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Original article

Macrofaunal community abundance and diversity and talitrid orientation as potential indicators of ecological long-term effects of a sand-dune recovery intervention

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ABSTRACT

In the last decades the increasing urban development on coastal areas have produced extensive modifications on shores all over the world, making critical the active management of pressures on sandy beaches. The use of engineering solutions to counteract beach erosion has been significantly increasing; the ecological indicators used to monitor these interventions generally focus on short- and medium-term effects, while little is known on their effectiveness on long-term temporal scales. The following ecological indicators have been tested in the present study: (a) macrofaunal community abundance and diversity and (b) orientation behaviour of *Talitrus saltator*, a talitrid amphipod widespread on Mediterranean and European Atlantic sandy beaches. Two sites were considered on a sandy beach of the Portuguese Atlantic coast, one located in front of a natural dune and the other at about 500 m of distance, where the dune had been rebuilt between 2000 and 2008 using geotextile tubes. In 2011 and 2012, macrofauna sampling and orientation experiments on *T. saltator* were performed at both sites in spring and autumn; contemporaneously the main environmental variables were registered. Macrofaunal data were analysed through multivariate statistical tests, and for the orientation distributions the circular statistics were calculated and multivariate analyses for angular data were performed. Geotextiles appeared to be successful in stabilising the recovered dunes; accordingly, the diversity of the macrofaunal communities and the orientation performances of *T. saltator* showed no differences between the altered and control sites. Significant reductions were nevertheless observed in the artificial-dune site regarding the abundance of *T. saltator* and, to a lesser extent, macrofaunal densities, likely ascribable to the presence of geotextiles instead of a vegetated natural dune, preventing invertebrates to burrow into the sand. These results, complementing a more comprehensive study on these two sites, indicate the abundance of *T. saltator* as the best indicator to follow long-term effects of this kind of soft-engineering intervention. The use of this bioindicator may be recommended for the late phases of monitoring procedures in dune-recovery processes.

1. Introduction

Sandy beaches are among the most important environments for human activities (Schlacher et al., 2008), being intensively exploited especially in the last two centuries (Nordstrom, 2000). In the coming decades about three quarter of the world's population will live within 60 km of the shoreline (Povh, 2000) intensifying human pressures both as direct and indirect impacts. Sandy beaches will be squeezed between rising sea level and coastal erosion on the marine side and expanding human populations and development on the landward side (Schlacher et al., 2008; van der Weide et al., 2001). To slow down this trend, an active management has become necessary for most coastal zones. Currently, managers involved in coastal defence tend to focus on physical and geomorphological features (James, 2000; Micallef and Williams, 2002), despite more and more evidences have been accumulated of ecological change in beach ecosystems due to human interventions (Brown and McLachlan, 2002; Defeo et al., 2009; Dugan et al., 2010; Jones et al., 2007; Schlacher et al., 2007, 2008). Sandy beaches are dynamic habitats, with specialised living communities structured mainly by physical forces (Defeo and McLachlan, 2005; McLachlan and Brown, 2006). A deep knowledge of biotic responses to modifications of the physical environment is therefore a critical step, and the effects of interventions on local communities should be always considered when planning management, conservation, or restoration strategies.

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The use of geosynthetic containers was initiated more than 50 years ago in the USA, The Netherlands and Germany (Saathoff et al., 2007), and has become increasingly popular. Although this intervention impedes the natural morphodynamics of the coast by preventing erosion, so that a static shoreline may develop, geosynthetic containers are considered a soft solution because, if an unforeseen environmental impact ensues, they can easily be sliced open and removed, spilling sand back onto the beach (Corbella and Stretch, 2012). Moreover, the use of geotextile tubes to create artificial dunes reduces costs, time and environmental damage, with the advantage of being adaptable to the morphology of the dune system and using locally available sand (Oumeraci et al., 2003; Stokes et al., 2012). Recent examples of successful application of geotextile tubes come from the coastal zones of USA (Harris and Sample, 2009), Australia (Jackson et al., 2004) and the Republic of Korea (Shin and Oh, 2007), where positive outcomes were obtained in terms of coastal protection. However, very little is known on the effects of dune recovery with geotextiles on biotic communities, if compared to the several studies on the ecological impacts of both beach nourishments (reviewed in Goldberg, 1988; Peterson et al., 2006; Speybroeck et al., 2006) and hard-engineering interventions (Bertasi et al., 2007; Dugan et al., 2008; Martin et al., 2005; Sobocinski, 2003). Negative nourishing effects were observed at the population, community and ecosystem levels on all the biotic components (Bishop et al., 2006; Fanini et al., 2009; Speybroeck et al., 2006). Generally, if the interventions were carefully planned, they may represent short-term, pulse disturbance (Peterson et al., 2006) and a rapid ecological recovery may occur after few months, as sandy-beach species are adapted to severe physical disturbances (Hall, 1994). On the other side, hard-engineering interventions often promote erosion by the development of rip currents (Hsu et al., 2007; Martin et al., 2005; Phillips and Jones, 2005), altering the hydrodynamic regimes of the coastal zone, which in turn drive the composition of benthic macrofaunal assemblages (Defeo and McLachlan, 2005; McLachlan and Brown, 2006). Substantial changes to the system ecology were generally observed after these interventions (Brown and McLachlan, 2002; Chapman and Bulleri, 2003; James, 2000; Speybroeck et al., 2006). Frequently, as eroding beaches tend to become narrower, the reduced habitat disposability directly impacts diversity and abundance of biota in the upper intertidal zone, with consequences at all the trophic levels, thus engendering long-term ecological effects on the whole community (Bertasi et al., 2007; Dugan et al., 2008; Martin et al., 2005; Sobocinski, 2003). To monitor the effects of dune-recovery using geotextiles, managers need effective ecological indicators. Furthermore, being the ecological effects of such interventions relatively unknown, various indicators should be considered to obtain indications fitted to different ecological compartments or functional roles, depending on the impacts to be assessed (Dale and Beyeler, 2001; Niemerijer and de Groot, 2008; Pinto et al., 2009; Salas et al., 2006).

The diversity and the structure of the macrofaunal community are considered representative bioindicators of impacts on sandy beaches (Fanini et al., 2009; Lercari and Defeo, 2003; Peterson et al., 2000; Schoeman et al., 2000). Intertidal invertebrates are at the basis of the food chain (Audisio, 2002; McLachlan and Brown, 2006), thus representing a key-component of the beach ecosystem. Arthropods in particular, well adapted to harsh climatic conditions and involved in the processing of nutrients from both sea and land, have been recognised as reliable bioindicators of ecosystem stability and recommended for use in conservation planning of sandy beaches (Colombini et al., 2003; Finnamore, 1996; Mattoni et al., 2000). However, a relatively little attention was given to the long-term effects of human-induced disturbances on the macrofaunal community structure of beaches (Bessa et al., 2013a; Lercari and Defeo, 2003; Schoeman et al., 2000).

