

Spatial distribution of marine macro-litter on the seafloor in the northern Mediterranean Sea: the MEDITS initiative

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Summary: Marine litter is one of the main sources of anthropogenic pollution in the marine ecosystem, with plastic representing a global threat. This paper aims to assess the spatial distribution of plastic macro-litter on the seafloor, identifying accumulation hotspots at a northern Mediterranean scale. Density indices (items km⁻²) from the MEDITS trawl surveys (years 2013-2015) were modelled by generalized additive models using a Delta-type approach and several covariates: latitude, longitude, depth, seafloor slope, surface oceanographic currents and distances from main ports. To set thresholds for the identification of accumulation areas, the percentiles (85th, 90th and 95th) of the plastic spatial density distribution were

computed on the raster data. In the northern Mediterranean marine macro-litter was widespread (90.13% of the 1279 surveyed stations), with plastic by far the most recurrent category. The prediction map of the plastic density highlighted accumulation areas (85th, 90th and 95th percentiles of the distribution, respectively, corresponding to 147, 196 and 316 items km⁻²) in the Gulf of Lions, eastern Corsica, the eastern Adriatic Sea, the Argo-Saronic region and waters around southern Cyprus. Maximum densities were predicted in correspondence to the shallower depths and in proximity to populated areas (distance from the ports). Surface currents and local water circulation with cyclonic and anticyclonic eddies were identified as drivers likely facilitating the sinking to the bottoms of floating debris

Keywords: marine macro-litter; plastic; Mediterranean Sea; GAM modelling; accumulation areas; MEDITS.

La distribución espacial de la macro-basura marina en el fondo del Mediterráneo norte: los resultados de las campañas MEDITS

Resumen: La basura marina es una de las principales fuentes de contaminación antropogénica en el ecosistema marino representando el plástico una amenaza global. El objetivo de este trabajo es evaluar la distribución espacial de las macro-basuras plásticas en el fondo marino, identificando los hotspots de acumulación en el Mediterráneo norte. Los índices de densidad (ítems km⁻²), procedentes de las campañas de arrastre MEDITS (años: 2013-2015), fueron modelados mediante Modelos Aditivos Generalizados, utilizando un enfoque de tipo delta y varias covariables: latitud, longitud, profundidad, pendiente del fondo marino, corrientes marinas y distancias desde los principales puertos. Para establecer los umbrales para la identificación de áreas de acumulación, se calcularon los percentiles (85-90-95) de la distribución espacial de densidad de plásticos en los datos ráster. En el Mediterráneo norte, la macro-basura marina estaba muy extendida (90.13% de las 1279 estaciones muestreadas), siendo el plástico, con diferencia, la categoría más recurrente. El mapa de predicción de la densidad de plásticos resaltó las áreas de acumulación (percentiles 85, 90 y 95 de la distribución, respectivamente, correspondientes a: 147, 196 y 316 ítems km⁻²), localizadas en el Golfo de León, Córcega oriental, Mar Adriático oriental, región Argo-Saronic y aguas que rodean el sur de Chipre. Se fijaron las densidades máximas a menor profundidad y cercanas a zonas pobladas (distancia desde los puertos). Las corrientes superficiales y la circulación local del agua, con giros ciclónicos y anticiclónicos, se identificaron como factores que favorecen el hundimiento de las basuras flotantes.

Palabras clave: macro-basura marina; plástico; mar Mediterráneo; Modelos Aditivos Generalizados (GAM); áreas de acumulación; MEDITS.

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INTRODUCTION

Humans impact the marine environment in several ways, and marine litter has been considered one of the main issues of anthropogenic pollution in the marine ecosystem in the last few decades (Galgani et al. 2015). Waste quantities are continuously and globally increasing and estimates from 2010 indicate 275 million t of plastic waste generated in 192 coastal countries, with 4.8 to 12.7 million t entering the ocean (Jambeck et al. 2015).

Waste production varies between countries and has been detected worldwide in all the marine habitats (Law 2017). With more than 700 t of plastics entering the basin every day (UNEP/MAP 2015), the Mediterranean Sea remains one of the most affected basins in the world (Eriksen et al. 2014, Cózar et al. 2015, Suaria et al. 2016).

Marine litter is consequently becoming a primary political and societal concern in many countries worldwide, prompting several major policy actions by international organizations. In 2015 the leaders of G7 recognized that marine litter, in particular plastic, represents a global challenge and stressed the need to address the identification and assessment of land and sea-based sources, removal actions, and education and research development (G7 2015). More recently, the

leaders of G20 reiterated the need for an action plan (G20 2017).

The Circular Economy Action Package (EC 2015) makes the recycling of plastics a priority, while, following the Green Paper on the European Strategy on Plastic Waste in the Environment (EC 2013), a new dedicated Plastics Strategy was very recently launched, including actions on marine litter (EC 2018).

The Convention of the United Nations on the Law of the Sea (UNCLOS) agreed upon the legal framework within which all activities in the oceans and seas must be carried out (United Nations 2016), including the need to prevent, reduce and control pollution of the marine environment from any source (e.g. dumping, PART XII, art. 194). For European Member States, the Marine Strategy Framework Directive sets the framework to achieve Good Environmental Status (GES) for marine waters by 2020, with descriptor 10 of this directive focusing specifically on marine litter and considering litter on the sea floor in its indicator 10DC1. Furthermore, 22 Mediterranean countries that were contracting parties to the Barcelona Convention (UN Environment/Mediterranean Action Plan) agreed to implement a novel and ambitious Integrated Monitoring and Assessment Programme of the Mediterranean Sea and Coast and Related Assessment Criteria (IMAP). This programme enabled for the first time a

quantitative, integrated analysis of the state of the marine and coastal environment, including two common indicators on marine litter,

- the trend in the number/amount of marine litter deposited on the coast;
- the trend in the number/amount of marine litter on the water surface and the seafloor,

and one candidate indicator of marine litter impact,

- trends in the amount of litter ingested by or entangling marine organisms, especially marine mammals, birds, turtles and sharks (Galgani et al. 2014).

