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Benthic litter distribution on circalittoral and deep sea bottoms of the southern Bay of Biscay: Analysis of potential drivers

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ABSTRACT

We analyze marine litter densities in soft bottoms of the southern Bay of Biscay using five years of demersal trawling data (2006–2010). Marine litter densities amounted to 43 ± 33 kg km^{-2} and 74 ± 28 items km^{-2}, with plastics and fisheries derived litter being the most widespread categories. Litter densities generally decreased along the water depth axis. To identify possible drivers for the observed litter distribution we performed a generalised additive model, which explained 14.8% of the variance and pointed to densely populated areas, number of fishing ports, geographical sector and fishing activity as the main explanatory factors. The most important driver for the benthic litter distribution was human population, as litter density linearly increased along this variable. Similarly, the number of ports in neighbouring areas had a positive effect on litter densities. Fishing effort had a negative and non-linear effect on benthic litter density which could be explained by litter delocalization during fishing operations. We hypothesise that litter might accumulate preferentially on the periphery of rocky bottoms, out of reach for our sampling methodology. Litter distribution differed among geographical sectors, pointing to other variables such as shipping traffic and oceanographic currents, which were not explicitly considered in the analysis. Our study sets a reference level for benthic macro-litter in the southern Bay of Biscay and identifies factors driving its distribution, which can be extrapolated to other continental shelf seas. Our findings lay the foundations to develop measures aiming to reduce macro-litter densities on the seafloor.

1. Introduction

Litter accumulation in the marine environment is a growing problem whose implications have not been comprehensively assessed to date. However, the concern on marine litter pollution has risen during the last decades, as indicated by the growing number of scientific publications on marine litter (Ryan, 2015) and its inclusion in the political agenda. Litter can be considered ubiquitous in the marine environment as it is present in the most diverse marine environments (Ramirez-Llodra et al., 2013; Pham et al., 2014; Galgani et al., 2015) either floating, stranded along the coast or deposited on the seabed (Galgani et al., 2015).

Regarding litter on the sea floor, existing studies are commonly based on bottom trawling (Galgani et al., 1995a, 1996, 2000; Stefatos et al., 1999; Moore and Allen, 2000; Lee et al., 2006; Koutsodendris et al., 2008; Keller et al., 2010; Sánchez, 2013; Strafella et al., 2015; Neves et al., 2015; Moriarty et al., 2016) although non-intrusive methodologies such as remote operating vessels (ROV) are gaining relevance (e.g. Mordecai et al., 2011 Schlining et al., 2013; Pham et al., 2014, Melli et al., 2017). These studies have described litter distribution along quite wide areas, elucidating, in some cases, the possible origin amongst ocean or land based sources. Regarding litter composition, plastic items constitute the majority of marine litter worldwide (reviewed in Derraik, 2002), although metallic objects, fishing gear and glass have also been commonly reported (Moore and Allen, 2000; Lee et al., 2006; Keller et al., 2010; Strafella et al., 2015). However, in spite of the scientific consensus considering marine litter as a major threat to ecosystems (Depledge et al., 2013; Pham et al., 2014), the main drivers determining the current litter distribution on shelf seas remain practically unknown.

The European Marine Strategy Framework Directive (2008/56/EC) identified marine litter as one of the necessary descriptors for describing environmental status within European marine waters, and its distribution and spatial-temporal trends on the sea floor is one of the criteria. Although the state of knowledge on the effects of marine litter on ecosystems is limited, a precautionary approach pleads for reducing the amount of marine litter in the environment. The most widely acknowledged effects of marine litter are due to the ghost fishing

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activity of derelict fishing gear, which continue to fish once lost or abandoned and can entangle a wide range of animals from invertebrates to marine mammals (Baeta et al., 2009; Gregory, 2009; Gilardi et al., 2010), as well as gaining aggregation capacity for potential predators (Matsuoka et al., 2005). Ingestion of macro-litter by marine mammals, turtles and birds is also a recognized risk of marine litter pollution (e.g., reviewed by Laist, 1997; Gregory, 2009; Gall and Thompson, 2015). In addition to the mechanical risk (obstruction of the gut, etc.) and the potential harm due to translocation of degradation products from the plastic to the organisms fluids (Browne et al., 2008), organic pollutants adsorbed on the litter surface might get released when ingested (Teuten et al., 2007; Graham and Thompson, 2009; Rios et al., 2010; Rochman, 2015). The latter is one of the main concerns regarding micro-litter microliter, with unknown effects at the individual and population levels and the potential of recirculation of these substances through the foodweb (Lusher, 2015). However, direct ingestion of macro-litter by benthic and demersal species is not common (Anastasopoulou et al., 2013; Deudero and Alomar, 2015). In addition, the degradation process of macro- litter in benthic habitats on the continental shelf is thought to be slower when compared with pelagic or coastal environments due to the relatively low hydrodynamism and the absence of light (Hanke et al., 2013), and these bottoms are thus considered long-term sinks for marine litter (Nauendorf et al., 2016).