Another potential indicator of shoreline changes is the behaviour of the invertebrates dwelling sandy beaches, which may represent a first response to changes in their life-environment. Almost all beach arthropods display common adaptive behaviours, such as digging attitudes, rhythmic activity patterns, and orientation abilities to quickly recover the safest zone on the littoral (Audisio, 2002; Schlacher et al., 2008). Several behavioural studies were carried out on the sandhopper *Talitrus saltator*, a widespread talitrid amphipod that often dominates (in term of abundance) sandy beach communities at temperate northern latitudes on Mediterranean and Atlantic coasts (Scapini, 2006). One of the most interesting behavioural aspects shown by this and related talitrid species is zonal recovery, namely the ability to come back to the intertidal beach zone after spontaneous or accidental displacements, searching for the right moisture conditions to burrow into avoiding dehydration risk (Pardi and Ercolini, 1986). The correct orientation is ensured by a redundancy of mechanisms, both heritable (sun-compass, beach slope) and learned (landscape features, reviewed by Scapini, 2006); orientation can also be modified according to the immediate climatic and ecological beach characteristics, adapting to an increasing risk of dehydration or submersion. Populations of *T. saltator* exhibit a higher seaward concentration on beaches that are stable in time and result more scattered if changes frequently occur (Borgioli et al., 1999a; ElGtari et al., 2000; Scapini et al., 1995). For this reason talitrid sun orientation was proposed as an indicator of human-impact on shoreline stability (Fanini et al., 2007; Scapini et al., 2005). Since the species' life-span in the Mediterranean area ranges from 6 to 9 months (Marques et al., 2003), orientation is expected to reflect the response to quite recent changes, while little is known about the effects on the populations' orientation over longer periods.

In this paper, the diversity and abundance of the macrofaunal community and the orientation behaviour of *T. saltator* were analysed on a sandy beach, where a dune-recovery intervention was carried out three years before. Two sites were defined, having the same physical conditions, to highlight eventual impacts ascribable to the intervention: (a) a control site, where no relevant alterations have been observed over the last two decades and (b) a site in front of the artificial dune. We aimed to assess which long-term impacts are susceptible of being detected by the selected indicators, assuming that three years represent a reasonably long temporal range in very dynamic and changeable environments such as sandy beaches (Dugan et al., 2008; Martin et al., 2005; McLachlan and Brown, 2006; Sobocinski, 2003). This study represented an extension of two previous studies in the same sites; the first one analysed the macrofaunal community features to detect eventual effects of the dune-recovery intervention (Bessa et al., 2013a), while the second represented a first assessment of behavioural adaptations in *T. Saltator* sub-populations on the same rehabilitated sandy shore (Bessa et al., 2013b). Here the same features were studied in parallel and the two sites were compared, to assess whether and which bioindicator may be proposed for long-term monitoring of dune-recovery with geotextiles.

2. Materials and methods

2.1. The study-site

The Leirosa beach (40° 02′ 57.33″ N, 08° 53′ 35.01″ W) is located to the south of Figueira da Foz, midway along the Portuguese Atlantic coast (Fig. 1a). The beach is mesotidal with semidiurnal tides, and waves frequently reach amplitudes of about 3 m. The well-developed sand dune system is about 10 km long, and protects two cellulose pulp and paper factories located behind it. In 1995 a submarine pipeline was built to discharge the industrial

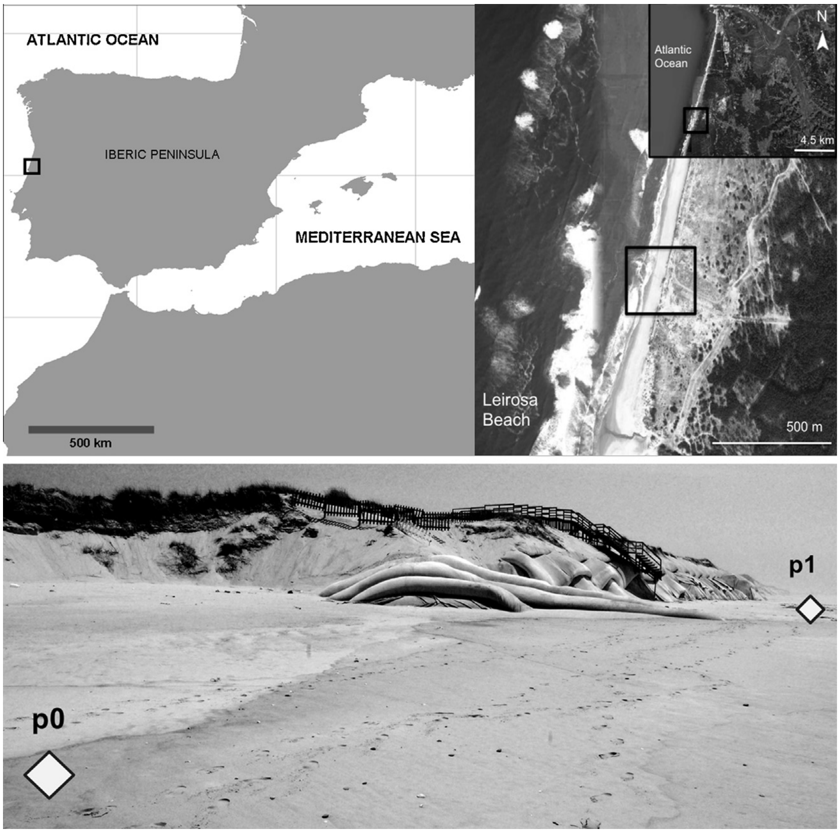

Fig. 1. (a) Study site: location of the Leirosa beach on the Portuguese coast (40° 02′ 57.33″ N, 08° 53′ 35.01″ W); photo credits for the image on the right: Google Earth, Version 6, accessed January 2012, adapted from Bessa et al. (2013b). (b) The experimental sites: p0 = shore in front of the natural dune, p1 = shore in front of the reconstructed dune, where the geotextile tubes are well visible (photo by D.H. Nourisson).