The main purpose was to facilitate the implementation of the Barcelona Convention and monitor related provisions to assess GES. The Meeting of the Contracting Parties in 2012 adopted ecological objectives, describing the desired results to be pursued to reach GES. In 2016 the Regional Cooperation Platform on Marine Litter in the Mediterranean was established at the invitation of the UN Environment/Mediterranean Action Plan (MAP) -Barcelona Convention Secretariat (<http://web.unep.org/unepmap/second-meeting-regional-cooperation-platform-marine-litter-mediterranean-and-first-steering>), aiming to foster the implementation of the Regional Plan on Marine Litter Management in the Mediterranean (https://wedocs.unep.org/bitstream/handle/20.500.11822/6012/13ig21_09_annex2_21_07_eng.pdf?sequence=1&isAllowed=y). This forum highlighted the need to harmonize and standardize monitoring and assessment methodologies and to ensure accuracy and predictability of the modelling tools.

Galgani et al. (2010) provided a comprehensive definition of marine litter, which is adopted in this paper. Marine litter is considered any persistent processed or manufactured materials lost, discarded or transported in the marine environment. It can originate by a direct human introduction into the natural environment: municipal sewage discharges, coastal industries, tourism, fishing, aquaculture and other offshore activities (Barnes et al. 2009, Leite et al. 2014, UNEP/MAP 2015). Intense maritime traffic is considered a potential cause of serious impacts. Indeed, marine transport is a strong traditional economic sector in the Mediterranean Sea, which is among the world's busiest waterways, accounting for 15% of global transport on water (UNEP/MAP 2012). By contrast, indirect introduction by litter dispersion could also result from the action of natural agents such as rainfall, rivers, currents, winds and natural disasters (Williams and Simmons 1985, Thompson et al. 2005, Jang et al. 2014). High accumulation rates of marine macro-litter are reported in estuaries, where heavy objects accumulate due to the reduction of water flow speed, and in deep marine waters—for example in the vicinity of canyons, where the steepness of the seafloor increases (Corcoran 2015).

Recently several papers have focused on a numerical circulation model at Mediterranean (Mansui et al. 2015, Liubartseva et al. 2018) or sub-basin scales (Liubartseva et al. 2016, Carlson et al. 2017, Politikos et al. 2017) to mimic marine litter transport and accumulation through virtual particles acting as Lagrangian tracers, also considering potential source and sink trajectories.

There is thus an increasing need to model the distribution of the marine macro-litter on the seafloor in order to provide information useful for identifying accumulation areas, and to prompt actions aimed at achieving effective management in an ecosystem conservation-oriented planning.

In the Mediterranean Sea only a few studies conducted in the northwestern basin have used explicit spatial model analysis to obtain distribution maps of marine litter on the seafloor (Galgani et al. 1996, 2000), based on direct observations from trawl surveys. A standardized collection of marine litter data over a Mediterranean-wide spatial scale was not available until the initiative in 2013 of the MEDITS project (Spedicato et al. 2019), which designed, within the framework of this scientific survey targeting demersal populations, a detailed protocol for data collection of marine litter on the seafloor (Anonymus 2017). The action was taken on a voluntary basis, though almost all the research groups involved in MEDITS felt committed to collect such data at the survey geographical scale (Fiorentino et al. 2013).

This paper therefore aims to model the distribution of marine litter on the seafloor and to identify hotspots, particularly of plastic, through a spatial analysis at a northern Mediterranean scale, using generalized additive models (GAMs) applied to the data collected in 18 geographical sub-areas (GSA; GFCM 2009).

Covariates (geographical descriptors and potential sources of litter) were used to describe their effects on the distribution of marine litter on the seafloor and accumulation areas: latitude and longitude, depth, seafloor slope, surface oceanographic currents, marine traffic and distance from main rivers and ports.

MATERIALS AND METHODS

Sampling

Marine macro-litter data were collected from the MEDITS bottom trawl survey using a standardized common protocol (Anonymous 2017) during the spring-summer of 2013, 2014 and 2015 in the following GSAs: 1, 2, 5, 6, 7, 8, 9, 10, 11, 16, 18, 19, 15 (data available for 2016), 17 (only the eastern coasts: Slovenia, Croatia), 20, 22, 23 and 25.

A total of 1279 hauls carried out yearly were distributed over the depth range 10-800 m and allocated to five bathymetrical strata (details on the stratification scheme are in the Anonymous 2017) (Fig. 1). Macro-litter data were catalogued using the nine categories and sub-categories of the MEDITS protocol (Anonymous 2017).

To obtain density indices (items km⁻²), the number of items collected per litter category was standardized to the km² according to the swept area method. Given that the time series was still short, a mean value of the density indices per haul was calculated among the available years (2013-2015) for all the GSAs. From GSAs 1, 2 and 5 only mass data (kg km⁻²) were available and could not be used in the model, which was set using observations on the number of items, because the collection of this type of data has been mandatory

