Light traps as an exploratory tool in light pollution studies: Assessment of vulnerable species and their migratory patterns

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ABSTRACT

Artificial Light at Night (ALAN) is one of the most widespread stressors on coastal marine habitats. Despite their sparse use in light pollution studies, light traps are a useful methodology to explore which species are attracted by ALAN. For that purpose, we placed light traps during the day and at night in the shallow subtidal adjacent to three natural sandy shores. Additionally, to determine the origin of the catches, the sediment and the water column were also sampled in both periods by a Van Veen grab and a plankton net, respectively. Our results showed that light traps catches at night were dominated by migrant fauna, mostly amphipod crustaceans emerging from the sediment. Other species that perform diel vertical migrations, such as calanoid copepods, were also attracted. This approach may help to understand which taxa are more susceptible to ALAN in these shallow habitats.

1. Introduction

Light traps are a common sampling method in marine studies since their great variety of designs and light sources allow its application to different purposes (McLeod and Costello, 2017). The explanation behind its efficiency is that artificial light at night (ALAN) serves as an exaggerated version of the moonlight stimulus, which is a main factor driving the biological rhythms (such as migration behaviours) in several aquatic organisms (Tessmar-Raible et al., 2011 and references therein). Many of these organisms live in deep waters during the day and then ascend to surface waters at night. This pattern of vertical movement is also reported in shallow habitats, involving bottom or near-bottom specimens rising in the water column during nighttime (Tranter et al., 1981; Moore et al., 2000). This is a widespread process called "Diel Vertical Migration" (DVM) and the adaptive significance of this behaviour has been investigated for decades. One of the most accepted hypotheses is the reduction in predation pressure by visual predators (e.g. planktivorous fishes) at night (Bandara et al., 2021 and references therein). Conversely, some smaller invertebrates are often preyed by nocturnal large invertebrates instead of fishes, so they conduct a reverse DVM by

descending at night (Ohman et al., 1983; Bandara et al., 2021). Both behaviours contribute to the dynamism of the community present in the water column at night and whose main modulator is the light, among others. Consequently, ALAN could alter these vertical movements (Berge et al., 2020). For these reasons, light traps are not only an efficient sampling method, but also may reveal which species apparently modify their DVM in response to ALAN.

The use of light traps has been previously proposed to field studies about light pollution (Tidau et al., 2021). This approach could be particularly interesting in marine shallow habitats where a part of the vertical migrating organisms comes from the bottom (Sponaugle et al., 2021). In this sense, Porter (1974) observed that most of zooplankton in a Caribbean reef at night came from the reef itself. Based on these observations, this author defined "demersal zooplankton" as the organisms living in the reef by day and migrating to the water column at night. However, the term "demersal" was originally established for those fishes that feed on the bottom (Bergstad, 2009), so it seems that this concept has been extrapolated to the vertical migrating part of the plankton since it comes from the bottom. On the other hand, according to the traditional distinction between benthos and plankton, establishing a clear

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limit it is overly complicated in shallow ecosystems (Emery, 1968; Kopp et al., 2015). The term "epibenthic" is more accurate to describe those species living over the substrate (Heidelberg et al., 2004) but it seems logical that these migrating organisms have been traditionally covered as "plankton" since the three-dimensional structure of the reef or another rocky substrate keeps them in the water column (Ohlhorst, 1982; Jacoby and Greenwood, 1988; Heidelberg et al., 2004; Yahel et al., 2005a; Nakajima et al., 2009; Smith et al., 2016; Peel et al., 2019; Tanaka et al., 2020). However, many organisms of coastal soft bottoms (e.g. amphipods, cumaceans or isopods) live on or buried in sediment during daytime and they just ascend to water column at night. Despite this fact, the term "plankton" has remained for these organisms associated with soft bottom (e.g. Stretch, 1985; Yahel et al., 2005b; Melo et al., 2010). For these reasons, some authors have preferred to name these organisms as emergent fauna or emergent benthic taxa (Kramer et al., 2013; Navarro-Barranco and Hughes, 2015; Santos et al., 2019), but it should be noticed that many of these organisms ascend from the surface of the sediment and they do not emerge from the sediment itself (e.g. mysids or some families of harpacticoid copepods). Therefore, they may be considered vertical migrants instead of emergent fauna.

Although emergent fauna has been typically studied through emergence and sediment traps (McLeod and Costello, 2017), these approaches could entail clear disadvantages for the study of other vertical migrants. Common emergence traps are based on an inverted cone open at the base (Alldredge and King, 1980), which prevents the influx of other vertical migrants of the water column. In addition, potential migrants located just over the sediment could be repelled during the deployment of the trap. Thus, even if the design includes a light source (e.g. Melo et al., 2010), the potential attraction effect would be limited to the covered area, which is very useful to study emergent fauna but no other vertical migrants. In this context, light traps may offer two clear advantages: 1) they can catch emergent fauna as well as other vertical migrants, especially in shallow waters (Sponaugle et al., 2021) and 2) their attraction could be considered as an exploratory approach of ALAN effects (Navarro-Barranco and Hughes, 2015).

In this sense, the present study deals with the use of light traps to identify the species potentially attracted by ALAN. Most of the previous studies addressing these migratory patterns are limited in terms of spatial and temporal replication, not allowing to elucidate life history strategies of such migrants according to their migratory movements (e.g. infauna emerging from the sediment, other vertical migrants ascending in the water column) and exploring their abundance changes along the day/night cycle (Heidelberg et al., 2004; Tanaka et al., 2020; Sponaugle et al., 2021). Moreover, these works are not conducted at species level of identification, assuming similar ecology among the species in each higher taxon. Thus, integrative studies encompassing the whole macrofaunal community (identified to species level) and including different sampling methodologies (plankton nets, Van Veen grabs and light traps) and periods (day and night) could clarify the actual migratory pattern of each species in order to explore those life history strategies more likely to be affected by ALAN. This approach may be very helpful in the framework of the marine light pollution since the 22.2% of the world's coastline was exposed to ALAN in the past decade (Davies et al., 2014). In fact, recent research has elaborated a global atlas of underwater ALAN and it revealed that almost 1.6 million km^2 of coastal shallow waters at 1m depth are affected (Smyth et al., 2021). Furthermore, these impacts are expected to increase due to the current demographic growth and the consequent degradation of marine habitats in coastal areas (Haq, 1997; Airoldi and Beck, 2007; Luijendijk et al., 2018). Henceforth, understanding the ecological effects of ALAN in these enlightened coasts has become increasingly necessary.

