vs.* low-to-stable erosion/accretion conditions). In this regard, regression trees have been successfully employed for identifying environmental thresholds describing plant diversity patterns (Svitok et al., 2016; Filibeck et al., 2019).

Only in those communities (i.e. EUNIS categories) suggested by the regression models as being significantly affected by coastal erosion/accretion processes we analyzed, using the information obtained from the regression trees, how diversity and evenness differed between areas featuring low-to-stable and high erosion/accretion conditions. To this aim we used rarefaction/extrapolation curves (hereafter, R/E curves) based on Hill numbers (Chao et al., 2014). Hill numbers integrate information on both species richness and species relative abundances in a class of diversity indices that differ only by an exponent q. In particular, Hill numbers correspond to species richness, Shannon and Simpson diversity of the assemblage when q is equal to 0, 1 and 2, respectively. Rarefaction/extrapolation curves allow statistical comparisons of assemblages' diversity by interpolating/extrapolating Hill numbers from a reference sample size to smaller/larger number of sampling units and by providing confidence intervals of the diversity estimators through bootstrap (Chao et al., 2014; Hsieh et al., 2016). Rarefaction/extrapolation curves (based on sampling-unit incidence frequencies data) were implemented using the function iNEXT included in the "iNEXT" R package (Hsieh et al., 2018). In particular, R/E curves were implemented for q equal to 1 and 2.

2.4.3. Analysis of the effect of coastal erosion/accretion on diagnostic species

Changes in the occurrence frequency of diagnostic species were tested between groups identified by the regression trees only in those EUNIS categories whose species richness turned out to be affected by coastal erosion/accretion. In particular, we performed tests only on those focal species that were most abundant in the database (highlighted in bold in Table 1). For each focal species, the change in occurrence frequency was tested performing a χ^2 2-sample test for equality of proportions (function prop.test, "stats", Yates correction disabled; R Core Team, 2017). In particular, we tested the null hypothesis of equality of proportions of species occurrences recorded in vegetation plots associated to low-to-stable and high erosion/accretion condition. When at least one of the expected counts was less than 5, a Fisher exact test (function fisher.test, "stats", R Core Team, 2017) was performed instead of the χ^2 test. In this case, the null hypothesis was that the given focal species would have equally occurred in coastal areas subjected to

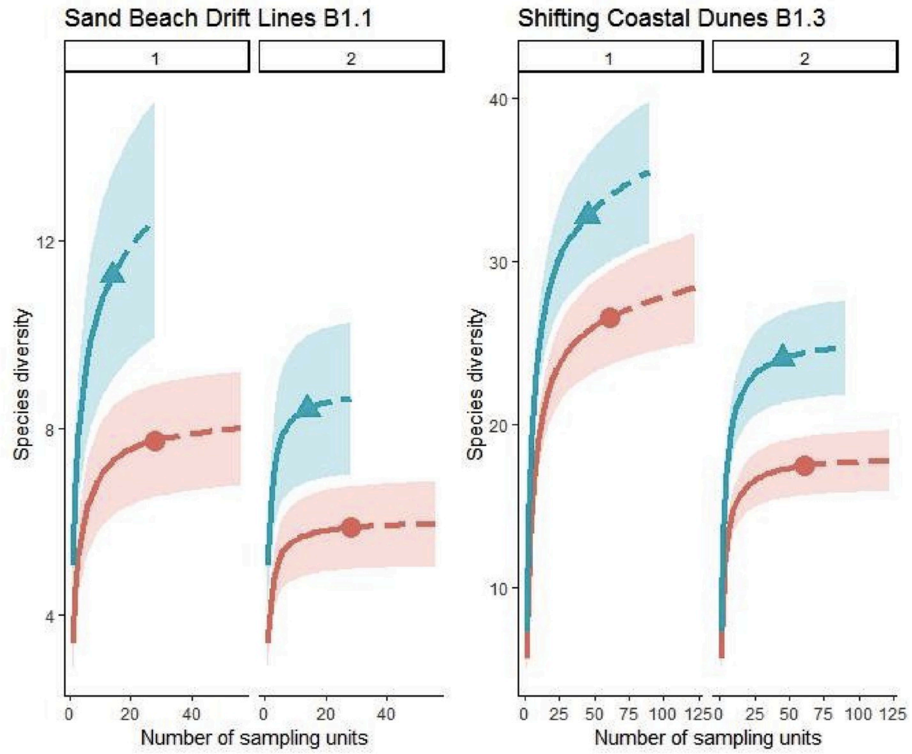

Fig. 3. Rarefaction/Extrapolation (R/E) curves for B1.1 and B1.3 EUNIS categories. For each habitat, Shannon diversity (panel 1) and Simpson diversity (panel 2) are displayed for vegetation plots occurring in coastal sectors associated to low erosion (blue curve) and high erosion (red curve). In both figures, lines represent Shannon and Simpson diversity values interpolated (solid line) and extrapolated (dashed line) from the reference sample (observed). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

Table 4
Model outcomes regarding the effect of coastal accretion on species richness of coastal dune habitats (identified through EUNIS categories). P/QP: Poisson/Quasi-Poisson model. Values of the z-test and *t*-test are reported in case of Poisson and QuasiPoisson models, respectively.