effluents, damaging the continuity of the dune system due to the use of heavy machinery. After this intervention the dune was rebuilt (March 2000), but in the following years a considerable erosion affected the whole coastline south of Figueira da Foz, due to important changes engendered by the various human interventions in the surroundings on the shore sedimentary dynamics (Antunes do Carmo et al., 2010; Duarte and Reis, 1992; Reis et al., 2008). Additional works were thus carried out to rehabilitate the sand dune system, the last of which in 2008, with the installation of geotextile prefabricated tubes filled with locally available sand and water. Although the structure as a whole has endured, strong erosion effects were still visible in Leirosa (Antunes do Carmo et al., 2010) and the tubes today are completely exposed, showing signs of geotextile disruption (Fig. 1b). The two beach points chosen to assess the effects of the reconstruction were called p0 (control site, in front of the natural dune) and p1 (the impacted site, in front of the artificial dune), at about 500 m to the south (Fig. 1c). In 2011 and 2012, sampling of macrofauna and orientation experiments on *T. saltator* was performed at the two sites, in spring and autumn. To characterise the environmental features we registered, during the ebbing tides, beach slope and width, the extension of the intertidal zone, sand temperature, water salinity, wave height and period. During the orientation experiments we also recorded air temperature, air humidity, sky cover (assessed on a conventional scale from 0/8 to 8/8) and solar radiation because of their possible effects on the orientation of *T. saltator*. The sky cover directly influences the solar visibility, thus allowing or preventing the use of the sun compass, while the solar radiation includes also information about climatic conditions, in particular increasing the dehydration risk of amphipods during the tests. The sun azimuth was estimated from the geographical coordinates of the site and the time of the day of each orientation test. The shoreline direction was also registered, from which the TED (Theoretical Escape Directions seawards) for sandhopper orientation was calculated, i.e. the perpendicular to the seashore.

2.2. *Macrofauna sampling*

Macrofaunal communities were sampled during low neap tides, simultaneously at p0 and p1, in May and October 2011 and in June and October 2012. Samples were taken at regular intervals along two shore-normal transects extending from the swash zone around the low tidewater mark to the base of the foredune; ten equidistant sampling levels were considered across each transect. The mean high water neap tide mark was used as a reference point to define the supralittoral and the intertidal zones. Five sampling levels were considered in the supralittoral zone of the beach and five in the intertidal one, adjusting the intervals between levels as necessary through the year. This sampling procedure was able to account for differences in the spatial distribution of macrofauna throughout the year (Gonçalves and Marques, 2011). For each level and each transect, three cores (inner diameter 25 cm, 30 cm deep) were taken. The sand was sieved through 1 mm mesh bags in the swash and the samples were fixed in situ with 5% formalin, to separate and identify the collected animals in the laboratory. To determine sediment characteristics, triplicate sediment cores (2.5 cm diameter, 30 cm deep) were also taken at each sampling level and kept in airtight plastic bags to analyse them in the laboratory. There sand granulometry was determined using the Wentworth scale (Brown and McLachlan, 1990), together with organic matter in the sediment and moisture content, according to the procedures described in Marques et al. (2003) and Gonçalves et al. (2009), using the GRADISTAT 8 software (Blott and Pye, 2001).

2.3. Orientation experiments on *T. saltator*

Orientation experiments were performed simultaneously at p0 and p1, in May and October 2011 and in June and October 2012. Adult amphipods were removed from the sand in the morning of the experiments and were tested in two experimental arenas (40 cm of diameter) having 72 pitfall traps of 5° each at their rim, placed horizontally at one metre height (Scapini et al., 2005). A transparent cylindrical screen covered each arena device and a white cardboard (10 cm height) was applied around it at alternate releases of 10 animals, to have one release with the landscape vision allowed and the following one with only the sky visible. About 80 individuals (4 releases of 10 animals with the landscape view and 4 with screened landscape) were tested in the morning (from 9:00 to 11:00, solar time) and 80 in the afternoon (from 15:00 to 17:00, solar time). After having registered the angles of orientation to the North of the trapped individuals, these were individually stored in alcohol 75% for later observations and measurements. In the laboratory, the sex (males, females and juveniles of a length < 5 mm, having no visible external sex characteristics) and the reproductive status (ovigerous, mature and immature females) were determined for each individual. The cephalic length and counted the number of right antenna articles of each individual as proxies of age were also measured (Marques et al., 2003; Williams, 1983).

2.4. Data analysis

To assess the effects of the artificial dune on the beach features a Principal Component Analysis (PCA) was performed using an Euclidean distance resemblance matrix from normalised data of the following variables: water salinity, beach width and slope, wave height and period, sediment organic matter contents, sediment moisture and temperature. Univariate biotic metrics (total faunal density, species richness, Shannon–Wiener diversity index) and the abundance of most abundant species were compared for p0 and p1 through a series of Permutational Analyses of Variance, PERMANOVA (Anderson et al., 2008), after converting them in Euclidean distance similarity matrices. The design included three fixed factors: (A) site (natural vs. artificial dune), (B) beach zone (supralittoral vs. intertidal) and (C) time (May 2011, October 2011, June 2012, October 2012). Multivariate differences in assemblage structure between p0 and p1 were tested through PERMANOVA tests, with the same three factors design used for the univariate metrics. When interactions between factors resulted significant, pairwise comparisons (Anderson et al., 2008) were also made. The abundance data were fourth-root transformed and converted on a Bray–Curtis resemblance function. Both the global analysis and the pairwise comparisons were based on 9999 permutations. All the statistics on macrofaunal assemblages were made using the software Primer 6 with the Permanova+ add on (http://www.primer-e.com).

Regarding the orientation data of *T. saltator*, the analysis of circular distributions was carried out and the following statistics were calculated: the mean angle, the mean resultant length (r) and the 95% confidence intervals of the mean direction (Fisher, 1993). The Rayleigh test for uniformity was applied to the circular distributions, based on the length of the mean vectors to test the concentration of the individual directions around the mean (Batschelet, 1981). The density curves, smoothed with the kernel method, were estimated and double plotted on Cartesian graphs, to better show the peaks of the distributions. Multiple regression analyses adapted to circular data (SPLM, Spherically Projected Linear Models) were applied, with the angles of orientation as dependent variables and environmental and intrinsic variables as independent ones (Marchetti and Scapini, 2003; Scapini et al., 2002). The best models, having the maximum likelihood with the least number of parameters, were chosen using the AIC (Akaike Information Criterion). The significance of each influencing factor was tested through the Likelihood Ratio Test (LRT), by comparing the best model with the nested ones without the tested variable.

Table 1
The main beach environmental variables, from measures obtained during the macrofaunal communities samplings (2011–2012). Values are indicated as mean ± SE and, when adequate, range (min–max).