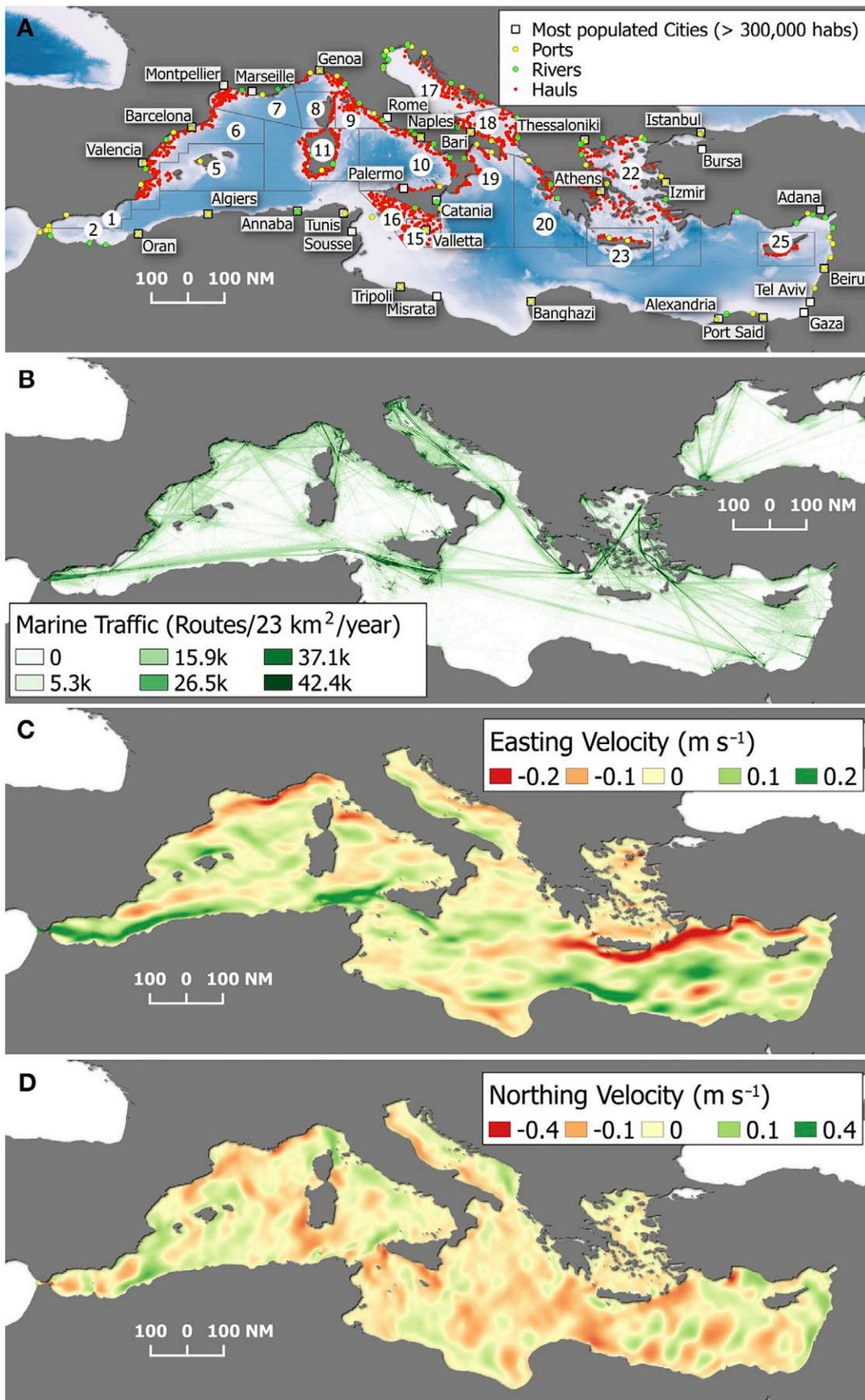


Fig. 1. – Location of the hauls (A) of the major ports and cities by GSA, maritime traffic (B) (marine traffic portal, k indicates thousand routes), easting (C) and northing (D) currents (from Mediterranean Monitoring and Forecasting Centre, Copernicus portal) used among the covariate layers of macro-marine litter observations.

Table 1. – Summary statistics of the data related to the informative layers used in the analysis (curx, easting component of the current velocity; cury, northing component of the current velocity).

	Min.	1st qu.	Median	Mean	3rd qu.	Max.
Longitude (degrees)	−0.99	12.57	15.63	16.69	24.12	34.86
Latitude (degrees)	34.39	37.42	39.76	39.81	42.22	45.76
Depth (m)	0.00	75.40	151.20	255.10	424.00	800.00
Slope (degrees)	0	0.27	0.81	1.61	2.05	48.85
Traffic (routes/23 km ² /year)	0	0	13523.1	12663.5	14133.3	42400
Distance from the rivers (km)	0	83.6	138.1	155.50	202.50	592.10
Distance from the ports (km)	0	40.31	63.73	68.73	92.63	228.17
curx (m s ^{−1})	−0.22	−0.017	−0.0006	0.003	0.02	0.87
cury (m s ^{−1})	−0.29	−0.03	−0.006	−0.01	0.01	0.24

since the beginning in the survey protocol. However, mass data of GSAs 1, 2 and 5 were used to describe the occurrence of litter categories.

Statistical analysis

An exploratory analysis was first conducted to assess the litter categories recurrent in the study areas. Hence, the frequency of occurrence of each litter category was computed. Considering the large dominance of plastic in marine macro-litters (see Fig. 2), this category (L1) was retained for modelling analysis.

To model the macro-litter distribution pattern, georeferenced informative layers were collated (Table 1), considering key factors linked to the following:

- Geographical and geomorphological characteristics (latitude, longitude, depth and bottom slope).

- Euclidean distance from the major harbours, as many studies report the highest litter densities close to the most important port cities (Watters et al. 2010, Leite et al. 2014).

- Euclidean distances from the most important river outlets, considering that considerable quantities of litter can be introduced in the marine environment by transportation from water courses (Williams and Simmons 1985, Neves et al. 2015, Lebreton et al. 2017).

- Ship traffic density (routes/23 km²/year) from the marine traffic portal, as marine traffic is also reported to be a mechanism likely linked to marine litter inputs (UNEP/MAP 2012) (Fig. 1). Marine traffic density was assigned to the hauls by sampling the raster of marine traffic density in the hauls' mean position using the R software (R Development Core Team 2013).

- Mean annual surface current velocity, both northing (cury) and easting (curx) components of sea water velocity, as the current is an important driver influencing the movement and accumulation of floating debris (Mansui et al. 2015, Carlson et al. 2017, Liubartseva et al. 2018) (Fig. 1).

Regarding geographical and geomorphological characteristics, Galgani et al. (2000) reported that in addition to the high accumulations described in the marine canyons, macro-litters are widely dispersed at slope and abyssal depths. Marine bottom geomorphology is supposed to influence the dispersion of inert materials, so the bathymetric metadata and digital terrain model data products have been derived from the EMODnet Bathymetry portal in the form of a raster file, after processing using QGIS software (QGIS Development Team 2017) to generate the bottom slope map. Informative layers of

current velocity (curx and cury) were obtained by the physical reanalysis component of the Mediterranean Monitoring and Forecasting Centre available on the Copernicus portal (<http://marine.copernicus.eu/>). Because of the coarse spatial resolution of current layers along the more nearshore areas, 69 hauls could not be included in the model prediction.

The main descriptive characteristics of the considered covariates are reported in Table 1.