For all these reasons, the aims of the present study were: i) to characterise the diel vertical migratory patterns of the macroinvertebrate communities present in shallow sandy bottoms, comparing the fauna caught by light traps with the fauna inhabiting sediments and water column, ii) to highlight which taxa are caught by the light traps (and which life strategies these taxa correspond to), and therefore, highly vulnerable to light disturbances.

2. Material & methods

2.1. Sampling processing and data collection

This study was carried out during December 2021 and February 2022 (Northern Hemisphere winter) in the south coast of Spain. In order to assess the potential effect of ALAN in non-enlightened beaches, three different stations were chosen in the Natural Park of Maro-Cerro Gordo (Málaga and Granada, Spain), located on the coast of Alboran Sea: Caleta de Maro (36°45′14.5″N 3°50′04.9″W), El Cañuelo (36°44′39.3″N 3°47′18.4″W) and Cantarriján (36°44′12.4″N 3°46′32.1″W) (Fig. 1). This place was designated as Marine Protected Area (MPA) under IUCN category II (Ornat and Reines, 2007). At each station, four replicates of light traps were placed during day and four at the following night (3–4 m of approximate depth), just before the sunset (18:30 h) and they were removed 3 h later. Light traps, as detailed in Navarro-Barranco et al. (2020), use a glow stick as a light source, which offers a low failure rate and 360° of light (McLeod and Costello, 2017). Despite the low light intensity of the glow stick, even these low values could potentially disturb ecosystems at population or community level (Sanders et al., 2020) and it could also cause a greater attraction effect than higher intensities (Forward, 1988). Sediment and water column samples were collected simultaneously with the removal of the light traps, both during each period, in order to characterise the migratory patterns of the species and determine the source of the species collected by the light traps. Four sediment replicates were collected at each period (i.e. day/night) from the soft bottom (near light traps) using a Van Veen grab (15 × 15 cm). Due to the relatively small size of the grab, each sediment replicate consisted of two additive samples (total area: 450 cm^2) (Guerra-García et al., 2021; Saenz-Arias et al., 2022). Similarly, a plankton net (mouth diameter = 40 cm; mesh sieve = 250 μm) was deployed from a kayak, and four water column replicates were collected during each period at intervals of 3 min, approximately at 20–30 m from the coast. The net was equipped with a Mechanical Flow Meter Model 438 110 at the centre of the mouth to estimate the volume of water filtered per tow. Due to the influence of the moonlight on the dynamics of vertical
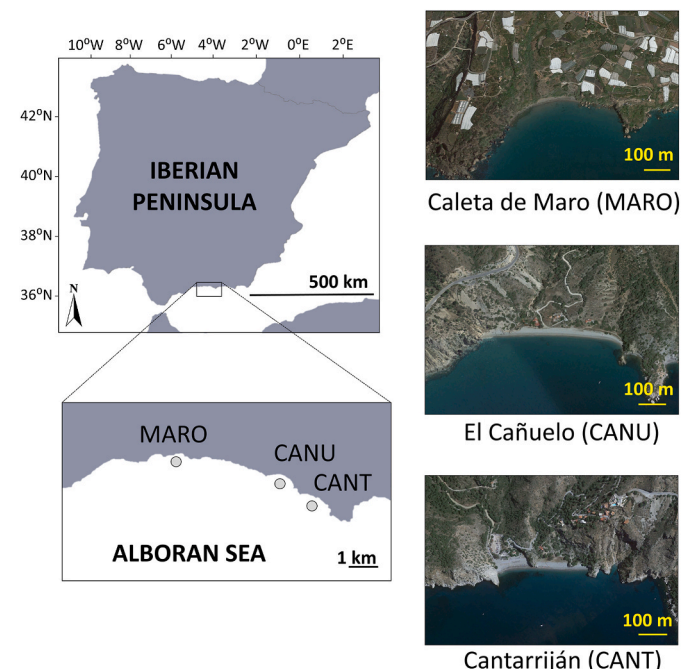

Fig. 1. Map of the study area and sampled locations.

migration (Alldredge & King, 1980, 2009; Jacoby and Greenwood, 1988; Anokhina, 2006; Last et al., 2016), sampling dates were selected when moon visibility was equal or less than 5%. Replicates collected by those three methodologies were washed through a 500 μm mesh and preserved in 96% ethanol (stained with Rose Bengal for sediment replicates). Abundance of certain groups such as gelatinous plankton could be underestimated because of the use of ethanol. However, a single fixative had to be used for all samples to allow proper comparisons among methodologies, and ethanol has been previously used in similar studies (e.g. Sponaugle et al., 2021). The selection of the aforementioned mesh size was made because most of emergent and vertical migrant fauna are usually macrofaunal organisms, i.e. peracarid crustaceans or polychaetes (Jacoby and Greenwood, 1988; Santos et al., 2019), and this has been previously considered in a similar study on emergent fauna (Yahel et al., 2005a).

Five replicates of night-sky brightness (mag/arcsec^2) were measured *in situ* in each beach through a Sky Quality Meter-L at night. The values of the Sky Quality Meter-L follow a logarithmic scale, therefore the readings are usually between 16 and 21: values close to 16 indicate astronomical light pollution (stars washed out by artificial light) or a full moon night while values close to 21 indicate a clear sky with many visible stars. Finally, three replicates of sediment were also taken in order to determine the granulometric composition. Grain size distribution was measured as percentages of 100 g of dry sediment graded through a sieve net (5 mm, 2 mm, 1 mm, 0.5 mm, 0.250 mm, 0.125 mm, 0.063 mm) (Guitian and Carballas, 1976).

In the laboratory, the macroinvertebrate taxa were sorted and identified to the lowest taxonomical level possible. Abundance was expressed as individuals/m^2 for the sediment replicates, individuals/m^3 for the water column replicates and individuals/replicate for the light traps. Species names follow the criteria of the World Register of Marine Species (WoRMS, 2023).