While the short and medium term effects of benthic macro-litter in the ecosystem are surrounded by high uncertainty, following a precautionary approach, measures aiming at reducing the amount of marine litter in these environments should be undertaken. To do so, determining the origins and drivers of benthic macro-litter distributions is of the upmost importance. Using the northern Spanish continental shelf as a case study, the aims of this study were (i) to determine the abundance distribution of macro-litter on the continental shelf and (ii) to identify factors driving this specific distribution.

2. Methods

2.1. Study area

The study area is located on the North Atlantic coast of Spain, spanning the continental shelf of the southern Bay of Biscay from the border with France on the east to the border with Portugal on the southwest (Fig. 1). The continental shelf in this area is characterised by its narrowness (min ≈ 30 km) and by being the frontier between Atlantic boreal, Atlantic macaronesian and Mediterranean fauna.

The main oceanographic patterns in the area are seasonal and of variable intensity, including the poleward current on the shelf-break predominant in winter months and upwelling events during the summer, which preferentially occur on the western edge of the study area. Spring and autumn are considered transitional seasons dominated by mesoscale circulation structures such as eddies (Gil, 2008). The rivers discharging in the area have generally low flows and do not make a major contribution to the regional oceanography (Gil, 2008).

2.2. Data used in the analysis

2.2.1. Marine litter data

Marine macro-litter on the sea bottom (hereafter "marine litter") was recorded during five bottom trawl oceanographic surveys (DEMERSALES surveys- under ICES IBTSWG standardisation, ICES, 2010) carried out every autumn between 2006 and 2010 in the Southern Bay of Biscay. The survey follows a randomly stratified sampling design in five geographical sectors and three depth ranges: 70–120 m (shallow circalittoral), 120–200 m (deep circalittoral) and 200–500 m (bathyal) with some additional tows outside these depth ranges (for a complete description of the survey design see Sánchez and Serrano, 2003). Between 2006 and 2010, 136 hauls on average were carried out on the shelf using a BAKA otter trawl with 20 mm meshsize at the cod end. Each haul consisted of 30 min trawling at 3 knots covering an area of approximately 0.051 km^2. After each haul individual items of marine litter were classified, cleaned of epibionts and weighed on board (wet weight to 0.1 gr. precision). Haul data were subsequently standardised as density per square km (both using number of litter items and weight) and averaged for a 5 × 5 nautical miles grid covering soft bottoms of the continental shelf (Fig. 1). In order to reduce the number of categories, and following technical group classification (Cheshire et al., 2009; ICES, 2010), litter items were binned into six groups based on their material composition, degradability and original activity, namely: Plastics, Solid hydrocarbons, Textile, Metal, Fisheries derived items and Other Materials (Table 2). The latter included wood, ceramics and glass with medium to large degradation times but low polluting potential, while fisheries derived items consisted on pieces of rope, nets, lobsterpots, etc.

2.2.2. Potential drivers

Several variables were considered as potentially influencing the amount of marine litter on the continental shelf bottom, including variables describing land-based and sea-based mechanisms for marine litter production. We considered thus, human population, industrial parks, river flow, ports/ harbours and their activities, and fishing activity. In addition we considered five geographical sectors over which the sampling design is based. These sectors were constructed by projecting the main capes towards the sea perpendicularly to the coast (see Fig. 1). Average river flow ($m\ s^{-1}$) was obtained from regional monitoring programs including the Cantabrian Hydrographic Confederation, the Hydrographic Confederation of Miño- Sil, and Aguas de Galicia, the organism managing continental waters from the Galician Regional Government (Xunta de Galicia, Spain). The index to compute the influence of neighbouring rivers (Gonzalez-Irusta et al., 2014) was calculated as follows:

$$River\ index = Distance\ to\ closest\ river\ mouth\ (km)/River\ flow(\mathrm{m}^3 \cdot \mathrm{s}^{-1})$$