EUNIS	P/QP	Formula	Estimate	Std. Error	*t*/*z*-value	Pr(>|*t*/*z*|)
B1.1 Sand beach drift lines	P	Sp. Rich. ~ SI_{change}	0.0415	0.0360	1.154	0.248
B1.3 Shifting coastal dunes	P	Sp. Rich. ~ SI_{change}	−0.01260	0.0125	−1.007	0.314
B1.4 Coastal stable dune grassland	P	Sp. Rich. ~ SI_{change}	−0.0282	0.0180	−1.564	0.118
B1.6 Coastal dune scrub	QP	Sp. Rich. ~ SI_{change}	0.0333	0.0159	2.093	0.0394

low-to-stable and high erosion/accretion (odds ratio is equal to 1).

3. Results

Overall, erosion and accretion did not affect homogeneously species richness and vegetation cover of plant communities along the coastal zonation. Specifically, coastal erosion appeared to negatively influence both species richness and vegetation cover of sand beach drift line communities (B1.1), while affecting only species richness of shifting coastal dunes (B1.3) and stable dune grasslands (B1.4). On the other hand, accretion processes seemed to positively influence species richness of coastal dune scrub (B1.6). Overall, communities' diversity and evenness resulted to be favored in low-to-stable erosion sectors and in areas undergoing high accretion.

3.1. *Effects of coastal erosion*

Species richness was negatively affected by increasing erosion intensity in coastal dune habitats occurring closest to the sea (sand beach drift lines, B1.1; shifting coastal dunes, B1.3). At the same time, we observed a negative effect on the species richness of coastal dune grasslands (B1.4) for particularly high SI_{change} values. No effect was

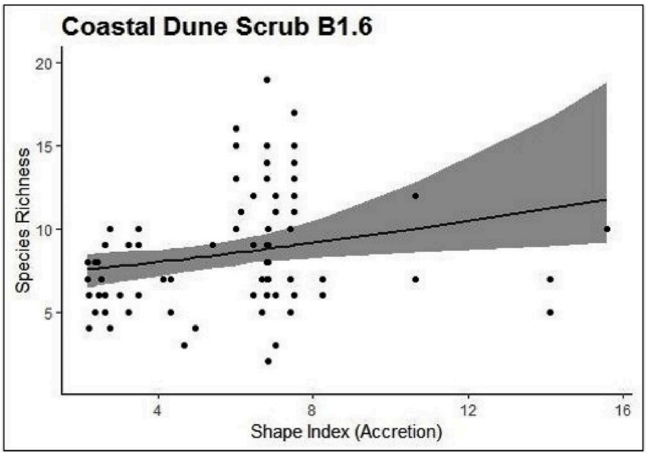

Fig. 4. Effect of coastal accretion on species richness of coastal dune scrub (B1.6). Grey bands represent the 95% confidence intervals of the mean computed as 0.025 and 0.975 quantiles from 500 bootstrap samples.

Table 5
Model outcomes showing the effect of coastal accretion on vegetation cover of coastal dune habitats (identified through EUNIS categories). Vegetation cover values were standardized and logit-transformed.

EUNIS	Formula	Estimate	Std. Error	*t*-value	Pr(>|*t*|)
B1.1 Sand beach drift lines	H. Cov. ~ SI_{change}	−0.014	0.1011	−0.139	0.891
B1.3 Shifting coastal dunes	H. Cov. ~ SI_{change}	−0.0021	0.0337	−0.063	0.9496
B1.4 Coastal stable dune grassland	H. Cov. ~ SI_{change}	0.0301	0.0440	0.683	0.4977
B1.6 Coastal dune scrub	H. Cov. ~ SI_{change}	−0.0517	0.0377	−1.373	0.1735

detected in habitats occurring landward, such as coastal dune scrub (B1.6). (See Table 2 for model outcomes and Fig. 2 for figures representing the effect of coastal erosion in EUNIS categories B1.1, B1.3 and B1.4).