2.2. Statistical analyses

For each methodology (Van Veen grab, plankton net and light trap), a two-way ANOVA was carried out to test differences in abundance of macroinvertebrates (N), number of taxa (S), Shannon-Wiener's diversity (H′) and Pielou's evenness (J). Two factors were considered in the statistical design: 'Period' [Pe], a fixed factor with two levels (Day *vs* Night) and 'Station' (St), a random factor with three levels (Caleta de Maro, El Cañuelo and Cantarriján) and orthogonal to [Pe]. The third factor named 'Methodology' (Van Veen grab, plankton net and light trap) was not included in the univariate analysis since the units of measure for the three methodologies were different, preventing an improper comparison in the univariate approach. Prior to ANOVA, the homogeneity of variances was tested using Cochran's test and transformation was applied when it was significant. If the heterogeneity of variances persisted after the transformation, untransformed data were analysed, and the level of significance was reduced (P < 0.01) in order to reduce type I error. Because ANOVA is a robust test for even non-parametric data in balanced experiments, normality was not checked (Underwood et al., 2002). Following the same procedure, differences between night-sky brightness of the three beaches were analysed by a one-way ANOVA based only on the factor 'Station'. When ANOVA indicated a significant difference for a given factor or interaction of factors, the Student-Newman-Keuls test (SNK) was applied to identify the source of differences. Univariate analyses were conducted with GMAV-5 (Underwood et al., 2002; Schmider et al., 2010).

For multivariate analyses, the statistical design included three factors: the two mentioned above (i.e. Period and Station) and 'Methodology' [Me], a fixed factor with three levels (Van Veen grab, plankton net and light trap) and orthogonal to the other factors. Due to differences in the units of measure for the three methodologies, total abundance per replicate was converted to relative abundance of 100%. In order to test for differences in the community, a permutational multivariate analysis of variance (PERMANOVA) was conducted. PERMANOVA was based on the Bray-Curtis similarity matrix using non-transformed data. A dummy variable (value = 1) was applied due to absence of data in some daytime light traps. (Clarke et al., 2006). When there were not enough permutations to get an appropriate test, Monte Carlo P values were calculated and they were considered to evaluate the significance instead of pseudo-F values (Anderson et al., 2008). Significant factors were examined through pair-wise tests. In order to explore the response of the different higher taxa assemblages to the considered factors, separate non-parametric multidimensional scaling ordination (nMDS) based on the same Bray-Curtis similarity matrix were conducted. Furthermore, the Similarity Percentages procedure (SIMPER) based on non-transformed data was conducted to identify the species that contributed the most to the similarity and dissimilarity among the levels of Methodology and its interaction with Period. Multivariate analyses were conducted with PRIMER v6 + PERMANOVA (Clarke and Gorley, 2001; Anderson et al., 2008).

Additionally, a qualitative category was assigned to each species based on their movement pattern, according to the results of the present study. Species present in the sediment that emerge to the water column at night were considered as emergent migrants (EME); those with greater abundance in the water column in either of the two periods as other vertical migrants (OTH), while ones with a similar abundance between both periods as planktonic (PLA); those that were found just in the bottom, regardless of the period, were considered residents in the sediment (SED). Due these categories were stablished only with our results, rare species (less than 10 individuals in the whole study), accidental catches, and others that did not offer enough information about their movement patterns were unassigned (*).

3. Results

3.1. Beaches features

The values of night-sky brightness indicated that the three beaches have clean skies; however, ANOVA showed that there were significant differences among them (*F* = 17.77; *P* = 0.0003). Specifically, Caleta de Maro has significant higher values of night-sky brightness (i.e. lower light pollution) than the other beaches. Regarding granulometric composition, Cantarriján has a higher percentage of coarse and very coarse sand and gravels than Caleta de Maro and El Cañuelo, whose sediment was mainly composed of fine sand (Fig. S1).

3.2. Macroinvertebrate community among methodologies

A total of 18 643 individuals belonging to 191 different taxa were collected in the present study (Table 1; Table S1). These taxa were represented by the following groups: crustaceans (97 species, accounting for 53% of the total abundance (TA)), polychaetes (67 species, 18% TA), molluscs (18 species, 2% TA), echinoderms (4 species, >1% TA), tunicates (3 species, 25% TA), chaetognaths (1 species, 2% TA) and cnidarians (1 species, >1% TA). Regarding their life history strategies, the most common category consisted of species residing in the sediment (33 species, 17% of the total species (TS)), followed by planktonic species (25 species, 13% TS), other vertical migrants (18 species, 9% TS) and emergent migrants (11 species, 6% TS). The remaining species were unassigned (104 species, 55% TS) due to the lack of information. With respect to the capture methods, 7 species were exclusively found in light traps, 51 in the plankton net and 84 in the Van Veen grab. Additionally, 49 species were collected by all three of these methods that were used. The most abundant species for each methodology were: the polychaetes *Sphaerosyllis bulbosa* Southern, 1914, *Parapionosyllis elegans* (Pierantoni, 1903) and *Sphaerosyllis taylori* Perkins, 1981 in the sediment (Van Veen grab); the tunicate *Oikopleura* spp., the copepods *Acartia (Acartiura) clausi* Giesbrecht, 1889 and *Clausocalanus furcatus* (Brady, 1883) in the water column (plankton net); the amphipods *Bathyporeia guilliamsoniana*

Table 1

Top ten of the most abundant species among the three methodologies according to their relative abundance (%). Relative abundance was estimated for each methodology and period. White: absence; Light blue: >0–5% of relative abundance; medium blue: >5–25%; dark blue: >25–40%. Total abundance (number of individuals) of these taxa in the whole study is provided in the last column. The complete list of taxa is in Table S1. VAN = Van Veen grab; NET = plankton net; TRA = light trap; D = day; N = night.