This index integrates thus the decreasing effect that the river might exert when getting further from the river mouth, with the strength of the river for transporting litter items given by the river flow. The updated census record of population from 2011, and the geographical location of each coastal municipality were obtained from the Spanish National Centre of Geographic Information (Nomenclator Geográfico de Municipios y Entidades de Población; www.cnig.es). From the centre of each 5 × 5 nm grid, the radius necessary for encircling a population of 50000 inhabitants was calculated in kilometres. These radii were thus used as a proxy for population stress on each grid within the study. The location of industrial parks in the neighbouring regions was obtained from the National Geographic Institute (www.ign.es), using the BCN25/BTN25 database on land use. We computed the area occupied by industrial activities within a 30 km radius from each marine grid centre, considering it as a proxy for industrial activity in the area. Port activity was evaluated using two different approaches. Firstly, we considered the number of ports within a 30 km radius from each grid centre, including leisure, fishing and commercial harbours. Additionally, we calculated the number of artisanal fishing vessels registered in harbours within a 30 km radius (approx. 17 nm). Artisanal vessels (< 12 m length) activity is not registered with a vessel monitoring system. These vessels do not normally operate far from their base, due to their limited facilities on board and their need to maximise cost-effectiveness, therefore they have a higher polluting potential than the commercial fleet in the vicinity of their base harbour. The activity of the fishing fleet (> 12 m vessel length) in the study area was obtained through the vessel monitoring system (VMS) data. Fishing activity in each grid was estimated as the elapsed time between successive signals, without discrimination between navigation time and fishing operations. Additionally, we also

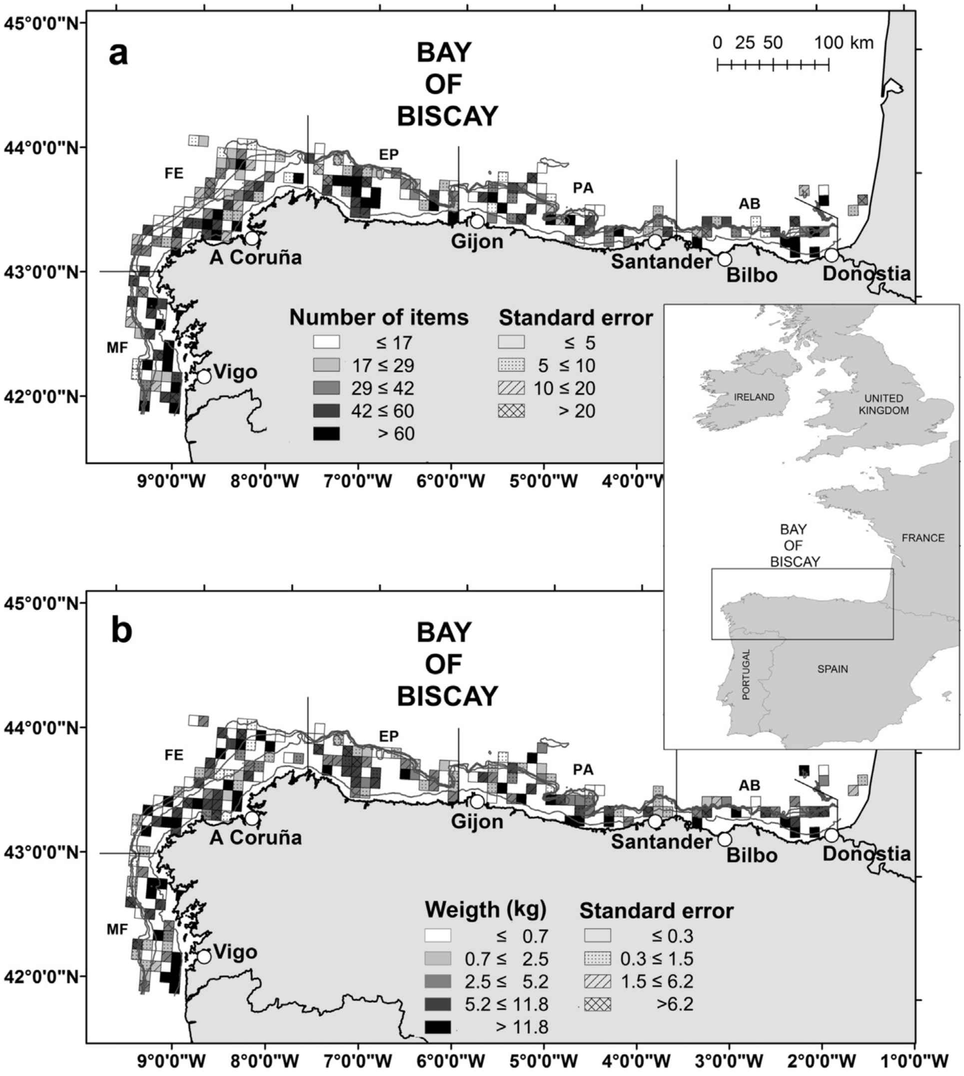

Fig. 1. Distribution of marine litter densities (averaged for the period 2006–2010) in the studied area by number of items (a) and weight (b). Geographical sectors are separated by lines perpendicular to the coast and named after the initial of the river or capes at their limits, i.e. MF = Miño River-Finisterre Cape, FE = Finisterre Cape- Estaca Cape, EP = Estaca Cape-Peñas Cape, PA = Peñas Cape-Ajo Cape and AB = Ajo Cape to Bidasoa River. The main coastal cities are also indicated.

considered distance to coast, computed as the minimum distance from the grid centroid to the coastline, and depth, obtained from the ship's ecosounder, in a first phase of the analysis.