For species richness of drift line communities (B1.1), regression tree split the observations in two statistically different groups at the threshold of $SI_{change} = 3.777$ (Appendix C, Fig. C1), with plots occurring in high erosion conditions being significantly poorer in species than plots occurring in coastal sectors associated to low-to-stable erosion. The same pattern could be observed for shifting coastal dunes, whose species richness turned out to be lower in plots occurring above the SI_{change} threshold of 4.157, thus subjected to high erosion (Appendix C, Fig. C2). Although model results showed a negative effect of strong erosion (high SI_{change} values) on species richness of coastal stable dune grassland (B1.4), regression tree did not produce any split of the vegetation plots.

Vegetation cover appeared to decrease significantly with increasing values of SI_{change} in drift line communities (Table 3; Fig. 2). Here, regression tree split vegetation plots in two groups at the SI_{change} threshold of 3.714 (Appendix C, Fig. C3). Consistently with species richness, vegetation cover appeared to be significantly lower in plots occurring in coastal sectors undergoing strong erosion.

R/E curves showed that drift line assemblages (B1.1) occurring in coastal sectors associated with low erosion were more diverse and more even than those located in areas subjected to high erosion (Fig. 3). The same pattern was observed for shifting coastal dunes (B1.3) (Fig. 3).

Regarding focal species, only *Chamaesyce peplis*, typical of the upper beach (B1.1), was found to occur less frequently in high erosion conditions (Odds Ratio = 10.02, *p*-value = 0.0032).

In foredune communities (B1.3), the occurrence frequency of *Pancratium maritimum* and *Cyperus capitatus* was significantly higher in plots associated to low erosion conditions (*P. maritimus*: $\chi^2 = 10.69$, *p*-value = 0.0011; *C. capitatus*: $\chi^2 = 4.06$, *p*-value = 0.04). In contrast, *Elymus farctus* occurred more frequently in proximity of coastal sectors experiencing strong erosion ($\chi^2 = 7.64$, p-value = 0.0057).

See Appendix D for the results of the proportion (Table D1) and Fisher exact (Table D2) tests performed on the entire set of selected focal species.

3.2. *Effects of coastal accretion*

Species richness was found to increase significantly along with SI_{change} only in coastal dune scrub (B1.6). (See Table 4 for model outcomes and Fig. 4 for figures representing the effect of coastal accretion on EUNIS category B1.6).

As for vegetation cover, no significant effect was detected in any of the analyzed coastal dune habitats (Table 5).

Regression tree performed on the species richness of coastal dune scrub (B1.6) divided the plots in two statistically different groups at SI_{change} equal to 4.941 (Appendix C, Fig. C4), with plots undergoing high accretion being statistically richer in species than those occurring in low-to-stable accretion zones.

Diversity and evenness of coastal dune scrub (B1.6) appeared to be higher in coastal sectors characterized by high accretion, as evidenced by the R/E curves (Fig. 5).

As regard to focal species, the occurrence frequency of *Lonicera implexa* was significantly higher in coastal sectors subjected to low accretion ($\chi^2 = 10.29$, *p*-value = 0.0013).

See Appendix D for the results of the proportion tests (Table D3) performed on the entire set of selected focal species.

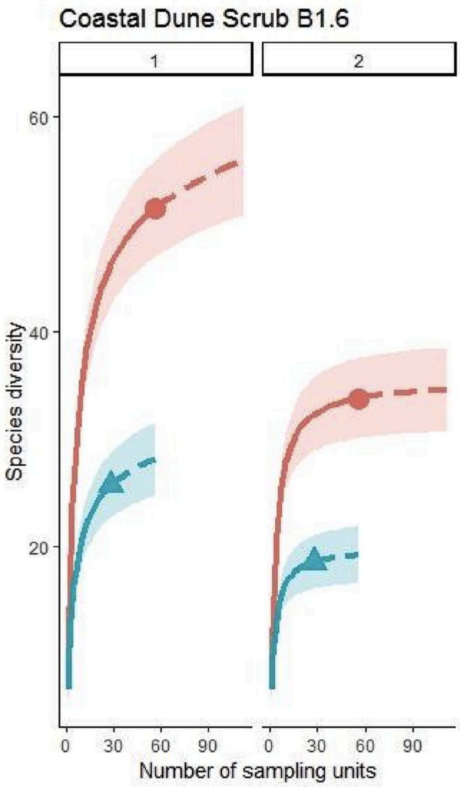

Fig. 5. Rarefaction/Extrapolation (R/E) curves for the B1.6 EUNIS category. Shannon diversity (panel 1) and Simpson diversity (panel 2) are displayed for vegetation plots occurring in coastal sectors associated to low accretion (blue curve) and high accretion (red curve). In the figure, lines represent Shannon and Simpson diversity values interpolated (solid line) and extrapolated (dashed line) from the reference sample (observed). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

4. Discussion

In this study, we provide a first quantification of the effects of erosion and accretion on Mediterranean coastal dune plant communities belonging to a wide portion of the sea-inland gradient. Overall, these processes appear to influence very differently plant communities along the coastal zonation. In particular, we observed that erosion appears to negatively affect plant communities of the sectors closest to the shoreline but its influence decreases as we move towards landward communities. On the contrary, accretion seems to have a positive influence on dune vegetation, although, surprisingly, subtle and restricted to fixed dunes. Moreover, no selective effect of erosion or accretion was detected on the analyzed focal species.