Variables	Leirosa beach	
	p0	p1
Beach slope	12.9 ± 1.8 (12.0–13.7)	9.8 ± 0.8 (7.2–12.0)
Beach width (m)	69.8 ± 3.7 (60.0–76.0)	43.8 ± 1.3 (40.0–46.0)
Sediment granulometry (mm)	Medium sand (0.25–0.50)	
Shoreline direction (°)	220 ± 0	
Seawards direction (°)	310 ± 0	
Organic matter – intertidal (%)	35.8 ± 8.5 (29.6–42.1)	
Organic matter – supralittoral (%)	16.8 ± 1.6 (16.7–17.0)	
Sediment moisture – intertidal (%)	12.3 ± 3.6 (8.7–15.9)	
Sediment moisture – supralittoral (%)	1.3 ± 0.6 (0.6–1.9)	
Sediment temperature – intertidal (°C)	14.5 ± 1.3 (12.0–18.0)	
Sediment temperature – supralittoral (°C)	23.8 ± 2.7 (21.0–28.0)	
Water salinity (PSU)	35.5 ± 0.2 (35.0–36.0)	
Wave height (m)	2.2 ± 0.3 (1.0–3.1)	
Wave period (s)	9.3 ± 0.5 (8.0–10.0)	

3. Results

3.1. Environmental features

The mean values of the environmental variables during the macrofauna sampling are given in Table 1. The beach slopes and widths were measured separately at p0 and p1, as the erosion effects were different at the two sites, producing higher slopes and smaller widths in the control site with respect to the reconstructed one. Leirosa beach had medium sand grains, according to the Wentworth scale, and organic contents of about 36% in the intertidal zone and 17% in the supralittoral one. The moisture of the intertidal zone's sediment was about ten times higher than that of the supralittoral one, while the sand temperature was almost ten degrees lower in the intertidal zone with respect to the supralittoral one (Table 1). The data on sand granulometry, wave period and height and intertidal width allow to classify Leirosa as an exposed beach (exposure rate: 15), according to the McLachlan's (1980) rating scheme. The PCA analysis indicated that five factors were responsible for the 95.2% of the total variance observed between p0 and p1, with the first principal component PC1 (accounting for the 39.8% of the variance) mainly influenced by the sediment features (moisture, temperature and organic matter contents) and the second principal component PC2 (18.3%) linked to wave height and water salinity.

During the orientation experiments on *T. saltator* (Table 2), the air temperature ranged from 18.2 °C in October 2012 to 35.5 °C in May 2011, the relative humidity ranged, conversely, from 26.7% in May 2011 to 100% in October 2012, when a storm interrupted the orientation experiments before the end of the experimental

Table 2
Environmental variables registered during the orientation experiments on *T. saltator* in the experimental period (2011–2012). Sky cloudiness percentages are referred to the ratio number of observations under each condition/total of observations. Values are indicated as mean ± SE – range (min–max).

Variables	Leirosa beach
Air temperature (°C)	23.9 ± 0.1 (18.2–35.5)
Air relative humidity (%)	70.6 ± 0.6 (26.7–100.0)
Solar radiation (lx)	74.6 ± 1.2 (10.1–133.4)
Sky cloudiness (% of observations)	0/8 = 48; 1/8 = 23; 2/8 = 2; 4/8 = 10; 5/8 = 6; 6/8 = 11

session. In October 2012 the solar radiation assumed the minimum value observed, of 10.1 lx, while it reached 133.4 lx in June 2012. In half of the observations, there were not clouds in the sky, but a minor percentage of sandhoppers was also tested with a sky cloudiness reaching 6/8 (in the conventional scale from 0 to 8/8) in October 2012.

3.2. Macrofaunal communities

A total of 739 individuals of 8 species were counted in the samples collected for this study. Six species were crustaceans, one was an insect and one was a polychaete. Numerically, crustaceans represented the 99% of all individuals, and among these 65% were amphipods, 30% were isopods and 5% were mysids. The most abundant species was *T. saltator* (42%), followed by *Tylos europaeus* (20%), *Talorchestia brito* (12%), *Haustorius arenarius* (11%) and *Eurydice pulchra* (10%). PERMANOVA tests on the univariate descriptors (Table 2) showed significant differences between the beach zones and the sampling time (month) concerning several univariate metrics, but between the natural and the artificial dune sites only the abundance of *T. saltator* resulted to be significantly different when considering the whole beach (Pseudo $F = 7.63$, P (perm) = 0.007, Table 3, Fig. 2a). Due to the significance of the interaction Site X Zone for both the abundance of *T. saltator* and faunal density (Table 2), pairwise PERMANOVA tests were carried out a posteriori, highlighting that both dependent variables were significantly lower in the supralittoral zone of p0 and p1, which is consistent with the strongest impact of the dune-recovery intervention in the latter sector of the beach (Fig. 2b and c). Other significant differences were found concerning the interaction Site X Time (Table 3), but the pairwise comparisons showed that no regular trends can be inferred, as some descriptors significantly differed between p0 and p1 in only one of the four sampling times, and the pattern was not the same for the whole experimental period.

The PERMANOVA analysis (Table 4) confirmed the differences between the beach zones and the times of the sampling, while between the two sites no significant differences were found. A pairwise test carried out a posteriori on the interaction Site X Time showed that a significant difference in the community of the two sites existed in May 2011 ($t = 1.98$, P (perm) = 0.017, unique perms. = 9968) and October 2011 ($t = 2.94$, P (perm) = 0.002, unique perms. = 9964), but not in the samples of 2012, when the two sites showed more similar communities.

3.3. Orientation experiments on T. saltator

For the orientation experiments a total of 1090 individuals of *T. saltator* were tested, of which 291 in May 2011, 272 in October 2011, 284 in June 2012 and 243 in October 2012. The main population characteristics' summaries for p0 and p1 are reported in Table 5. At both sites the individuals had highest numbers of antennal articles in October 2012, while the cephalon lengths were shortest in June 2012 both at p0 and p1. The sex ratios were generally in favour of males, the immature females were always much more abundant than the mature ones, and the same was observed for the adults with respect to the juveniles. No significant differences appeared between p0 and p1 (antennal articles and cephalon lengths = Wilcoxon rank sum test; frequencies of males, females, mature, immature females, juveniles, adults = Chi-square test P-values > 0.05). In the whole experimental period the seawards direction, representing the theoretical escape direction for the sun orientation of *T. saltator*, was at 310° to the North, in both sites and the observed directions were generally quite adherent to the TED (Table 6). The highest deviations were observed when the individuals were tested with the landscape screened off, when they also showed the lowest concentrations around the mean. The Rayleigh tests indicated that all distributions obtained with visible landscape were highly significant, while the distribution observed in October 2012 at p0 without the landscape cues resulted scattered (Rayleigh test: P-values > 0.05). The circular distributions obtained at p0 and p1 with visible landscape (Fig. 3) showed the main differences between the two sites in October, both 2011 and 2012, while

Table 3
Summary of one-way PERMANOVA comparing univariate descriptors at the natural (p0) and reconstructed site (p1) at each of the two shore zones (supralittoral vs. intertidal) and during four different times (M11 = May 2011, O11 = October 2011, J12 = June 2012 and O12 = October 2012). *df* residual = 64, total = 79. Bold values: significant results.