2.3. Statistical analyses

The correlation between the continuous explanatory variables was checked for colinearity prior to any subsequent statistical analysis using both Pearson correlation coefficients and variance inflation factors (VIFs; Zuur et al., 2009). We selected a final pool of explanatory variables (human population, river flow, number of ports within a 30 km radius, fishing activity and geographical sector) whose correlation values were lower than 0.6 (Table 1) and whose VIFs lower than 3. The number of litter items per square kilometre (haul data) was modelled using General Additive Models (GAMs), applying the implementation gam in the package "mgcv" (Wood, 2011). There was evidence of slight over-dispersion in the standard errors which was corrected by applying a quasi-Poisson model where variance is given by the dispersion parameter multiplied by the mean (Zuur et al., 2009). To avoid edge effects extreme outliers were eliminated from the database. The model selection followed a forward stepwise criterion by adding a term each time and assessing the improvement in the GCV value and

Table 1
Pearson correlation coefficients among the 6 continuous explanatory variables considered, distance to coast and depth. All the values > 0. 6 are showed in bold.

	Industrial area index	N ports 30 km	N artisanal vessels 30 km	Population radius	River index	VMS	Distance to coast
N ports 30 km	0.46						
N artisanal vessels 30 km	0.18	**0.82**					
Population radius	**−0.72**	−0.58	−0.29				
River index	−0.29	−0.32	−0.16	0.55			
VMS	−0.16	−0.14	−0.04	0.22	0.13		
Distance to coast	−0.53	**−0.60**	−0.31	**0.87**	**0.62**	0.19	
Depth	−0.44	−0.50	−0.27	**0.70**	0.43	0.08	**0.78**

the model deviances (using ANOVA F test). To test if this procedure had any effect on the variables being selected, we also conducted a backwards stepwise elimination. The relative importance of each variable was tested by removing the targeted variable from the final model and computing the deviance variation. The spatial autocorrelation of residuals was analysed using the variogram implementation in the gstat package (Pebesma, 2004) and the Moran's I test, computed using the R implementation Moran.I in the package "ape" (Paradis et al., 2004). The semi-variance of the residuals did not show any trend with distance in any year and the Moran's I statistic was not significantly different from the expected value, so the spatial autocorrelation in the residuals was discarded. All calculations were performed with the software R for statistical computing (R Development Core Team, 2015) additionally using the R packages "argosfilter" to calculate distances between geographical locations (Freitas, 2012) and "maptools" to determine geographical areas within a certain distance radius (Turner, 2012).

3. Results

3.1. Distribution and effect on benthic habitats

Average marine litter density in the area sampled was 43 ± 33 kg km^{-2} and 74 ± 28 items km^{-2}. In general, the largest concentrations of marine litter were found: in the Rías Baixas at southern edge of the study area, in front of the city of A Coruña at around 43.3°N-8.5°W, east of Estaca de Bares Cape at 7°W and in the innermost part of the Bay (Fig. 1). Marine litter was found in the majority of grids sampled (95%), with plastics being the most widespread category followed by fisheries derived debris (Table 2). Regarding litter densities, plastic was also the most abundant category, followed by other materials (Table 2). The average density of litter was lowest in bathyal area (23 ± 9 items km^{-2} at depths > 500 m and 36 ± 9 items km^{-2} in the stratum 200–500 m), increased in the deep circalittoral (48 ± 5 items km^{-2}), and achieved maxima in shallow circalittoral areas (78 ± 16 items km^{-2} in the depth stratum 71–120 m and 103 ± 70 items km^{-2} at depths shallower than 70 m). The relative area littered also decreased along the depth gradient (Fig. 2). Similar trends were found when considering average litter weight instead of litter density.

Table 2
List of litter items pooled into seven categories, indicating frequency of occurrence, its mean density and the relative density.