4.1. Effects of erosion

Results suggest that erosion breaks off coastal zonation, with the potential effect of strengthening the so-called process of coastal "squeezing" in urbanized coastal areas (see Doody, 2004; Feagin et al., 2005; Malavasi et al., 2013). As observed by Acosta et al. (2006) and Bertacchi et al. (2016) in Mediterranean sandy ecosystems and by Bitton and Hesp (2013) and Miller (2015) in Atlantic dunes, erosion appears to negatively affect mainly plant communities colonizing the sectors closest to the shoreline. Indeed, we observed that, due to their proximity with the shoreline, drift line communities and shifting dunes occurring in areas undergoing strong erosion are subjected to a substantial change not only in terms of species richness and vegetation cover, but also of communities' diversity and evenness. However, it is worth to highlight that strong erosion can also produce negative effects on plant communities establishing more landward, such as coastal dune grasslands (B1.4), most likely as a result of the degradation of those seaward habitats (e.g., foredunes), whose presence is known to create sheltered conditions for plant communities that are less tolerant to stress.

The strongest impact of erosion was observed in pioneer communities of the upper beach (B1.1). Here, both species richness and vegetation cover tend to decrease when the intensity of erosion increases. Moreover, R/E curves show that B1.1 communities tend to be less even when occurring in coastal sectors undergoing strong erosion. However, it should be noticed that, as pioneer communities of the upper beach are characterized by a restricted pool of species discriminated by a relatively low cover (Prisco et al., 2012; Sperandii et al., 2019b), even a minimum loss in their species assemblage can cause a significant reduction in their diversity, evenness and cover. Nevertheless, the loss of species characterizing drift line communities (B1.1) is able to trigger the weakening of the ecomorphodynamic processes that are the basis of dune building and formation. Indeed, pioneer communities of sand beach drift lines constitute the first barrier to sand movement, affecting the development of the embryo dunes (Prisco et al., 2012; Konlechner et al., 2019). In this regard, the diagnostic species *Chamaesyce peplis* was found to occur less in high erosion conditions than in stable-to-low erosion sectors.

Shifting coastal dunes (B1.3) were similarly affected, showing a substantial decrease not only in the species richness but also, as highlighted by the R/E curves, in the diversity and evenness of communities located in coastal sectors undergoing strong erosion. The detrimental effect of erosion processes on the diversity of these communities might have, in turn, worrying implications on their functionality. Indeed, shifting coastal dunes are characterized by rhizomatous species such as *Elymus farctus* and *Ammophila arenaria* that, due to their being tolerant to burial and capable of accumulating sand (Maun, 2009), play a pivotal role in the formation and stabilization of embryonic and mobile dunes. Interestingly, we observed that *Elymus farctus* occurs more frequently in coastal sectors undergoing high erosion. This could be in line with Sykes and Wilson (1990), who reported that *Elymus farctus* tends to replace *Ammophila arenaria* in condition of low sand budget, or point to secondary embryo dunes colonizing eroded dunes (Doing, 1985), although our analysis on diagnostic species did not highlight any substantial difference in the occurrence of *Ammophila arenaria*. At the same time, we found that erosion has a negative impact on *Pancratium maritimum*, whose occurrence frequency appears substantially lower where the intensity of erosion is high. In this regard, Balestri and Cinelli (2004) observed that the germination of *P. maritimum* might be prevented in coastal sites characterized by low deposition of sand due to coastal erosion.

The slightly negative effect of strong coastal erosion on species richness of stable dune grasslands (B1.4) could be also related to the detrimental influence of erosion phenomena on upper beach (B1.1) and, in particular, on shifting dunes (B1.3). Plant communities of well-developed foredunes act as a barrier mitigating disturbance factors coming from the sea (e.g., salt spray), therefore providing favorable conditions for landward communities to successfully establish and grow (Acosta et al., 2000; Durán and Moore, 2013). For these reasons, in case of foredunes damaging due to strong erosion, negative implications on the species diversity of stable and fixed coastal dunes plant communities should be expected.