The marine macro-litter density data were firstly tested for normality of distribution using the Shapiro-Wilk normality test (Shapiro and Wilk 1965), and in cases of non-normal distribution, the data were log-transformed. The spatial analysis predictions were performed using a 0.03° resolution grid, which was created sampling the above described informative layers (Table 1 and Fig. 1).

The multivariate analysis was based on the use of GAMs, a nonparametric extension of GLMs that includes smooth functions (a piecewise polynomial curve) of explanatory variables (Wood et al. 2006). GAMs are generally used when there is no a priori reason for choosing a particular response function (linear, quadratic, etc.); in this study we applied the two-steps or Delta models (Rubec et al. 2016). This method is suitable in cases of large proportions of zeros in the observations. In this Delta-type modelling approach, the positive values were fitted by a GAM using a Gaussian distribution, while the presence-absence data were fitted by a GAM with a binomial distribution. As the data predicted by the binomial model are not in the same scale as the raw data, they need to be transformed with the following formula (Zuur et al. 2012):

$$\hat{\pi}_i = \frac{e^{\text{logit}(\pi_i)}}{1 + e^{\text{logit}(\pi_i)}}$$

where $\text{logit}(\pi_i)$ is the prediction computed by the binomial GAM and π_i is the rescaled value of the prediction. The two models were then multiplied to predict the litter density values on the grid described above. The smoother function used was a penalized cubic regression spline; the procedure automatically selects the degree of smoothing based on the generalized cross-validation (GCV) score.

A step-wise procedure was used to generate GAMs, using a one-dimensional smoother for each covariate and two-dimensional smoothers for geographic coordinates and current components. Collinearity between the covariates was analysed by means of variance inflation factor (VIF) values (Zuur et al. 2010). Variables

with a high Pearson's correlation coefficient (r) (>0.5 , absolute value) and a high VIF value (>3) were considered correlated, and consequently only one of the two was retained in the following analysis. The chosen cut-off value for VIF was more conservative than the rule of thumb for VIFs (O'Brien 2007).

In the forward inclusion approach (Legendre and Legendre 1998, Wood 2001), variables are added to the model one at a time. In each step, variables that are not already in the model are tested for inclusion. Covariates were excluded from the models following three criteria: (i) the estimated degrees of freedom was close to 1; (ii) the confidence interval was zero at each point of the function; and (iii) the GCV score (Gu and Wahba 1991) decreased when the term was removed. The model uses the Gaussian error distribution belonging to the exponential family and the parameter $\gamma=1.4$ as a heavier penalty on each degree of freedom to counterbalance the tendency of overfitting.

GAMs were fitted using the *mgcv* package (Wood 2001) in the open source statistical software R, version 3.3.2 (R Development Core Team 2013). The best model was then selected using the criteria of explained deviance, the GCV score and the Akaike Information Criterion (AIC), which provides a balance between model fit and parameters used. Finally, the percentiles (85th, 90th and 95th) of the predicted distribution were computed on the raster data of the plastic spatial density, so three levels close to the higher values were empirically set to ease the identification of hotspot accumulation areas. These thresholds can also be useful as reference in monitoring programmes to assess the move towards ecological objectives.

RESULTS

In the northern Mediterranean Sea marine macro-litter is widely distributed and was found at 90.13%

of the 1279 surveyed stations. In the Gulf of Lions (GSA 7), eastern Corsica (GSA 8), the Ligurian and northern Tyrrhenian seas (GSA 9) and Crete (GSA 23), 100% of the hauls were positive to bottom macro-litter. Overall, plastic is by far the most recurrent macro-litter category, with a frequency of occurrence ranging from around 58% in Sardinian waters (GSA 11) to about 99% in the Gulf of Lions (GSA 7). In most of the GSAs the frequency of occurrence is higher than 90%. Secondly, macro-litter categories such as metal (L3), clothes/natural fibres (L4) and glass/ceramic/concrete (L5) had a frequency of occurrence ranging from 20% to 30% (Fig. 2). Plastic was mostly between 70% and 90% of all the macro-litter when computed on a density index (items km^{-2}).

Overall, density indices (Fig. 3) per GSA were quite similar except in GSA 7 (Gulf of Lions), GSAs 22 and 23 (Aegean Sea), GSA 25 (southern Cyprus waters) and, to a greater extent, GSA 8 (eastern Corsica), in all of which density was higher than average. If depth is considered, the density among the strata was, on average, quite comparable among GSAs, except in the deeper strata in GSA 8, where extremely high density indices of plastic were observed. In most of the GSAs, in depth strata B and C (51-200 m) the mean density was higher than that in the other depth strata (Fig. 3). On average at GSA level, the density in terms of items km^{-2} ranged from 534 in eastern Corsica to 198, 136 and 112, respectively, in the waters around Cyprus, the Aegean Sea (especially the Argo-Saronic region), including Crete, and the northern-central Adriatic Sea (eastern side). The seafloor around the northern Ionian Sea, Sardinia and Malta was less impacted (36, 39, and 32 items km^{-2} , respectively) than the other areas (Fig. 3).

A bubble plot of the plastic density indices by haul (items km^{-2}) is presented in Figure 4, showing areas with higher plastic density in the Gulf of Lions (GSA