	VAN		NET		TRA		Total
	D	N	D	N	D	N	
Phylum Annelida							
Parapionosyllis elegans (Pierantoni, 1903)							1494
Sphaerosyllis bulbosa Southern, 1914							644
Phylum Arthropoda							
Acartia (Acartiura) clausi Giesbrecht, 1889							3285
Apherusa sp.							111
Bathyporeia guilliamsoniana (Spence Bate, 1857)							385
Clausocalanus furcatus (Brady, 1883)							2207
Pectenogammarus cf. *nudus* (Stock, 1971)							5
Pontocrates arenarius (Spence Bate, 1858)							85
Phylum Chordata							
Oikopleura spp.							4833
Phylum Mollusca							
Macomangulus tenuis (da Costa, 1778)							100

(Spence Bate, 1857), *Pontocrates arenarius* (Spence Bate, 1858) and *Apherusa* sp. in the light traps. 30 species were found exclusively during the day, 51 at night and 110 in both periods.

According to PERMANOVA and ANOVAs, different day/night patterns were determined after the considered methodologies. There were significant differences in abundance, number of taxa (higher values at night) and community structure among light traps deployed by night and day (Table 2; Table 3; Fig. 2; Table S2). Conversely, sediment samples collected at night and day were similar in most of the cases, both considering abundance, number of taxa and community structure. Finally, day/night changes in the abundance and community structure of the water column were largely dependent on the station considered, for example, significant differences were observed at Cantarriján for both variables, but no daily changes were found at El Cañuelo, neither considering community structure nor abundance values. However, regarding the number of taxa present in the water column, it was higher at night, regardless the station. Diversity and evenness did not show a clear pattern between day and night (Table S3; Table S4). On the other hand, pair-wise tests for the significant triple interaction (PexStxMe) showed by PERMANOVA also evidenced significant changes for all pairs of levels of Methodology, both at night and day periods.

The nMDS for the whole community showed two groups according to the methodology: one formed by the sediment and part of the light traps and other by the water column and the rest of the light traps, regardless the period or the station (Fig. 3). A similar pattern was observed for the crustacean assemblage, which is the dominant group in terms of number of species and individuals. Aside of being collected almost exclusively on the water column, no clear pattern was obtained for chaetognaths and tunicates. On the other hand, echinoderms (and also molluscs) were only
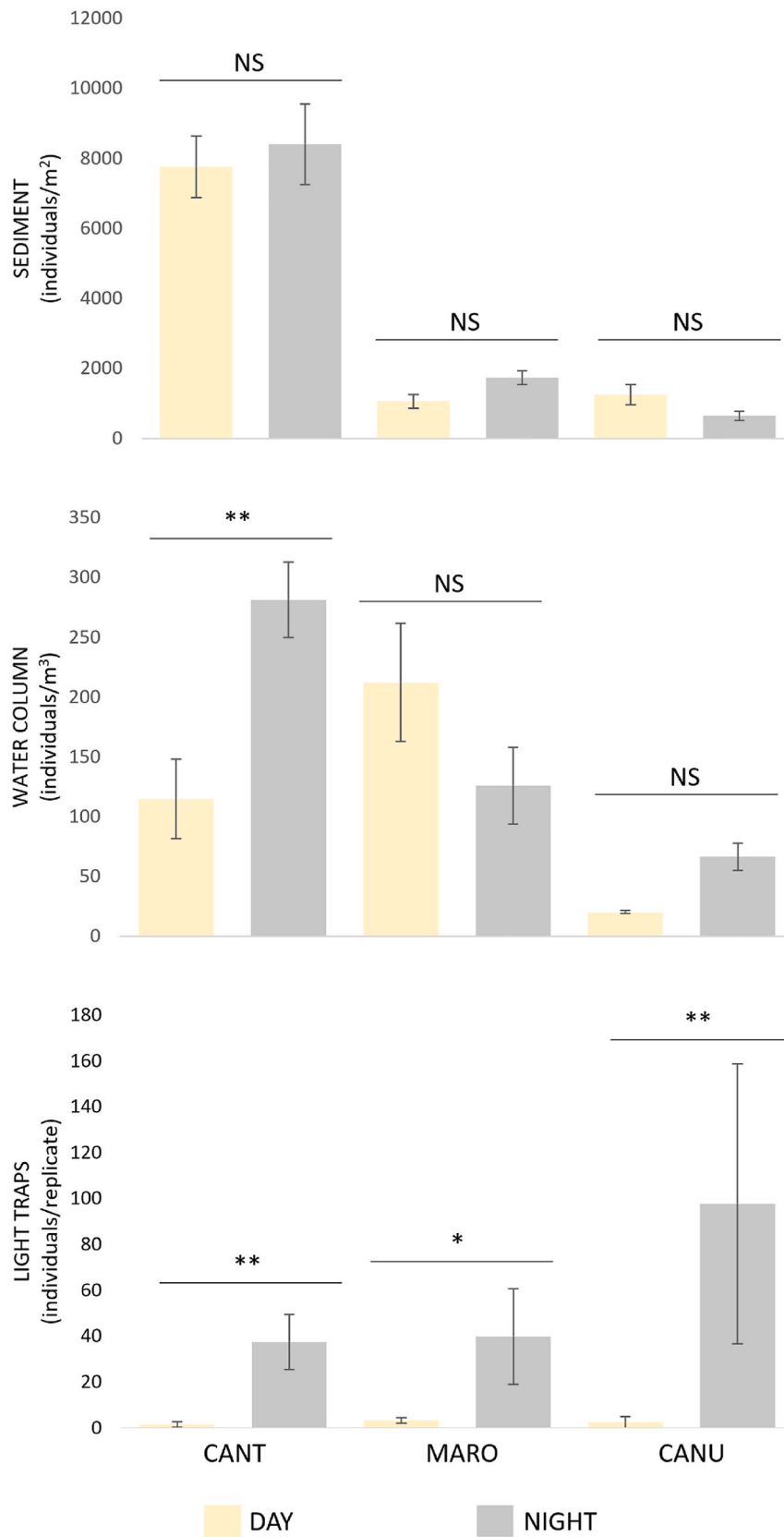
Table 3

Results of the PERMANOVA analyses conducted for macroinvertebrates community based on Bray-Curtis similarity matrix. Data untransformed. Pe = Period; St = Station; Me = Methodology. df: Degrees of freedom; MS: Mean Squares; p(MC): Level of significance (Montecarlo tests): *P < 0.05; **P < 0.01; ***P < 0.001.

| Source of variation	df	MS	Pseudo-F	Unique permutations	P(MC)
Pe	1	10836	2.407	38	0.0296*
St	2	13581	9.9651	9885	0.0001***
Me	2	42202	3.6316	6087	0.0018**
PexSt	2	4501.8	3.3031	9865	0.0001***
PexMe	2	9571.3	1.9793	9939	0.0255*
StxMe	4	11621	8.5267	9845	0.0001***
PexStxMe	4	4835.8	3.5482	9836	0.0001***
Residual	54	1362.9			
Total	71				

found on sediment samples. Cantarriján (sediment) was clearly different from the other two locations according to polychaete and mollusc composition, regardless the period. Polychaetes were also collected by light traps and plankton nets and, in this sense, replicates obtained by these two methodologies were grouped in a homogeneous group.