4.2. Effects of accretion

While the influence of sand deposition on *psammophilous* species is generally acknowledged as positive, some studies suggested that accretion may actually limit the establishment of plants less tolerant to burial (Maun, 2008, 2009). In this regard, our results did not reveal any substantial effect of accretion on plant communities usually subjected to burial (B1.1 and B1.3) in sites undergoing accretion. On the contrary, accretion seemed to have a positive effect on fixed dunes (B1.6), where species richness appears to be higher than in areas experiencing erosion. Furthermore, R/E curves suggest that such communities are more diverse and evenly distributed in sectors experiencing high, rather than stable-to-low, accretion. This suggests that sand accumulation favors the formation of well-developed foredunes, promoting in turn higher plant diversity in landward sectors less prone to sand deposition. Here, the diagnostic species *Lonicera implexa* occurs more frequently. Nevertheless, these findings have to be interpreted carefully as landward communities, especially Mediterranean coastal shrubs, are subjected to human-related disturbances that may enhance diversity due to the spread of ruderal species (Acosta et al., 2006; Buffa et al., 2012; Fantinato, 2019).

5. Conclusions

In this study, we provide a first assessment of the effect of erosion and accretion processes on Mediterranean coastal dune plant communities. In particular, the influence of these processes is analyzed on European habitats (*sensu* 92/43/EEC) and on selected focal species, therefore providing useful insights for their protection and management in the context of the monitoring and reporting obligations set up by the Habitats Directive. As far as erosion is concerned, drift line communities and shifting dunes appeared as the most negatively affected habitats. Given the fundamental role played by these communities, especially foredunes, in the ecomorphodynamic processes of dune formation, their degradation and disruption due to coastal erosion might have dramatic implications not just on the functioning of the whole dune ecosystem, but also on its capacity to provide key associated ecosystem services strongly related to safety and human well-being such as, e.g., coastal defense.

Although erosion and accretion are natural processes contributing to intrinsic shoreline dynamics, it is their acceleration and intensification (especially that of erosion) that appears to be the problem (Pranzini et al., 2015). In this context, our results highlight the need of planning habitat-specific monitoring activities with the aim of tracking changes in community features that could contribute to a) early detect exacerbated shoreline dynamics and b) timely develop counteracting measures to prevent alterations of the ecomorphodynamic process and habitat disruption.

With this study we stress the need of preserving ecosystem functioning through the maintenance of a proper ecomorphodynamism to guarantee the supply of key coastal ecosystem services, especially in a context of climate and human-induced global changes.

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Author contributions

A.A. conceived the idea with M.B; M.B. and M.G.S. analyzed the data and wrote the first draft of the manuscript. A.A., M.M., M.L.C. contributed substantially to improve the manuscript, which was led by M.B and M.G.S.