Source		A: Site (p0 vs. p1)	B: Zone (sup. vs. intert.)	C: Time (M11, O11, J12, O12)	A × B	A × C	B × C
df		1	1	3	1	3	3
Total density (ind. m^{-2})	MS	208.83	948.82	779.04	1564.2	723.17	387.62
	Pseudo *F*	0.78	3.56	**2.93**	**5.87**	**2.72**	1.46
	P (perm)	0.389	0.063	0.040	0.016	0.049	0.241
Species richness (S per sample)	MS	0.01	5.51	13.08	1.01	3.45	2.41
	Pseudo *F*	0.01	**4.30**	**10.21**	0.79	2.69	1.88
	P (perm)	0.918	0.043	<0.001	0.372	0.053	0.138
Species diversity (Shannon-Wiener index)	MS	0.004	1.50	5.94	0.03	0.88	1.60
	Pseudo *F*	0.01	2.01	**7.94**	0.05	1.17	2.13
	P (perm)	0.94	0.161	<0.001	0.830	0.329	0.100
Abundance *T. saltator* (ind. per sample)	MS	5.49	17.60	1.19	2.98	0.55	0.51
	Pseudo *F*	**7.63**	**24.46**	1.65	**4.14**	0.76	0.70
	P (perm)	0.007	<0.001	0.184	0.044	0.526	0.570
Abundance *T. brito* (ind. per sample)	MS	6.05	14.45	14.9	5	1.88	5.02
	Pseudo *F*	1.53	3.65	**3.77**	1.26	0.48	1.27
	P (perm)	0.224	0.052	0.013	0.264	0.712	0.30
Abundance *T. europaeus* (ind. per sample)	MS	14.45	217.8	9.48	16.2	53.68	9.43
	Pseudo *F*	1.24	**18.74**	0.82	1.39	**4.62**	0.81
	P (perm)	0.284	<0.001	0.520	0.261	0.003	0.517

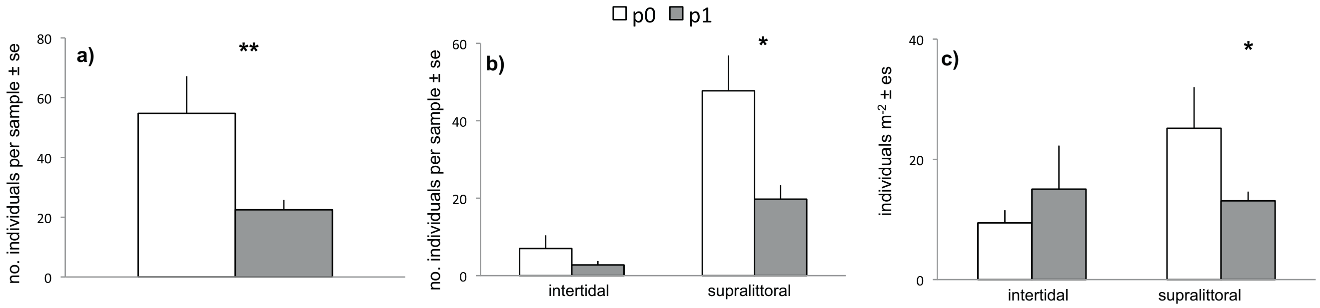

Fig. 2. Differences between sites: (a) total abundance of *Talitrus saltator*; (b) abundance of *T. saltator* in each beach zone; (c) faunal density in each beach zone. Mean values (±SE). Significance values: PERMANOVA tests described in Table 2 and in the text: $^{***}P < 0.001$; $^{**}P < 0.01$; $^{*}P < 0.05$.

Table 4
Summary of three-way PERMANOVA comparing macrofaunal assemblages at the natural (p0) and reconstructed site (p1) in each one of the two beach zones (supralittoral vs. intertidal) and at four different times (M11 = May 2011, O11 = October 2011, J12 = June 2012 and O12 = October 2012). Data fourth-root transformed. Bold values = significant results.

Source	*df*	MS	Pseudo *F*	*P* (perm)	Unique permutations
A: Site (p0 vs. p1)	1	2157.1	2.62	0.06	9957
B: Zone (supralittoral vs. intertidal)	1	21 403	**26.03**	<0.001	9961
C: Time (M11, O11, J12, O12)	3	5310.1	**6.46**	<0.001	9935
A × B	1	1008.0	1.23	0.322	9969
A × C	3	1606.8	**1.95**	0.050	9932
B × C	3	1621.6	**1.97**	0.047	9946
Residual	64	822.3			
Total	79				

Table 5
T. saltator population variables for each experimental session, relative to the samples used in the orientation experiments at p0 and p1.

Month		p0	p1
May 2011	Antennal articles – mean ± SE	22.7 ± 0.5	20.5 ± 0.5
	Range (min–max)	(10–38)	(6–35)
	Cephalon length (mm) – mean ± SE	1.13 ± 0.03	1.24 ± 0.04
	Range (min–max)	(0.37–2.05)	(0.44–2.11)
	Sex ratio m/f	49/94 = 0.20	12/109 = 0.11
	Fem mat/immat	22/76	3/106
	Juveniles/adults	0/143	27/121
October 2011	Antennal articles – mean ± SE	22.26 ± 0.37	20.60 ± 4.33
	Range (min–max)	(11–38)	(11–38)
	Cephalon length (mm) – mean ± SE	1.28 ± 0.02	1.18 ± 0.03
	Range (min–max)	(0.56–2.11)	(0.67–2.44)
	Sex ratio m/f	46/107 = 0.43	41/76 = 0.54
	Fem mat/immat	2/105	3/73
	Juveniles/adults	2/153	0/117
June 2012	Antennal articles – mean ± SE	21.01 ± 0.42	21.81 ± 0.49
	Range (min–max)	(12–33)	(14–35)
	Cephalon length (mm) – mean ± SE	0.93 ± 0.02	0.95 ± 0.03
	Range (min–max)	(0.52–1.48)	(0.44–1.68)
	Sex ratio m/f	55/87 = 0.63	69/66 = 1.05
	Fem mat/immat	9/78	4/62
	Juveniles/adults	4/142	2/135
October 2012	Antennal articles – mean ± SE	25.98 ± 0.39	25.62 ± 0.44
	Range (min–max)	(15–36)	(16–40)
	Cephalon length (mm) – mean ± SE	1.26 ± 0.02	1.21 ± 0.02
	Range (min–max)	(0.61–2.00)	(0.72–1.89)
	Sex ratio m/f	65/62 = 1.05	54/63 = 0.86
	Fem mat/immat	0/61	0/63
	Juveniles/adults	0/126	0/117