In agreement with the results obtained by ANOVA and PERMANOVA, SIMPER analyses also pointed out the dissimilarity of the communities caught by the light traps between the day and night (Average dissimilarity = 93.64%). 16 species were captured by the light traps during the day, which could be assumed as accidental catches due to their low abundances. On the other hand, 42 species appeared in the light traps at night but only 8 species were considered to be attracted to

Table 2

Results of ANOVAs for total abundance in each methodology. Sediment data were transformed by square(x+1) and Water column data by Ln(x+1). Pe = Period; St = Station (CANT: Cantarriján, MARO: Caleta de Maro, CANU: El Cañuelo). df: Degrees of freedom; MS: Mean Squares; P Level of significance: *P < 0.05; **P < 0.01; ***P < 0.001.

Source of variation	Sediment (Van Veen grab)				Water Column (Plankton net)				Light traps			
	df	MS	F	P	df	MS	F	P	df	MS	F	P
Pe	1	5.9640	0.03	0.8741	1	10628.3314	0.33	0.6224	1	44.3497	33.65	0.0285*
St	2	8479.9431	125.98	0.0001***	2	54169.7305	14.22	0.0002***	2	0.2791	0.28	0.7587
PexSt	2	184.9978	2.75	0.0909	2	31966.6410	8.39	0.0027**	2	1.3182	1.32	0.2906
Residual	18	67.3137			18	3808.9701			18	0.9950		
Total	23				23				23			
SNK tests:					SNK tests:				SNK tests:			
St	CANT > (MARO = CANU)				PexSt	CANT NIGHT > CANT DAY			Pe	NIGHT > DAY		

Fig. 2. Total abundance of macroinvertebrates (Mean ± Standard 300 error) present in the sediment, water column and light traps during the day and the night (CANT: Cantarriján, MARO: Caleta de Maro, CANU: El Cañuelo). NS = no significant, *P < 0.05, **P < 0.01. Total abundance was transformed by square(x+1) in the case of sediment and by Ln(x+1) in light traps.
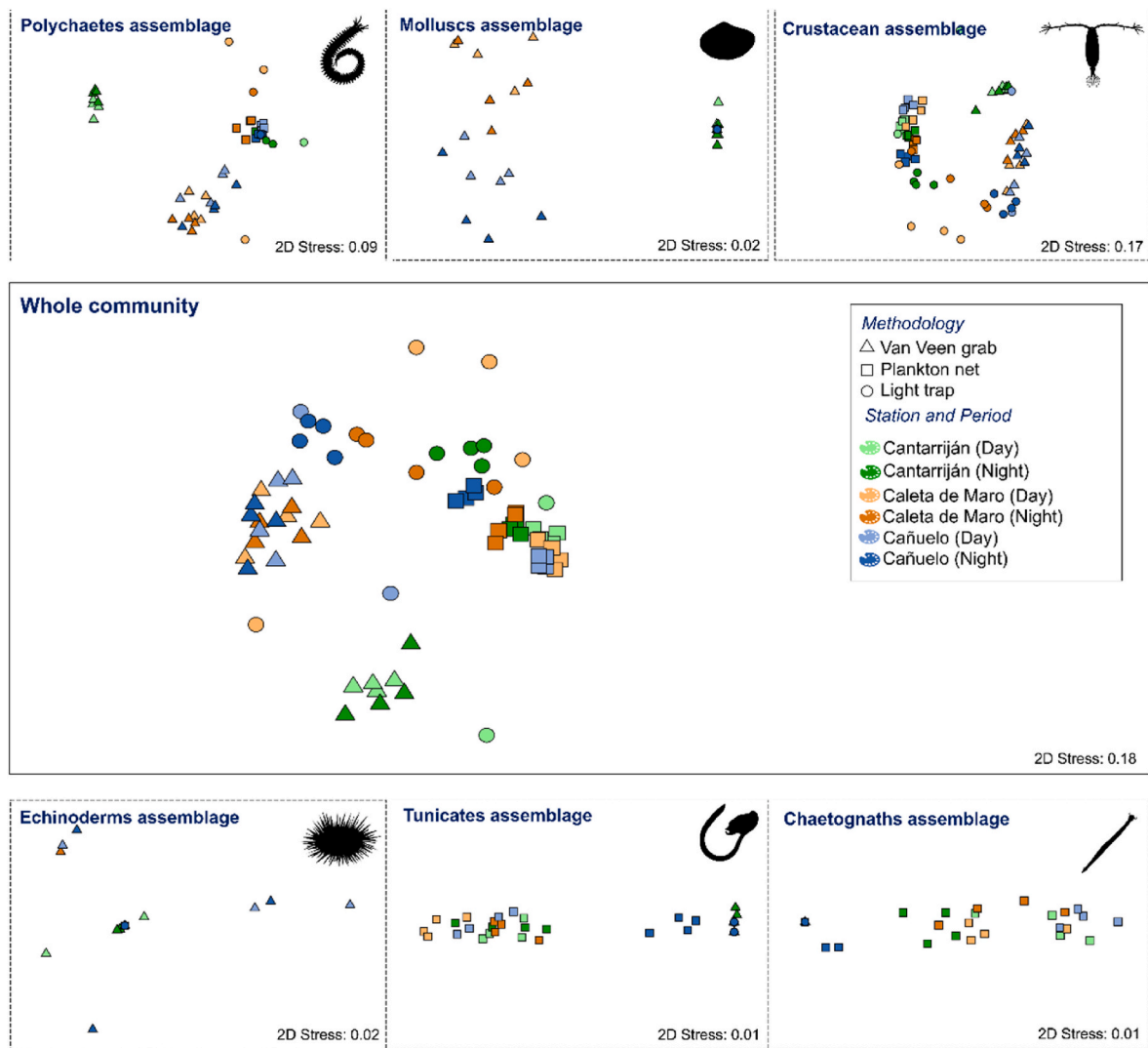
Fig. 3. Two-dimensional nMDS plot showing the complete macrofaunal community and the higher taxa assemblages based on species relative abundance. Cnidarians were not included since they were represented only for one species and its abundance was very low.