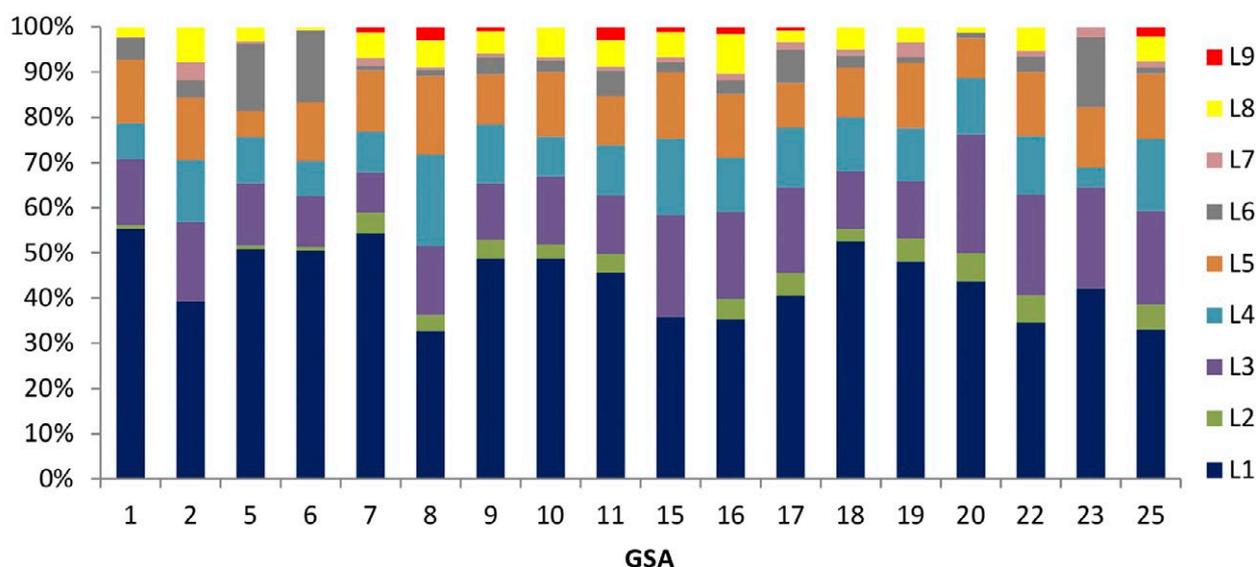


Fig. 2. – Frequency of occurrence (in percentage) of litter categories by GSA in all the hauls. Occurrences were computed for density data (items km^{-2}), except GSAs 1, 2 and 5, where they were computed for mass data (kg km^{-2}) (L1, plastic; L2, rubber; L3, metal; L4, glass, ceramic and concrete; L5, clothes/natural fibres; L6, processed wood; L7, paper and cardboard; L8 other; L9, unspecified).

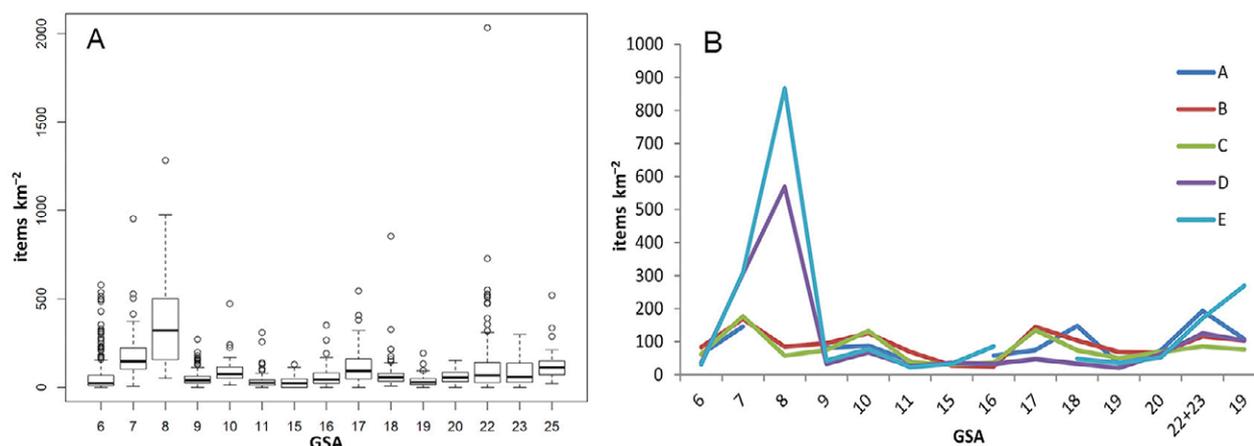


Fig. 3. – Box plots (2013–2015) of the density indices of plastic (in items km⁻²) (A) and average by GSA and depth stratum (B); A, 10–50 m; B, 51–100 m; C, 101–200 m; D, 201–500 m; E, 501–800 m (data refer to the average among the three years).

Table 2. – Main results of the tested models (X, Longitude; Y, Latitude; curx, easting component of the current velocity; cury, northing component of the current velocity). The best model used in the analysis is highlighted in bold, while the models in italics were excluded because the estimated degrees of freedom of at least one smoother was close to 1. R², determination coefficient; % dev, deviance in percentage; GCV, generalized cross-validation; AIC, Akaike information criterion.

N	Models	R ²	% dev.	GCV	AIC
1	marine litter ~ s(X, Y)	0.300	30.0%	9910	13075
2	marine litter ~ s(depth)	0.001	0.1%	13111	13404
3	marine litter ~ s(slope)	0.009	1.3%	13085	13399
4	marine litter ~ s(traffic)	0.002	0.3%	13105	13403
5	marine litter ~ s(river)	0.046	5.0%	12603	13358
6	marine litter ~ s(ports)	0.000	0.0%	13114	13405
7	marine litter ~ s(curx, cury)	0.071	8.7%	12564	13343
8	marine litter ~ s(X, Y)+s(curx, cury)	0.440	45.0%	8140	12845
9	marine litter ~ s(X, Y)+s(depth)	0.430	40.4%	8599	12914
10	marine litter ~ s(X, Y)+s(slope)	0.339	32.8%	9660	13042
11	marine litter ~ s(X, Y)+s(river)	0.310	32.4%	9665	13044
12	marine litter ~ s(X, Y)+s(traffic)	0.284	28.2%	10124	13099
13	marine litter ~ s(X, Y)+s(ports)	0.300	30.0%	9910	13075
14	marine litter ~ s(X, Y)+s(curx, cury)+s(depth)	0.507	51.2%	7393	12732
15	marine litter ~ s(X, Y)+s(curx, cury)+s(slope)	0.478	48.8%	7758	12785
16	marine litter ~ s(X, Y)+s(curx, cury)+s(traffic)	0.456	46.8%	8045	12825
17	marine litter ~ s(X, Y)+s(curx, cury)+s(ports)	0.440	45.0%	8140	12845
18	marine litter ~ s(X, Y)+s(curx, cury)+s(river)	0.462	47.4%	7950	12812
19	marine litter ~ s(X, Y)+s(curx, cury)+s(depth)+s(slope)	0.521	53.0%	7270	12706
20	marine litter ~ s(X, Y)+s(curx, cury)+s(depth)+s(river)	0.520	52.9%	7277	12707
21	marine litter ~ s(X, Y)+s(curx, cury)+s(depth)+s(traffic)	0.524	53.0%	7289	12708
22	marine litter ~ s(X, Y)+s(curx, cury)+s(depth)+s(ports)	0.507	51.2%	7393	12732
23	marine litter ~ s(X, Y)+s(curx, cury)+s(depth)+s(slope)+s(ports)	0.523	53.3%	7266	12703
24	marine litter ~ s(X, Y)+s(curx, cury)+s(depth)+s(slope)+s(traffic)	0.519	52.6%	7295	12711
25	<i>marine litter ~ s(X, Y)+s(curx, cury)+s(depth)+s(slope)+s(river)</i>	0.516	52.3%	7322	12717
26	<i>marine litter ~ s(X, Y)+s(curx, cury)+s(depth)+s(slope) +s(ports)+s(traffic)</i>	0.524	53.4%	7248	12701