in May 2011 and June 2012 the experimental results at the two sites were very similar. On the other side, when tested without landscape (Fig. 4) sandhoppers were orientated in a similar direction in October 2011 and June 2012, when they were quite well seawards directed, while in May 2011 and October 2012 differences were observed between the two sites, with mean vectors directed longshore or dune-wards. The SPLM analyses highlighted the effects on the orientation distributions of the following variables and factors: site (p0, p1), year (2011, 2012), month (May, June, October), season (spring, autumn), tide (ebbing, rising), landscape visibility (visible, not visible), time of the day, sun azimuth, cloudiness (from 0/8 to 8/8), global insulation, air temperature, air humidity, sex and reproductive status, number of antennal articles and cephalon length of the individuals. Starting from a simple additive model, we also developed alternative models including interactions of the most significant factors with all the other parameters. The best model chosen according to the AIC, showed a significant interaction of the landscape with the other factors, as follows:

Orientation ~ landscape visibility*** (month*** + sun azimuth*** + solar time*** + cloudiness***) + air humidity** + air temperature* + tide

(Likelihood = 3465.6524, AIC = 3525.6524, degrees of freedom = 1060; $^{*}p < 0.05$; $^{**}p < 0.01$; $^{***}p < 0.001$).

Factors without $^{*}(p > 0.05)$, although not significant, were retained as they improved the AIC of the model; the factors not included in the interaction acted in the same way on the orientation behaviour independently from the landscape visibility.

4. Discussion

In our study, the geomorphological measurements seem to confirm that the intervention lowered the effects of the sea erosion, as in the reconstructed site p1 the beach was flatter than in the control site, p0 (Table 1). Nevertheless, a specific morphodynamic study should be required (Mendonça et al., 2012), to assess the erosive rates at both the sites, in order to exactly evaluate whether the observed differences are ascribable to the dune-recovery

Table 6

Summary circular statistics for the orientation experiments on *T. saltator* at the two sites (p0 = natural dune, p1 = artificial dune) for the period of the study (2011–2012). TED = theoretical escape direction, perpendicular to the shoreline direction. TED and observed directions: degrees (°) to the North. SE: confidence interval for the mean direction, $\alpha = 0.05$.

	Landscape		Site	
			p0	p1
May 2011	Visible	TED (°)	310	310
		Observed direction ± SE (°)	289.80 ± 16.01	296.40 ± 13.34
		Mean vector length (r)	0.53	0.60
		Sample size (N)	71	71
		Rayleigh test for randomness	$p < 0.001$	$p < 0.001$
	Not visible	TED (°)	310	310
		Observed direction ± SE (°)	57.85 ± 46.06	80.52 ± 43.73
		Mean vector length (r)	0.21	0.22
		Sample size (N)	72	77
		Rayleigh test for randomness	$p < 0.001$	$p < 0.001$
October 2011	Visible	TED (°)	310	310
		Observed direction ± SE (°)	297.00 ± 18.48	328.80 ± 15.68
		Mean vector length (r)	0.47	0.57
		Sample size (N)	73	60
		Rayleigh test for randomness	$p < 0.001$	$p < 0.001$
	Not visible	TED (°)	310	310
		Observed direction ± SE (°)	334.20 ± 32.01	334.80 ± 17.01
		Mean vector length (r)	0.28	0.51
		Sample size (N)	82	57
		Rayleigh test for randomness	$p < 0.001$	$p < 0.001$
June 2012	Visible	TED (°)	310	310
		Observed direction ± SE (°)	282.60 ± 12.43	277.20 ± 15.77
		Mean vector length (r)	0.62	0.57
		Sample size (N)	73	70
		Rayleigh test for randomness	$p < 0.001$	$p < 0.001$
	Not visible	TED (°)	310	310
		Observed direction ± SE (°)	309.60 ± 29.71	301.30 ± 21.81
		Mean vector length (r)	0.31	0.37
		Sample size (N)	73	68
		Rayleigh test for randomness	$p < 0.01$	$p < 0.001$
October 2012	Visible	TED (°)	310	310
		Observed direction ± SE (°)	275.70 ± 21.86	243.40 ± 17.30
		Mean vector length (r)	0.43	0.58
		Sample size (N)	66	58
		Rayleigh test for randomness	$p < 0.001$	$p < 0.001$
	Not visible	TED (°)	310	310
		Observed direction ± SE (°)	124.10 ± undet.	177.50 ± 23.97
		Mean vector length (r)	0.07	0.41
		Sample size (N)	60	59
		Rayleigh test for randomness	n.s.	$p < 0.001$

intervention. In other words, p1 became a more dissipative beach with respect to p0 that showed a more reflective typology (McLachlan and Brown, 2006). This change is likely to have engendered variations also in the biotic assemblage structure that is driven mainly by physical forces. However, the macrofaunal community showed a quite undiversified species composition, as it is the rule for exposed mesotidal beaches (Brazeiro, 2001; Defeo and McLachlan, 2005); crustaceans were the most abundant, and *T. saltator* represented the dominant species during the whole experimental period. Looking at the univariate macrofaunal descriptors, only the abundance of *T. saltator* showed a significant reduction from the natural-dune site to the reconstructed one considering the whole shore-normal transects (Table 3, Fig. 2a). This result is in accordance with the findings obtained by Bessa et al. (2013a) on this same beach in 2010–2011, and with those by Fanini et al. (2007) on an Italian microtidal beach, indicating that this effect is substantial enough to make the *T. saltator* abundance a reliable long-term impact indicator. Indeed, the difference between the control and the artificial-dune sites resulted to be concentrated in the supralittoral sector (Fig. 2b), where also the faunal density was smaller at p1 with respect to p0 (Fig. 2c). This is likely ascribable to the geotextiles emergence, as most of the coverage sand was removed by the sea and wind that left a sandy layer too thin for animals burrowing into. It is noteworthy that, on the contrary, faunal density was higher, though not significantly, in the intertidal zone of the artificial dune site compared to the control one (Fig. 2c). The conditions at p1 after the soft-engineering intervention seem to favour in some way the intertidal species, which is an opposite finding with respect to what was observed for the hard-engineering solutions (Bertasi et al., 2007; Dugan et al., 2008; Martin et al., 2005; Sobocinski, 2003). Such differences between the two main beach zones are in agreement with the results of the PCA, indicating that the most influencing environmental variables were those linked to the sediment features that distinguish the intertidal beach zone from the supralittoral one (Table 1).