Declaration of competing interest

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

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Appendix A

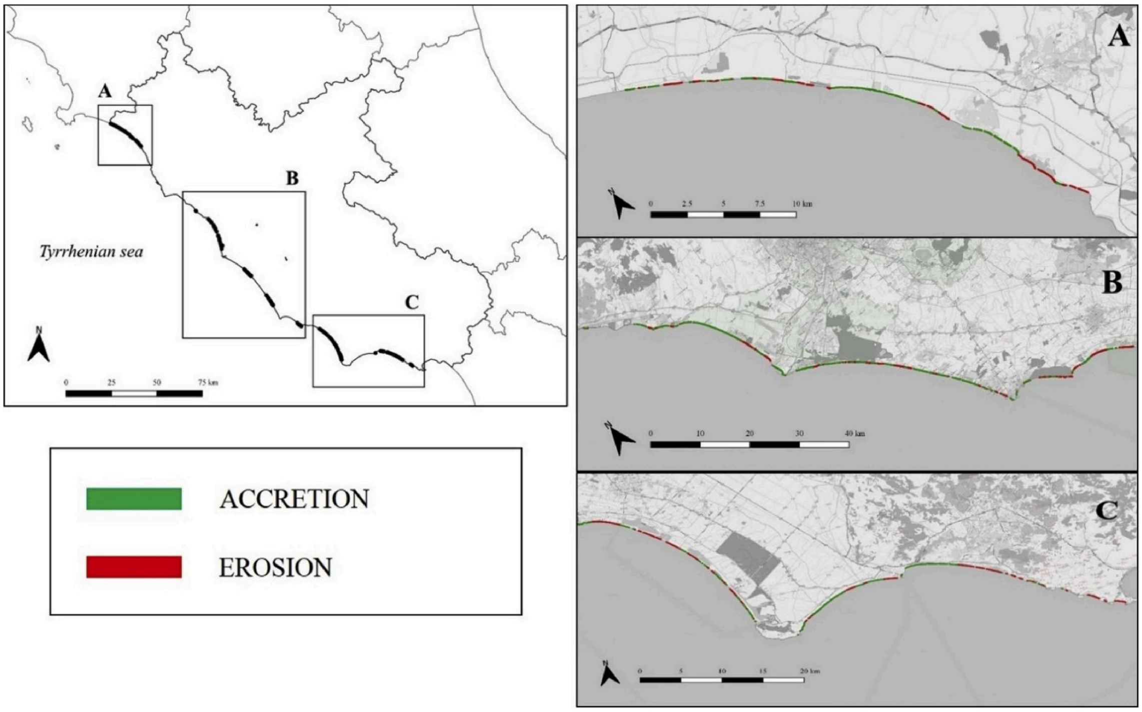

Fig. A. Study area map. Coastal dune systems occurring along the study area are reported in black in the upper left part of the figure. The study area is divided in three sections (A, B, C) and detailed maps of the corresponding coastal sectors are reported in the right part of the figure. Accretion and erosion areas are represented in green and red, respectively.

Appendix B

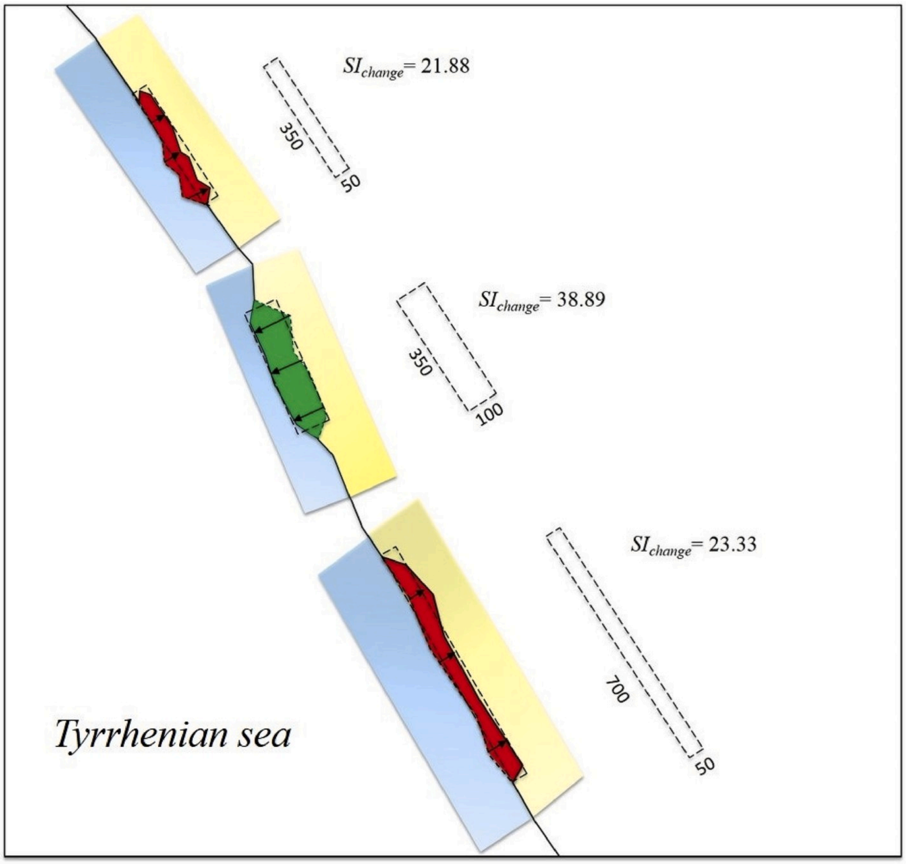

Fig. B. The picture describes the behavior of the Shape Index (SI_{change}) under different scenarios of coastal erosion/accretion. The SI_{change} (adim.), computed as the area/perimeter ratio of polygons, summarizes the net change in coastal extent gained or lost due to the retreating or progradation of the shoreline occurred over the period 1994–2012. Examples are provided for both erosion (red polygons) and accretion (green polygon) processes. Black arrows point to the (main) change direction of the shoreline position. Each polygon is wrapped in an ideal rectangle indicating the local extent (approx. length and width) of erosion/accretion process. On the right side of each coastal polygon the corresponding rectangle is reported along with illustrative measures of its length, width, and value of the SI_{change}. As it can be seen, SI_{change} increases with stronger erosion/accretion processes (i.e. wider polygons), but it also accounts for the extent of the process along the coastline (summarized by the length of the polygons).