7), eastern Corsica (GSA 8), the eastern coasts of the Adriatic Sea (GSA 17 and GSA 18), the Argo-Saronic region of Greece (GSA 22) and southern Cyprus waters (GSA 25). As multicollinearity was not detected by either Pearson’s correlation coefficient (<0.5, absolute values) and VIF values (<3), all the covariates reported in the Table 1 were included in the analysis.

The main results of the tested models are reported in Table 2. The best model was selected taking into account the lowest GCV value, the highest percentage of explained variance, the AIC (GCV=7265.7; AIC=12703.4; %DEV=53.3%) and the significance level of the smoothing functions. The selected GAMs (see Equations 1 and 2) identified statistically significant additive effects of latitude and longitude, current components, depth, slope and distance from ports, with latitude, longitude, current velocity and depth explaining most of the deviance:

$$\log(\mu_i) \sim \alpha + f_1(\text{Lon}_i, \text{Lat}_i) + f_2(\text{curx}_i, \text{cury}_i) + f_3(\text{depth}_i) + f_4(\text{slope}_i) + f_5(\text{ports}_i) + \epsilon \quad (1)$$

$$\text{logit}(\mu_i) \sim \beta + g_1(\text{Lon}_i, \text{Lat}_i) + g_2(\text{curx}_i, \text{cury}_i) + g_3(\text{depth}_i) + g_4(\text{slope}_i) + g_5(\text{ports}_i) + \epsilon \quad (2)$$

The binomial model (2) described 20.5% of the explained deviance in presence-absence data. All the variables used in the model had a significant effect on the probability of macro-litter presence (Table 2).

Smooth term prediction for each of the four smooth terms used in the GAM and in the presence-absence GAM are reported in Figure 5. The smoothing terms show the presence of four local maxima for the depth effect at approximately 200, 400 and 600 m depth (Fig. 5A, left panel). The effect of the distance from the ports is high in the proximity of the important port cities, lower at intermediate distances (around 80 km) and then in-

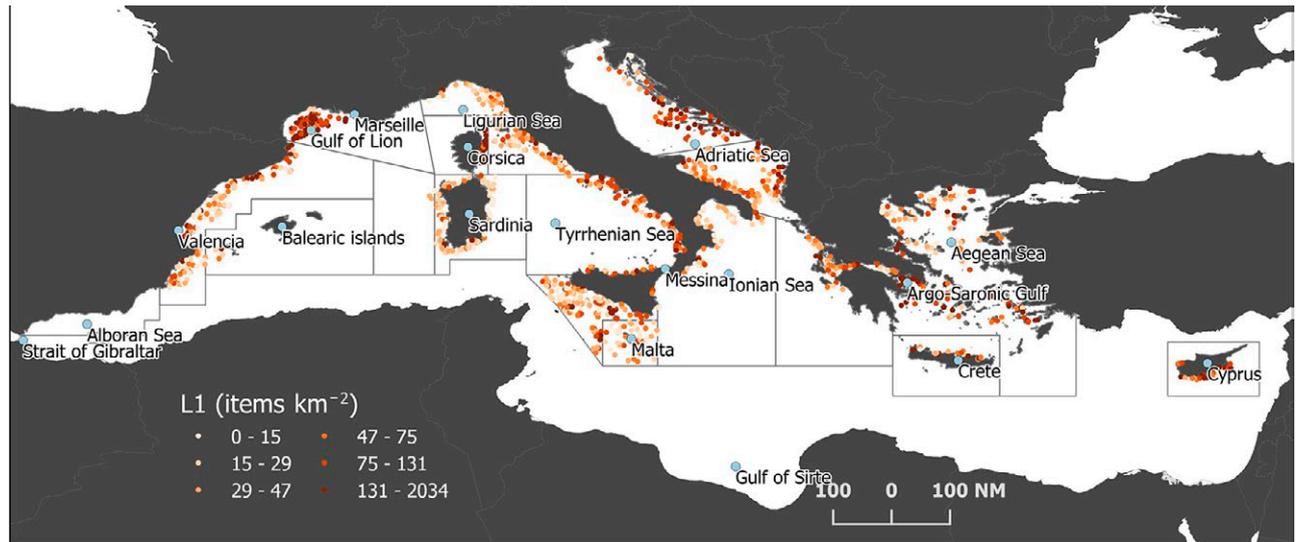


Fig. 4. – Bubble plot of plastic data by haul from the MEDITS surveys of 2013, 2014 and 2015; for each haul an average value among the three years is showed.