Category	Items recorded	Frequency (%)	Mean density (N km^2)	Relative density (%)
Plastics	Plastic foam Plastic pieces	**84**	**21 ± 1**	**45**
Fisheries derived debris	Ropes Fishing cages Buoys Trawling nets Gillnets Longlines Other nets	**74**	**3**	**7**
Other materials	Ceramics Glass Rubber Wood Paper	**53**	**13 ± 1**	**30**
Metal		**45**	**5 ± 1**	**11**
Textile	Cloths Fabric pieces	**28**	**2**	
Solid hydrocarbons	Coal Dense fuel	**12**	**2 ± 1**	**4**

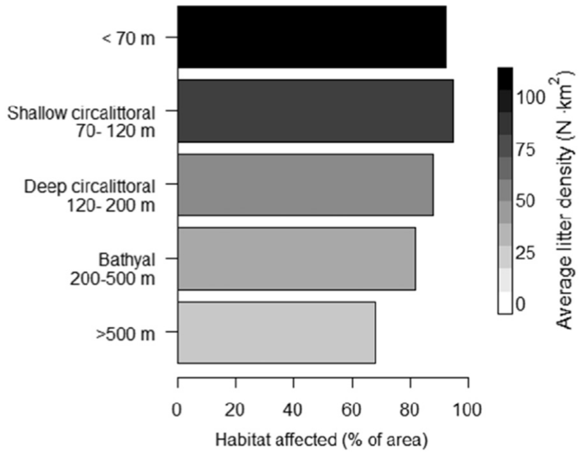

Fig. 2. Percentage of area surveyed affected by marine litter and litter density (N items km^{-2}) by depth strata.

3.2. Drivers of distribution

Geographical sector, population radius, fishing effort and number of ports (see distribution of these variables in the Supplementary material) had a significant effect on the litter distribution (Fig. 3) and became explanatory variables in the final quasipoisson GAM (n = 650). From the five variables tested, only river index was not included in the final model. The model explained 14.8% of the total deviance and the value of the Spearman coefficient used to measure the correlation between the predicted and the observed values was 0.38 (Table 2).

Population radius was the variable with highest explanatory power (Table 3). Litter concentration decreased linearly along this variable, when moving away from the influence of population nuclei. Geographical effort was the second variable in terms of relative importance. The sector Peñas-Ajo showed the lowest values of litter concentration whereas Rías Baixas (in the border with Portugal Peñas) was the sector with the highest densities of marine litter, followed by Ajo-Bidasoa (in the border with France), Estaca-Peñas and Finisterra-Estaca. Fishing effort was the only variable whose effect on the litter distribution was non-linear, litter densities decreased with increasing fishing effort reaching a plateau at about 7000 fishing hours (Fig. 3). Number of ports, the last variable selected (Table 3) had a linear effect on litter densities, which increased along with the number of ports within a 30 km radius, however, the effect of this variable was not statistically significant.

4. Discussion

Marine litter showed a widespread distribution across the continental shelf in the southern Bay of Biscay, although the densities recorded were not particularly high. Previous studies in European shelf seas generally recorded higher litter densities (Table 4), particularly in our neighbouring regions, i.e., mean litter densities recorded with a similar methodology in the northern Bay of Biscay ranged up to 142 items km^{-2} (Galgani et al., 2000) while the density recorded in the north of Portugal using a meshsize far larger than ours averaged 78.7