ALAN according to their abundances: the copepod *A. clausi*, the amphipods *Apherusa* sp., *B. guilliamsoniana, Megaluropus massiliensis* Ledoyer, 1976, *P. arenarius* and *Perioculodes longimanus* (Spence Bate and Westwood, 1868) and the cumaceans *Cumella (Cumella) limicola* Sars, 1879 and *Pseudocuma (Pseudocuma) longicorne* (Bate, 1858). Of the total number of species caught by the light traps, those that contributed most to the similarity among the night replicates were mainly emergent species from the sediment (Table 4). According to SIMPER results, the community found at water column at night was the most similar to the one collected by nocturnal light traps; however, average similarity values were low (11.87%). The comparison of both groups at night (Light traps *vs* Water column) revealed that the species which contribute the most to these differences were mainly emergent species and other migrants (Table 5A). Species such as *B. guilliamsoniana, Apherusa* sp., *P. arenarius* and *M. massiliensis* were emergent species with higher dominance on night traps than on water column samples. On the

Table 4
Results of SIMPER based on relative abundance for the main species captured by the light traps at night (cut-off criterion of 90% of accumulative similarity). EME: emergent migrants; OTH: other vertical migrants; UA: unassigned. Species with a total abundance lower than 15 individuals in all light traps at night were considered as accidental catches and they were marked with an asterisk.

Species	Average abundance	Average similarity	Contribution (%)	Accumulate (%)	Origin
Average similarity = 21.98%					
Bathyporeia guilliamsoniana	19.66	5.16	23.48	23.48	EME
Apherusa sp.	13.14	3.47	15.77	39.25	EME
Perioculodes longimanus	7.95	2.91	13.25	52.50	EME
Pontocrates arenarius	11.27	2.89	13.16	65.66	EME
Acartia (Acartiura) clausi	8.32	2.50	11.37	77.03	OTH
Megaluropus massiliensis	6.27	1.17	5.34	82.36	EME
Cumella (Cumella) limicola	3.44	0.92	4.21	86.57	EME
Nototropis swammerdamei	2.26	0.63	2.87	89.44	UA
Pseudocuma (Pseudocuma) longicorne	3.55	0.56	2.54	91.98	EME

Table 5
Results of SIMPER based on relative abundance for the main species captured in (A) the water column and the light traps at night and (B) the water column during the day and at night (cut-off criterion of 70% of accumulative dissimilarity). PLA: planktonic; EME: emergent migrants; OTH: other vertical migrants.

	Species	Group "NIGHT WATER COLUMN" Average abundance	Group "NIGHT LIGHT TRAP" Average abundance	Contribution (%)	Accumulate (%)	Origin
A) Average dissimilarity = 88.13%	*Acartia (Acartiura) clausi*	35.88	8.32	16.44	16.44	OTH
	Bathyporeia guilliamsoniana	0.00	19.66	11.15	27.60	EME
	Oikopleura spp.	16.45	0.00	9.33	36.93	PLA
	Apherusa sp.	0.65	13.14	7.49	44.42	EME
	Pontocrates arenarius	0.00	11.27	6.39	50.81	EME
	Euterpina acutifrons	8.33	1.89	4.92	55.73	OTH
	Periculodes longimanus	0.05	7.95	4.50	60.23	EME
	Clausocalanus furcatus	7.33	1.67	4.41	64.64	OTH
	Megaluropus massiliensis	0.45	6.27	3.62	68.26	EME
	Rhopalophthalmus cf. *mediterraneus*	5.92	0.33	3.42	71.68	OTH

	Species	Group "NIGHT WATER COLUMN" Average abundance	Group "DAY WATER COLUMN" Average abundance	Contribution (%)	Accumulate (%)	Origin
B) Average dissimilarity = 64.57%	*Acartia (Acartiura) clausi*	35.88	8.36	21.83	21.83	OTH
	Oikopleura spp.	16.45	37.80	19.09	40.92	PLA
	Clausocalanus furcatus	7.33	20.97	11.58	52.50	OTH
	Euterpina acutifrons	8.33	0.02	6.44	58.94	OTH
	Rhopalophthalmus cf. *mediterraneus*	5.92	0.00	4.58	63.52	OTH
	Centropages chierchiae	1.62	5.68	3.91	67.43	PLA
	Sagittoidea undet.	1.95	5.93	3.34	70.77	PLA

contrary, species as *A. clausi* or *Euterpina acutifrons* (Dana, 1847) were considered as other vertical migrants since their relative abundance is much higher in the water column at night (which could be interpreted as a DVM signal; Table 5B) but they do not come from the sediment.

4. Discussion

4.1. Migratory patterns and ALAN attraction

Our results support that ALAN from light traps produce a greater attraction effect on the migratory species, especially emergent migrants.