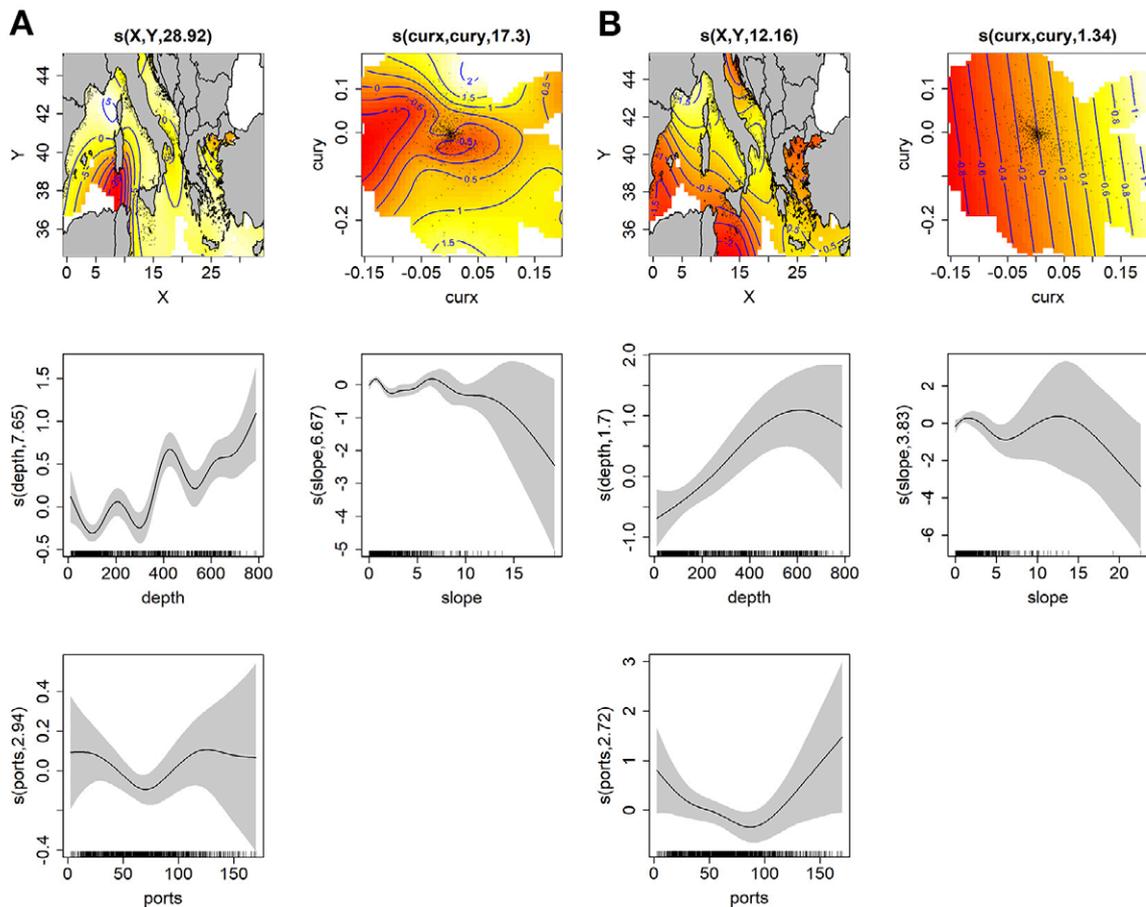


Fig. 5. – Smooth term prediction for each of the five smooth terms used in the GAM of litter density (X, longitude; Y, latitude) (A, two panels) and the presence-absence GAM (B, two panels).

creases again at greater distances. The slope effect is quite stable at the lower slope level and decreases at levels of around 12. Table 3 reports descriptive statistics related to observations, predictions and residuals. No trends were detected in the residuals and the predictions matched the observations (Pearson correlation coefficient=0.72).

Table 3. – Comparison between predictions and observations using the quantile distributions of the data.

	Min.	1st qu.	Median	Mean	3rd qu.	Max.
observations	0	21.48	45.58	79.19	92.89	1283.94
predictions	1.75E-22	11.36	46.19	70.49	99.50	1110.37
residuals	-226.80	-32.56	6.32	8.71	39.35	453.30

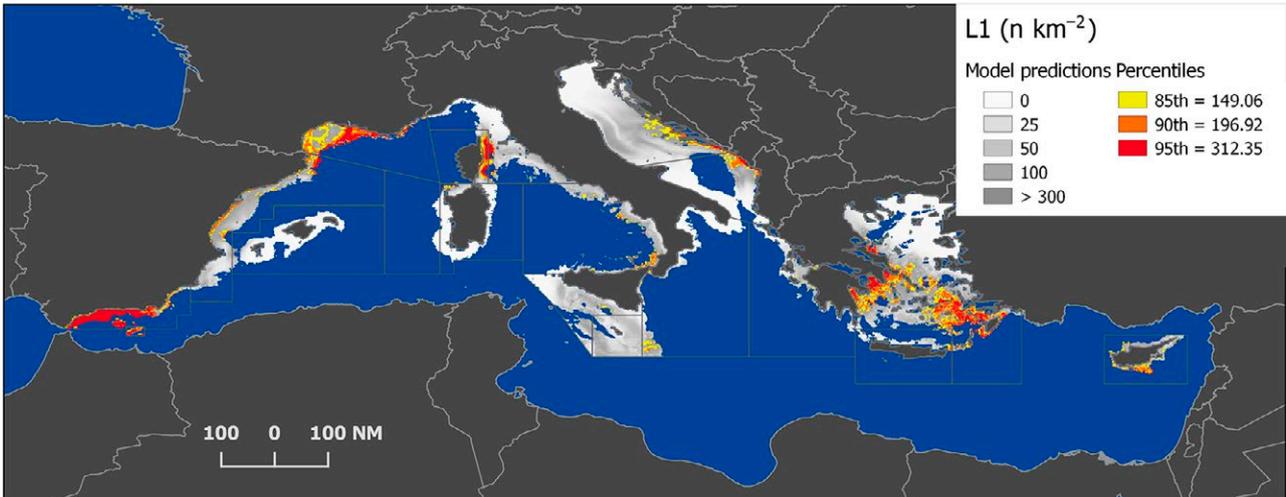


Fig. 6. – Map of the model predictions of plastic density on the seafloor in the northern Mediterranean basin. Density thresholds to identify hotspot areas are indicated in the legend in correspondence to the 85th, 90th and 95th percentiles of the raster data.