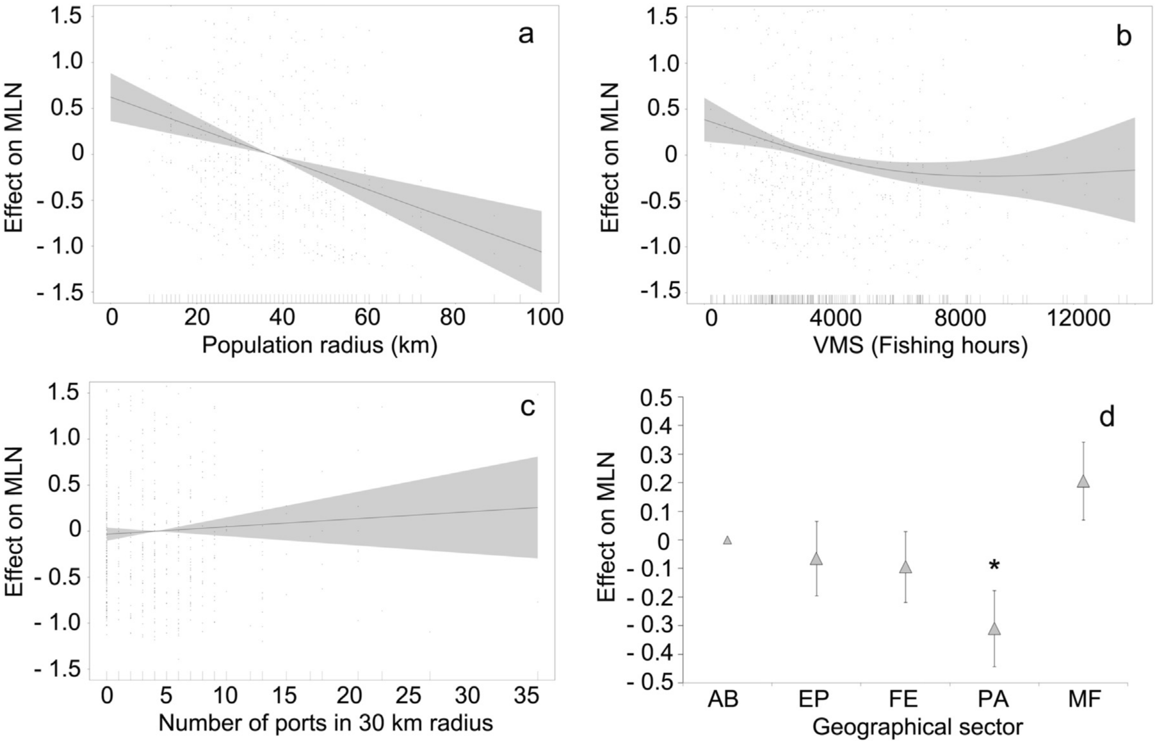

Fig. 3. Effect on the predicted density of marine litter of the explanatory variables: population radius (a), fishing effort (VMS) (b), number of ports in 30 km. radius (c) and geographical sector (d). The shaded area represents the nominal confidence intervals (95%) and the points indicate the residuals.

Table 3
Summary result from the final model selected using a backwards/forwards stepwise process. The table shows the model formula (β is the intercept, s is an isotropic smoothing function, f indicated the variable that was included as a factor and Ɛ is the error term), the explained deviance, the Spearman coefficient (between predicted and real values), the degrees or estimated degrees of freedom (d.f/e.d.f.) and the statistical significance and relative importance (Δ deviance) of the explanatory variables.

GAM results				
		N	Spearman coefficient	Explained deviance
Model: MLN ~ β_1 + population radius + number of ports in 30 km + s_1(VMS) + f(geographical sector) + Ɛ		650	0.38	14.8%
Variables	Δ Deviance	d.f./e.d.f.	F	P-value
Population radius	829.16	1	22.96	< 0.001
Number of ports in 30 km	25.34	1	0.86	0.35
Geographical sector	524.45	4	3.57	< 0.01
VMS	505.71	1.95	6.1	< 0.01

items km^{-2}. Different reasons could contribute to the lower litter densities observed in our study site compared with other shelf seas, such as: the relatively lower population on the coast, the smaller size and flow of rivers discharging in the area (Gil, 2008; Gonzalez-Nuevo and Nogueira, 2014) and the possible delocalizing effect of the fishing fleet (see below). Although densities were relatively low in most of the study area, there were some important exceptions in the Rías Baixas (close to the Miño river mouth), in front of A Coruña city, east of Estaca Cape, and in the innermost part of the Bay. These areas are located in the proximity of some of the largest ports in northern Spain. In addition, these areas are characterised by the presence of mesoscale gyres during autumn (Gil, 2008), which could play a role in concentrating adjacent floating litter. Plastic debris was the most common litter type in our study site. Plastic litter has very low degradability (Andrady, 2015) and it has recurrently been described as the dominant litter type over continental shelf seas (Galgani et al., 2000; Koutsodendris et al., 2008; Keller et al., 2010; Sánchez et al., 2013; Strafella et al., 2015; Neves et al., 2015; Moriarty et al., 2016). Fishing derived litter was the second most widespread litter type found in our study site. Discarded fishing gear has been found to be the dominant type of litter in some areas, such as the East China Sea and the Pacific coast of USA (Moore and Allen, 2000; Lee et al., 2006).

It is widely acknowledged that several variables strongly influence the distribution of benthic litter such as hydrodynamics and geomorphology as well as distance from the coast (particularly from river mouths and population centers) (Galgani et al., 1995b, 1996, 2000; Pham et al., 2014). Our analysis included several variables indicative of land-based (e.g., population radius, river index) and ocean-based litter sources (e.g., VMS, number of ports).

Population radius was the variable with higher explanatory power of the model. Previous studies had related high litter densities with population nuclei (Stefatos et al., 1999; Galgani et al., 1996) and while the effect of this variable possibly gains further relevance out of the range of our study area, i.e., in very shallow areas (depth < 30 m) not covered by our sampling methods, it still drives the distribution of litter on the continental shelf. This variable is highly correlated with distance to coast and secondarily to water depth, but neither of these variables can be considered per se drivers of the marine litter distribution. Therefore, although litter density decreases with depth, with higher densities on the shelf than on the continental slope, it seems that the reason is the distance from the main litter source (the coast) to the deeper areas. These results contrast with the findings of Moore and Allen (2000) and Keller et al. (2010) for the western US coast. These authors reported bottom litter to increase with depth, a trend which has been explained by a possible ocean based origin of the litter (Keller et al., 2010). Since our study site is mainly the southern part of a semi-enclosed sea (i.e. the Bay of Biscay), there is minor maritime traffic along the Cantabrian Sea area except in the Galician Continental Shelf where maritime traffic converges, with several routes running parallel

Table 4

Summary of studies on benthic litter in European shelf seas, indicating area of study, mean density of litter found, sampling gear with minimum mesh size at the cod end and the data source.