Despite molluscs comprising different planktonic stages/taxa (e.g. heteropods, pteropods or even veliger larvae), molluscs were not present in the water column or light traps. Similarly, holoplanktonic taxa such as chaetognaths and gelatinous plankton (e.g. cnidarians, appendicularians or thaliaceans) were not attracted by ALAN. In fact, even though many gelatinous organisms have sensory organs to detect the light (Graham et al., 2001), to our knowledge there is no evidence of ALAN influence in the movement of these taxa. Additionally, even though migratory behaviour has been reported among the aforementioned taxa, it has not been detected in our study. Some open sea thaliaceans, as salps or pyrosomes, have shown vertical migratory patterns related to thermohaline structure (Wiebe et al., 1979; Madin et al., 1996; Giachini Tosetto et al., 2022) but when this behaviour has been suggested in shallow waters it has been considered as a very weak migration (Park et al., 1989). In a similar way, Irigoien et al. (2004) studied the abundance of several zooplankton groups across different years and depths, and they did not report vertical migratory behaviour for appendicularians, except when a strong thermocline was established and a reverse DVM took place. Regarding to chaetognaths, DVM has been usually observed linked to the vertical distribution of their preys, even in relatively shallow waters (Irigoien et al., 2004; Kehayias and Kourouvakalis, 2010). According to our results, chaetognaths, appendicularians and thaliaceans did not show a clear migratory pattern, but DVM is a flexible behaviour which depends on taxonomical groups (Heidelberg et al., 2004; Sponaugle et al., 2021), sex or development stage (Rejas et al.,

2007), predation risk, intraspecific or interspecific competition (Vander Vorste et al., 2017; Rejas et al., 2007; Kehayias and Kourouvakalis, 2010), and abiotic factors such the environment (Bandara et al., 2021).

Regarding emergent species from the sediment, we found that the main taxon attracted to ALAN were peracarid crustaceans, which are commonly collected by light traps (Meekan et al., 2001; Navarro-Barranco *et al.*, 2015; Andradi-Brown et al., 2017). Peracarids were represented mainly by amphipods, which have been previously recorded not only as a dominant emergent group in terms of biomass (Anokhina, 2006), but also as a sensitive group to ALAN (Navarro-Barranco and Hughes, 2015; Navarro-Barranco et al., 2020). Particularly, the dominant species in the light traps was the amphipod *B. guilliamsoniana* (approximately 300 individuals in all the light traps at night). Vertical migration from the sediment at night has been recorded in several *Bathyporeia* species and the moonlit is considered one of the main modulators in the emergence, swim direction, and return to the sediment (Preece, 1971), although a free-running rhythm was also documented in dark conditions (Fincham, 1970). The vertical pattern of *Bathyporeia* does not seem to rely on feeding or reproduction (Watkin, 1939, 1941), so the factors behind this daily vertical movement despite the risk of predation are still unknown. Despite of this, a dominance of swimming males has been reported for populations of this genus, but the sex ratio has been reverted in other species and conditions (Preece, 1971 and references therein). In the present study, the individuals of *B. guilliamsoniana* found in the sediment at night were mainly females while males were present in the light traps (personal observation). Regarding to the light effect, this genus has been previously found in light traps too (e.g. Fincham, 1969; Ruffo, 1989; Navarro-Barranco et al., 2020), but the consequences of being attracted to light were only studied by Garratt et al. (2019) who reported a negative effect of ALAN associated to an increased predation on the light-mediated aggregation of individuals. Similarly, Navarro-Barranco et al. (2020) reported a lower number of amphipods collected in light traps on sandy areas than on rocky bottoms. However, it must be noted that sandy coastlines are more common in the Mediterranean (Luijendijk et al., 2018), so the risk of ALAN exposure is potentially higher on such habitats. In this sense,

the present study has confirmed that emergent fauna is the most vulnerable ecological group to ALAN, especially various amphipod species. This is particularly interesting due to the limited capacity of horizontal mobility of amphipods at fine-spatial scale resulting from small physicochemical gradients and changes (McManus and Woodson, 2012; Navarro-Barranco et al., 2020). Therefore, a hypothetical avoidance movement of these emergent migrants from lit to darker areas could be prevented, altering the population structure.

Regarding species considered as vertical migrants but not emergent, *A. clausi* was the dominant one in the light traps at night. Although the observed day/night abundance differences of this species in the water column could be caused by horizontal movement, its vertical migratory pattern was previously noted by Kouassi et al. (2001) and they concluded that this behaviour, along with its diet, contributes to the segregation among other copepods. Another species considered as vertical migrant was *C. furcatus*, although it was not attracted by the light traps. SIMPER results for the water column revealed a greater abundance of this copepod during the day than at night, which suggests a reverse DVM. Previous studies carried out in a higher vertical amplitude found a relatively high night/day abundance ratio for this species, but its vertical distribution changed through the night itself. Thus, *C. furcatus* was more abundant in the surface water at night but its abundance increased in the lower layers beyond midnight (Lo et al., 2004). Although a peak of catch rate of invertebrates normally happens near dusk in shallow waters (Tranter et al., 1981), some species are more common a few hours later (Ohlhorst, 1982), as it seems for *C. furcatus*. These results pointed out that species here considered as non-migrants could have fit in other category if the sampling had carried out at different times during the night. However, the time of sampling does not seem to modify the attracted species by the light traps.

Polychaetes included both migrant (primarily meroplanktonic species) and non-migrant species (composed by bottom-dwelling organisms). Meroplankton is one of the most abundant components of the water column at night in shallow waters in comparison with deeper areas, mainly due to the proximity of the benthic adults which produce planktonic larvae (Sponaugle et al., 2021). According to our results, the polychaete assemblage found in the water column and the light traps was relatively homogeneous, independently of the station; however, there were clear differences in polychaete sediment fauna among stations according to the granulometry. One explication for our results could be the homogenization of the water column among the whole sampling area due to their proximity and the action of high-speed winds and waves in winter (Sánchez-Laulhé et al., 2021). In any case, there is no evidence of DVM in polychaete larvae in shallow waters (meroplanktonic movements implied punctual events rather than repeated daily behaviour). Upwelling mediated by wind has been suggested as an important modulator of larval DVM (Garland et al., 2002), so the lack of depth could restrict the vertical migration of this taxon as well. Concerning the light attraction, many polychaetes perform a seasonal vertical migration that is synchronized to the phases of the moon in order to maximize the chances for fertilization (Bartels-Hardege and Zeeck, 1990; Naylor, 1999; Prentiss, 2020), but it is not considered DVM as such. Despite of the light as modulator in some species, the scarce abundance of polychaetes in our light traps at night does not provide enough evidence to consider this a consequence of light attraction.