Appendix C

Effects of coastal erosion

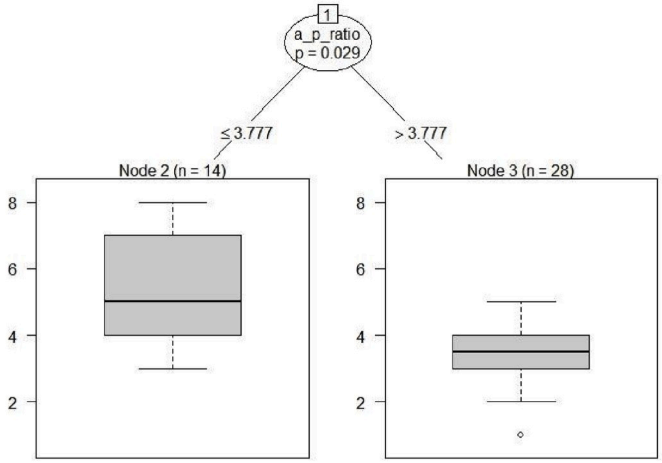

Fig. C1. Regression tree output for the model: species richness ~ SI_{change} in sand beach drift lines (B1.1). Two groups of plots were identified by the regression tree according to the difference in species richness. In particular, species richness was significantly higher in coastal sectors characterized by stable-to-low erosion (node 2 group). Groups were divided at the SI_{change} threshold of 3.777.

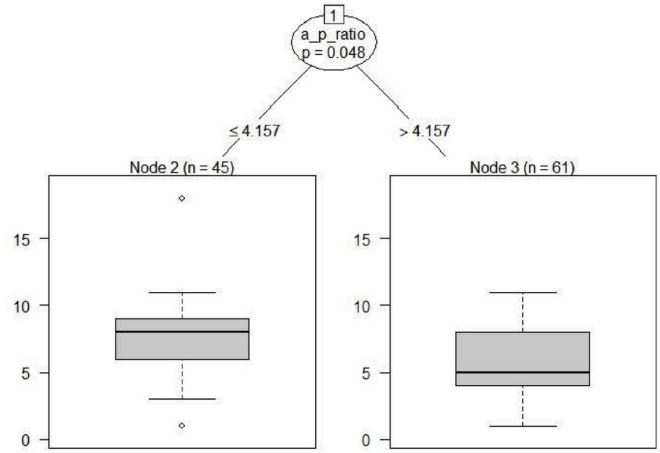

Fig. C2. Regression tree output for the model: species richness ~ SI_{change} in shifting coastal dunes (B1.3). Two groups of plots were identified by the regression tree according to the difference in species richness. In particular, species richness was significantly higher in coastal sectors characterized by stable-to-low erosion (node 2 group). Groups were divided at the SI_{change} threshold of 4.157.

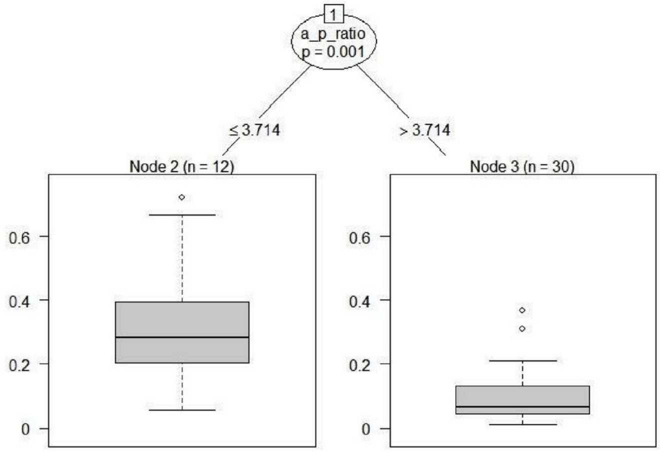

Fig. C3. Regression tree output for the model: vegetation cover ~ SI_{change} in sand beach drift lines (B1.1). Two groups of plots were identified by the regression tree according to the difference in cover values. In particular, vegetation cover was significantly higher in coastal sectors characterized by stable-to-low erosion (node 2 group). Groups were divided at the SI_{change} threshold of 3.714.

Effects of coastal accretion

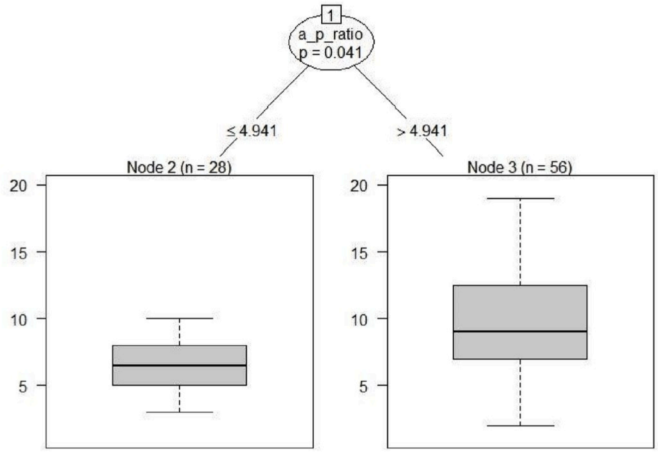

Fig. C4. Regression tree output for the model: species richness ~ SI_{change} in coastal dune scrub (B1.6). Two groups of plots were identified by the regression tree according to the difference in species richness. In particular, species richness was significantly higher in coastal sectors characterized by high accretion (node 3 group). Groups were divided at the SI_{change} threshold of 4.941.