At the assemblage level no separation was produced between the samples from p0 and p1. In fact, the pairwise PERMANOVA tests on the interaction Site X Time highlighted that the composition at the two sites was different in May 2011 and October 2011, but not in the following year (2012). It is possible that the effects of the dune reconstruction were still visible in 2011 and had totally vanished in 2012, but this explanation is speculative, as seasonal/random variations may also explain these differences.

Concerning the orientation performances of *T. saltator*, the amphipods were tested under various environmental conditions (Table 2) and in different life-stages, including juveniles, males,

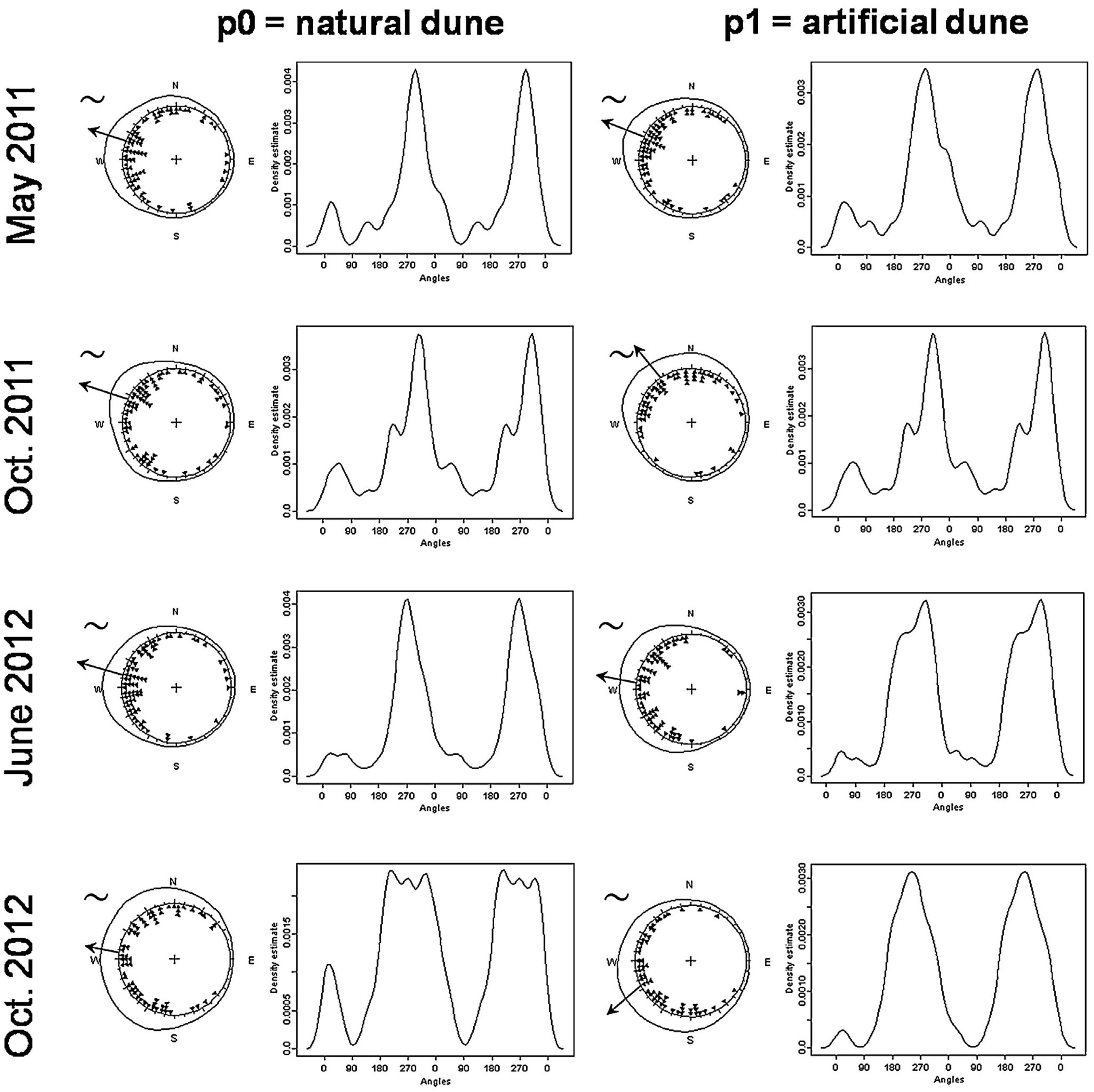

Fig. 3. Angular distributions obtained in the sun orientation experiments on *T. saltator* carried out with visible landscape. On the left: circular plots of the orientation angles. On the right: density estimates (kernel method) double plotted on Cartesian graphs. Black waves: sea direction, corresponding to the Theoretical Escape Direction (TED) for seawards orientation. Arrows: mean vectors for each distribution, with the lengths proportional to the concentration (r, mean vector length that may vary from 0 to 1). Summaries of circular statistics for each distribution are reported in Table 6.

mature and immature females according to the expected population frequencies for these latitudes (Marques et al., 2003). The main factor affecting the orientation performances resulted to be the landscape visibility (Figs. 3 and 4, Table 6), which interacted with the other variables. This result was expected on this beach that had a well-developed dune system and is in agreement with previous findings on Mediterranean coasts (Borgioli et al., 1999b; Scapini, 2006) and on the same Leirosa beach (Bessa et al., 2013b), confirming that populations from beaches with a prominent dune rely mainly on landscape visual cues, in contrast to populations from flat beaches, which use preferentially the sun compass (Hartwick, 1976; Scapini et al., 1992). Other highly significant factors on orientation were those involved in the use of the sun compass (sun azimuth, solar time, sky cloudiness) that played its role mainly when the landscape was not visible, and the time (month) of the experiments. This result highlights a close relation between the amphipods' behaviour and the immediate climatic conditions (Nardi et al., 2003; Scapini et al., 2005), and is confirmed by the significance of air humidity and temperature and the tidal phase. The site was not included in the model, which actually is not surprising, as behaviour represents the immediate response of animals to changes in their life-environment. Thus, orientation may be an excellent early warning indicator, but it is not suitable to highlight long-term effects. On the other hand, if the dune recovery at p1 had not stabilised the beach morphodynamics, some effects on the behaviour of *T. saltator* should be still visible; hence the lack of