Area	Depth	Mean litter density (N/km^2)	Sampling gear	Min mesh size (mm)	Reference
Baltic Sea	Continental Shelf	126	Otter trawl	20	Galgani et al. (2000)
Celtic Sea	Continental shelf	528	Otter trawl	20	Galgani et al. (2000)
North Sea	Continental Shelf	156	Otter trawl	20	Galgani et al. (2000)
Bay of Biscay	Continental Shelf	142	Otter trawl	20	Galgani et al. (2000)
Bay of Biscay (southern)	Continental shelf	74.14	Otter trawl	20	This study
Portuguese coast (North)	Continental Shelf	78.7	Otter trawl	55–80	Neves et al. (2015)
Portuguese coast (Central)	Continental Shelf	53.5	Otter trawl	55–80	Neves et al. (2015)
Portuguese coast (South)	Continental Shelf	17.3	Otter trawl	55–80	Neves et al. (2015)
Catalan Sea	Shallow circalittoral	6000	Beam trawl	10	Sánchez et al. (2013)
Gulf of Lion	Continental Shelf	143	Otter trawl	10	Galgani et al. (2000)
Murcian Sea	Shallow circalittoral	3400	Beam trawl	10	Pilar et al., 2013
Malta	Circalittoral	97	Otter trawl	20	Mifsud et al. (2013)
Tyrrhenian Sea	Shallow circalittoral	5950	Beam trawl	10	Sánchez et al. (2013)
Ionian Sea	Shallow circalittoral	2300	Beam trawl	10	Sánchez et al. (2013)
NW Mediterranean	Continental Shelf	1935	Otter trawl	20	Galgani et al. (2000)
Patras Gulf (Greece)	Continental Shelf	240	Otter trawl	15	Stefatos et al. (1999)
Western and Southern Greece	Continental shelf	165	Otter trawl	15	Koutsodendris et al. (2008)

to the coast (Lloret et al., 2012). Coastal population density stands thus as the main reason behind the observed patterns of benthic macrolitter distribution on the shelf, despite the relatively low population density in our study area. Litter densities were higher in the geographical sectors located at both edges of our study area. These geographical sectors could act as proxies for several human activities for which explicit data were not available. For instance, shipping routes run on the western coast of the study area, along the sectors MF and FE which have their own traffic separation scheme, but not within the Bay of Biscay where only the entrance to the main commercial ports are important routes (Lloret et al., 2012). Geographical sectors could also be associated with the complex oceanography of the area. The dominant currents flow to the inner Bay with marked seasonality (Koutsikopoulos and Le Cann, 1996) and the mesoscale gyres, which occur predominantly east of the capes during autumn (Gil, 2008), could influence the distribution of floating debris before its settlement to the bottom. Geographical sectors can be used as a proxy for other spatially explicit variables affecting benthic macrolitter distribution.

Fishing activity displayed an asymptotic effect on litter density, with higher litter densities at low fishing effort values, and low litter densities from intermediate fishing efforts onward. We hypothesise that fishing activities could remove litter from the areas where it was initially deposited and drop it somewhere else during navigation, contributing thus to the delocalization of litter. This hypothesis is supported by the fishermen behaviour described by Neves et al. (2015) in neighbouring Portuguese waters, as fishermen tend to dump the litter along with the discarded fish after the fishing operations. This delocalization prevents identifying the litter origin and masks the relation between fishing effort and litter density. For example, this delocalization may explain conflicting results found when addressing litter presence vs. litter density distribution. While Moriarty et al. (2016) found a positive correlation between fishing effort and litter presence in the Celtic Sea, Sánchez et al. (2013) did not find fishing effort and litter density to be correlated in Mediterranean waters. Fishing grounds in the Cantabrian Sea, particularly trawling fishing grounds, have a thread-like configuration, separated by vast areas of rocky bottom (Punzón, unpublished data). Therefore, all litter reaching these rocky areas would not be further accessible with our sampling methods. Since litter tends to accumulate in small depressions and channels, around rocks (Galgani et al., 1996) or next to other settled debris (Mordecai et al., 2011), the periphery of rocky habitats might concentrate much higher litter densities than recorded on soft bottoms of the continental shelf (Melli et al., 2017). Fishing activity seems thus to relocate the litter from its site of original settling and possibly contribute to its accumulation away from the fishing grounds. We highlight that, according to our model, trawling fishing activities have potential for cleaning the seabed by landing the fished marine litter.