In summary, our results showed that only a small percentage of the total species found in the coastal sandy areas perform vertical migrations (15%). This value was represented by infauna emerging from the sediment at night (6%) and other vertical migrants ascending in the water column (9%). Emergent fauna was the most vulnerable group among these to the attraction of light traps, mostly amphipod crustaceans. Although vertical migratory patterns have been reported in other habitats for species here considered as non-migrants, shallow coastal habitats are of special interest because of the exposure to ALAN from the cities. The most widespread kind of urban light is LED, and it is expected to increase in the following decades (Zissis et al., 2021). Chan et al.

(2016) compared the efficiency of glow stick and LED for collecting organisms in shallow waters, revealing a greater abundance in the latter. However, we cannot make assumptions about the origin and the migratory patterns of these catches since it could vary among the species of a certain taxon. Other relevant considerations in the use of light traps to explore the potential ALAN impacts in the migratory patterns, regardless of the light source, are disorientation or repulsion. The way ALAN produces any given disturbance depends on the light type and intensity, as well as the spectral sensibility of the affected taxa (Forward, 1988 Gal et al., 1999; McConnell et al., 2010; Navarro-Barranco and Hughes, 2015). While these effects have been demonstrated in many marine organisms, as turtles (Tuxbury and Salmon, 2005; Thums et al., 2016), seabirds (Rodríguez et al., 2017; Dias et al., 2019), fishes (Becker et al., 2013; O'Connor et al., 2019) and also invertebrates (McConnell et al., 2010; Berge et al., 2020; Lynn et al., 2021), these could hardly be proved by light traps.

4.2. Dark night conservation in natural areas

The number of studies related to light pollution is increasing each year (Davies and Smyth, 2017) but its incorporation into management programs, as it happens for other stressors, does not seem to be consolidated. For example, it is very common to find lit zones in MPAs, even in those designated with the highest status of protection according to the IUCN, and indeed the 14.7% of the total MPAs significantly increased ALAN intensities between 1992 and 2012 (Davies et al., 2015). Despite the existence of minor light sources along the considered MPA and the permissiveness of the current IUCN category II, the ecological status of the beaches of the Natural Park of Maro-Cerro Gordo, at least in terms of light pollution, seems apparently appropriate. In fact, the Regional Government which administers the Park developed a specific law (GICA: Integrative Management of Environmental Quality) that includes a section regarding light pollution (BOE, 2007). This law establishes different zones according to the appropriate levels of ALAN in order to protect and preserve the natural conditions of the nocturnal sky and ecosystems, which ranged from E1 or dark areas (restrictive regulations) to E4 or urban areas (permissive regulations). Since the Park is considered as E1 (Red de Información Ambiental de Andalucía, 2015) the artificial illumination of its coasts is forbidden according to the current legislation, with justified exceptions. However, while the law considers that the surrounding area for E1 should be treated as E2, this requirement is not currently fulfilled (Red de Información Ambiental de Andalucía, 2015). In addition, ALAN from nearby urban areas but outside of the Park could increase the luminance of the sky through the clouds reflection and spread the sky glow into the non-illuminated area (Kyba et al., 2011). Nonetheless, even though the confirmation of the light status of the Park is not the aim of the present study, the measures of sky brightness taken indicated a high-quality night sky. While this parameter provides direct information about the astronomical light pollution, the ecosystem may be altered by levels and kind of light which does not cause sky glow, and vice versa (Longcore and Rich, 2004), so we cannot conclude if there is a continuous regimen of ALAN in the ecosystem of the sampled beaches of the Natural Park.

In any case, management legislation about light pollution must be promoted, especially in vulnerable ecosystems such as marine habitats. Marangoni et al. (2022) proposed a management strategy for dark night conservation in marine habitats based on ten rules, from local to large scale. As these authors pointed out, these rules could be especially useful to mitigation of ALAN in marine ecosystems since the current regulation of light pollution is generally based on guidelines and permissive rules guided by non-government organizations instead of laws. Additionally, these organizations usually focus their efforts on astronomical light pollution or the ecological effects of ALAN in a single, usually charismatic, taxon. Concerning the Natural Park of Maro-Cerro Gordo management, a new draft regulation has been proposed to update the current legislation according to the recent scientific and technological advances,

but it is still unpublished (Junta de Andalucía, 2016). In this context, the information here provided, as well as further studies addressing the effects of ALAN on macroinvertebrate communities, provide valuable information in order to establish conservation measures. Migrating species play a key role in many ecological processes on coastal areas and their alterations may cause ecological cascade effects in the whole coastal community (Longcore and Rich, 2004; van Langevelde et al., 2011).

5. Conclusion

The use of light traps has endorsed the exploration of ALAN effects in shallow coastal habitats. Results obtained characterised the night/day composition across spatial distribution of macrofaunal communities inhabiting coastal sandy areas, highlighting those species with a migrating behaviour as well as those likely to be attracted by ALAN; these are mainly motile species emerging from the sediment to perform a vertical migration, mostly peracarid crustaceans (e.g. the amphipod *Bathyporeia guilliamsoniana*). Other less abundant vertical migrants were also attracted by the light, such as calanoid copepod species. However, many species found in the present study have not performed a definite migratory behaviour, but there is evidence of vertical migration under other conditions. Even if depth seems to be one of the main factors that explain these differences, the community of shallow coastal habitats is particularly interesting due to their vulnerability to light disturbances. Thus, promoting light pollution management, especially in these habitats, may be essential to prevent ecological ALAN alterations in macroinvertebrate community and the potential ecosystem interactions.

CRediT authorship contribution statement

Pablo Saenz-Arias: Conceptualization, Data curation, Formal analysis, Funding acquisition, Investigation, Methodology, Software, Supervision, Writing – original draft, Writing – review & editing, Validation. **Carlos Navarro-Barranco:** Conceptualization, Data curation, Formal analysis, Funding acquisition, Methodology, Supervision, Validation, Writing – review & editing, Software. **Juan Moreira:** Data curation, Formal analysis, Methodology, Supervision, Validation, Writing – review & editing. **María José Reyes-Martínez:** Data curation, Formal analysis, Methodology, Supervision, Validation, Writing – review & editing. **José Manuel Guerra-García:** Conceptualization, Data curation, Formal analysis, Methodology, Software, Supervision, Validation, Writing – review & editing.

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.

Data availability

Data will be made available on request.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.ocecoaman.2024.107207.

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