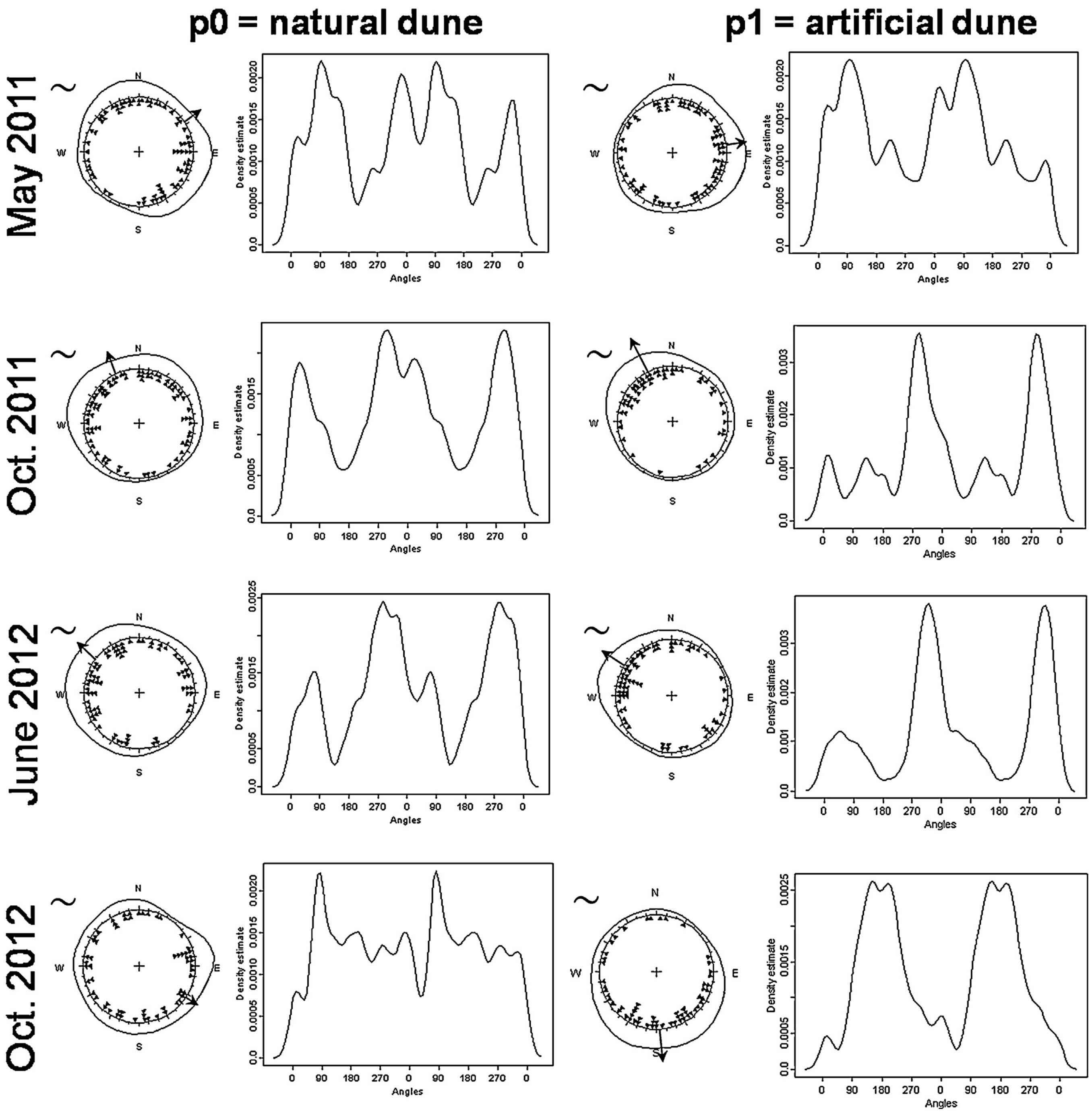

Fig. 4. Angular distributions obtained in the sun orientation experiments on *T. saltator* carried out with screened landscape. The meaning of graphs and symbols is the same as in Fig. 4; summaries of circular statistics for each distribution are reported in Table 6.

differences can be considered as a proof of the effectiveness of the recovery in terms of shoreline stability.

5. Conclusions

This study showed that the use of geosynthetic containers in coastal defence, even though less impacting than building seawalls or groynes, has some long-term effects making these interventions not fully comparable to soft-engineering procedures, generating short-term pulse disturbance (Leewis et al., 2012; Peterson et al., 2006). In this case, the main issue seems to have been the partial removal of the sandy coverage after the dune-recovery, preventing the beach animals to burrow into the sand. This phenomenon is not uncommon, and mathematical models used in planning interventions may fail in forecasting the evolution of erosive processes, particularly when these are produced by several factors acting at the same time (Jetten et al., 2003; Thieler et al., 2000). Two main aspects were highlighted by this study; firstly, the importance of designing long-term monitoring studies when planning interventions on beaches, especially regarding the impacts of relatively recently introduced methodologies (as it is the case for the geotextile containers), which can modify the ecosystem features in unforeseen directions. Environmental restoration has to be planned with a long-term vision, but current practices tend to concentrate on immediate socio-economic benefits and rarely consider the future developments of the impacted ecosystems (McLachlan et al., 2013; Phillips and Jones, 2005). Secondly, there is a need to combine different ecological indicators in order to include the maximum number of possible effects on the biotic ecosystem components, choosing specific sets of indicators for the different phases of the monitoring procedure (Osenberg and Schmitt, 1996). The macrofaunal community analysis and the orientation behaviour of *T. saltator*, proven effective bioindicators to monitor the immediate, short and medium-term impacts of human interventions on sandy beaches, have proven to be unsuitable on longer temporal scales. However *T. saltator*, a key-species of beach ecosystems, showed a long-term effect in a reduced population abundance that therefore may be considered for the later phases of monitoring plans. The total faunal density resulted a less powerful bioindicator in detecting the impacts at the whole beach scale; however, a significant difference was shown for the supralittoral zone, the most impacted beach sector. To conclude, there is a need of a major integration between ecologists and engineers (Chapman and Underwood, 2011); both the categories have to engage to fulfil gaps in what is known on coastal defence intervention effects, aiming at reducing impacts as much as possible and reach equilibrium between the immediate socio-economical needs and environmental sustainability.

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