The number of ports (highly correlated with the number of artisanal vessels operating in the area) was also included in the model although with a low significance value. This indicates that small-scale fisheries and recreational boats could act as vectors for marine litter production; due to their reduced size these vessels do not have facilities on board for handling the garbage they produce. Indeed, the small-scale fisheries fleet in the Southern Bay of Biscay is among the largest in European waters with over 5000 vessels (Stobberup et al., 2017). In summary, our model identifies an increase in litter densities in regions with densely located small-scale fisheries, possibly related to direct garbage dumping. On the other hand, intense fishing activity by the industrial fleet shows an inverse relation with litter density, which could be explained by the delocalization of the litter distribution.

River influence, which is recurrently found in the literature as an important driver of benthic litter distribution (Galgani et al., 1995a, 2000; Hess et al., 1999), was not included in the model, as it did not significantly improve the model goodness of fit. River plumes can be noticed in the sea surface by their significant decrease of the water salinity; they stretch over the continental shelf and could thus be a dispersal vector for buoyant litter items. However, most of the rivers in the north of Spain are short with relatively low flows (Gonzalez-Nuevo and Nogueira, 2014), excepting the river Miño in the southernmost edge of our study site. After the results of Galgani et al. (2000) for the Ardour River in southwestern France, the river effect is only noticeable within a narrow radius, probably not larger than 5 nm from the river mouth, and thus this effect would possibly remain undetected by our sampling design. However, we note that the river index used in our study oversimplifies the effect of the river plumes as it does not consider the plumes' hydrography. A more detailed description of the plume, considering its actual direction, would possibly improve the explanatory power of this variable, provided the river had a sufficiently large discharge. Floating litter items tend to sink as they become ballasted by biofouling (Ye and Andrady, 1991). The distance they travel from their source before sinking depends on their initial size and buoyancy (Fazey and Ryan, 2016). Therefore, the use of detailed hydrographic data, derived from circulation studies, could also aid in predicting the distribution of litter items from land-based sources.

Another source of uncertainty in the distribution of macrolitter in benthic environments is its possible burial in sedimentary habitats. Sedimentation rates in the muddy deposits of the inner Bay of Biscay are between 0.13 and 0.5 cm yr^{-1} (Jouanneau et al., 2008), but these soft sediments are commonly trawled by commercial fisheries several times annually (Gonzalez- Irusta, unpublished data), preventing the burial of benthic macro-litter. Therefore, while differences in sedimentation rates and burial of benthic macrolitter in sedimentary habitats is a factor to be considered, the activity of the trawling fleet, which can swept these sedimentary bottoms several times annually might edge out the possible litter burial.

To our knowledge this is the first attempt to model benthic litter density distribution in shelf seas. The modelling approach allows to ascribe confidently the observed litter distribution to several factors commonly deemed to drive litter on the continental shelf. In addition, using a generalised additive model, we could identify non-linear relations, such as the effect of the industrial fishing activity on the distribution of benthic litter density. While our analysis has a moderate explanatory power, it confidently identifies several variables as drivers of the distribution of benthic litter. However, as discussed above, several factors as the delocalizing effect of the fishing fleet, the edge effect of rocky bottoms not accessible with bottom trawling, the lack of detailed hydrographic data, and the burial of litter in sedimentary habitats limit the effective modelling of benthic litter distribution. Previous studies on the northern area of the Bay show that non-buoyant items possibly sank in the areas where they were found (Galgani et al., 1995a). On the contrary, in our study it stands out that fishing activities might contribute to the delocalization of litter items and that land- based sources are crucial to explain the distribution of marine litter in the continental shelf of northwestern Spain.

5. Concluding remarks

Our study illustrates the distribution of litter on the North Atlantic continental shelf and slope of the Iberian Peninsula (southern Bay of Biscay). Litter distribution was found over the majority of the sampled area, but generally in lower densities than reported for other shelf seas. This result possibly stands from the relatively small anthropogenic pressure of the coastal regions in our study area. Nevertheless, human population on the coast was the main driver of the benthic litter distribution on the shelf, pointing out the importance of land-based sources. Among the several variables which contributed to the explanation of the observed litter distribution, fishing activity had an unexpected effect on the benthic macro-litter distribution, as it contributed to its delocalization. Based on our results, we hypothesise that the trawling fleet is removing benthic macro-litter from sedimentary bottoms and dumping it elsewhere, possibly contributing to the accumulation of macro-litter in the periphery of rocky habitats. In light of our results, we recognize the urgency of (i) monitoring hard substrate habitats as accumulation sites for marine litter, (ii) implementing measurement aiming at persuading fishermen to land marine litter found during fishing operations and (iii) implement policies to discourage litter dumping by small scale fisheries and recreational boats.

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Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.csr.2017.07.003.

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