Appendix D

Results of proportion and Fisher exact tests performed to compare the occurrence frequencies of focal species recorded in coastal sectors associated to stable-to-low and high erosion intensity. For the proportion test, the null hypothesis is that the frequency of occurrence does not change according to the increasing intensity of coastal erosion. For the Fisher exact test, the null hypothesis is that focal species equally occur in coastal areas undergoing different intensities of erosion/accretion (odds ratio is equal to 1).

Table D1

Results of the proportion test. Prop_{low}: occurrence frequency (occurrences/number of plots) of focal species in coastal sectors associated to stable-to-low erosion. $\text{Prop}_{\text{high}}$: occurrence frequency (occurrences/number of plots) of focal species in coastal sectors associated to high erosion. Chi-sq.: value of the Chi-sq. statistic. d.f.: degree of freedom. Conf. Int. $\text{Diff}_{\text{prop}}$: 95% confidence interval of the difference in proportions.

EUNIS	Species	$Prop_{low}$	$Prop_{high}$	*Chi-sq.*	*d.f.*	*p-value*	*Conf. Int.* $Diff_{prop}$
Shifting coastal dunes (B1.3)	*Ammophila arenaria australis*	0.31	0.24	0.55	1	$p > 0.05$	$-0.11 \leq Diff_{prop} \leq 0.24$
	Elymus farctus	0.53	0.79	7.64	1	$p = 0.0057$	$-0.43 \leq Diff_{prop} \leq -0.07$
	Anthemis maritima	0.62	0.57	0.25	1	$p > 0.05$	$-0.14 \leq Diff_{prop} \leq 0.24$
	Pancratium maritimum	0.33	0.08	10.69	1	$p = 0.0011$	$0.09 \leq Diff_{prop} \leq 0.4$
	Cyperus capitatus	0.29	0.13	4.06	1	$p = 0.04$	$0.0005 \leq Diff_{prop} \leq 0.31$

Table D2

Results of the Fisher exact test. Conf. Int. OR: 95% confidence interval of the Odds Ratio (OR).

EUNIS	Species	*Odds Ratio*	*p-value*	*Conf. Int. OR*
Sand beach drift lines (B1.1)	*Cakile maritima*	∞	$p > 0.05$	$0.01 \leq Odds\ ratio \leq \infty$
	Salsola kali	∞	$p > 0.05$	$0.63 \leq Odds\ ratio \leq \infty$
	Polygonum maritimum	1.38	$p > 0.05$	$0.1 \leq Odds\ ratio \leq 13.78$
	Chamaesyce peplis	10.02	$p = 0.0032$	$1.92 \leq Odds\ ratio \leq 65.7$
Shifting coastal dunes (B1.3)	*Medicago marina*	0.66	$p > 0.05$	$0.1 \leq Odds\ ratio \leq 3.29$

Results of proportion tests performed to compare the occurrence frequencies of focal species recorded in coastal sectors associated to stable-to-low and high accretion intensity. The null hypothesis is that the frequency of occurrence does not change according to the increasing intensity of coastal accretion.

Table D3

Prop_{low}: occurrence frequency (occurrences/number of plots) of focal species in coastal sectors associated to stable-to-low accretion. $\text{Prop}_{\text{high}}$: occurrence frequency (occurrences/number of plots) of focal species in coastal sectors associated to high accretion. Chi-sq.: value of the Chi-sq. statistic. d.f.: degree of freedom. Conf. Int. $\text{Diff}_{\text{prop}}$: 95% confidence interval of the difference in proportions.

EUNIS	Species	$Prop_{low}$	$Prop_{high}$	*Chi-sq.*	*d.f.*	*p-value*	*Conf. Int.* $Diff_{prop}$
Coastal dune scrub (B1.6)	*Juniperus oxycedrus macrocarpa*	0.28	0.37	0.66	1	$p > 0.05$	$-0.3 \leq Diff_{prop} \leq 0.12$
	Pistacia lentiscus	0.5	0.55	0.21	1	$p > 0.05$	$-0.28 \leq Diff_{prop} \leq 0.17$
	Phillyrea angustifolia	0.68	0.61	0.41	1	$p > 0.05$	$-0.14 \leq Diff_{prop} \leq 0.29$
	Lonicera implexa	0.46	0.14	10.29	1	$p = 0.0013$	$0.11 \leq Diff_{prop} \leq 0.53$

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