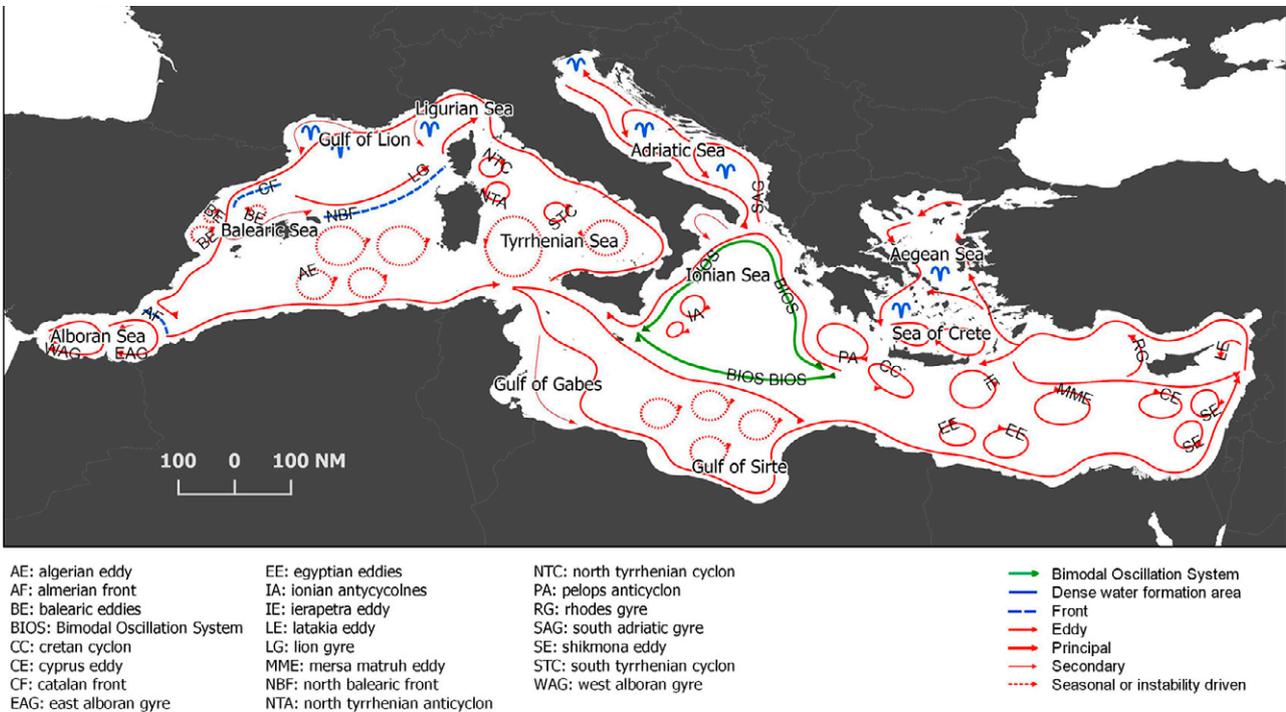


Fig. 7. – Map of the general circulation patterns in the Mediterranean basin (data obtained from the Oceanography WMS service of the CoCoNet portal).

Figure 6 illustrates the map of the model predictions of plastic density in the northern Mediterranean basin, highlighting hotspots in terms of threshold densities corresponding to the 85th (149.1 items km⁻²), 90th (196.9 items km⁻²) and 95th (312.3 items km⁻²) percentiles. Figure 7 shows the map of the general circulation patterns in the Mediterranean basin based on data obtained from the Oceanography WMS service of the CoCoNet portal.

DISCUSSION

This study gives evidence of widespread presence of marine macro-litter at a northern Mediterranean ge-

ographical scale, occurring at 90% of the 1279 examined stations sampled yearly during the MEDITS survey in the period 2013-2015. This occurrence ranged from about 69% in Sardinian waters (GSA 11) to 100% in the Gulf of Lions, eastern Corsica, the Ligurian and northern Tyrrhenian seas, and waters around Crete (respectively GSAs 7, 8, 9 and 23). Plastic was the most abundant litter category sinking on the seafloor, as stressed in previous studies (e.g. Iñiguez et al. 2016) in the Ligurian and northern Tyrrhenian Sea (e.g. Serena et al. 2011), the waters around Malta (Mifsud et al. 2013, Pace et al. 2007), the Strait of Sicily (Fiorentino et al. 2015), the northern Adriatic Sea (Strafella et al. 2015, Pasquini et al. 2016, Melli et al. 2017) and the

Aegean Sea (e.g. Stefatos et al. 1999, Lefkaditou et al. 2013, Ioakeimidis et al. 2014).

Among marine litter materials, plastic is surely the most resistant to biodegradation and the most easily transportable by wind and current. For the moment little or no information is available regarding the lifetime of the synthetic polymers in the environment, and only a few studies have examined the lifetime of plastic items lying on the seafloor of the Mediterranean (Ioakeimidis et al. 2016). In general, the use of additives improves the resistance properties of plastics, explaining the proportion of plastic in comparison with other litter materials, as observed in all the surveyed GSAs of this study. Before sinking on the seafloor, plastic marine litter could have been transported from the place of origin on the water surface or in the water column in response to the local oceanographic conditions, which can facilitate the accumulation of macro-litter even far from the expected accumulation sites (such as in the proximity of ports or rivers estuaries) (Frias et al. 2014, Corcoran 2015, Lusher 2015).

On average, depths ranging from 50 m to approximately the border of the continental shelf (200 m) were the most affected by the presence of plastic, though exceptions were observed in deeper waters. For example, in eastern Corsica, values were higher on seafloors deeper than 200 m and especially between 500 and 800 m depth. This is not surprising given that the variability within a GSA was sometimes higher than that between GSAs, indicating a contagious distribution of plastic on the seafloor, but also the fact that several factors may affect this distribution (e.g. Sánchez et al. 2013, Pham et al. 2014), as discussed below.

The objective of identifying hotspots of plastic accumulation was achieved using GAM modelling and testing geographical, environmental and anthropogenic variables, to highlight the most important drivers influencing accumulation in the sinking areas. A wide range of mechanisms is potentially responsible for litter accumulation in the marine environment. Highly populated centres are the potential primary origin of marine macro-litter, as wastes are produced by direct disposal of domestic or tourism infrastructure activities to the sea (UNEP/MAP 2009) or through river inputs (Stefatos et al. 1999, Ioakeimidis et al. 2014, Iníguez et al. 2016). Marine traffic activities could also be an important source of marine macro-litter (UNEP/MAP 2012, Munari et al. 2016, Pasquini et al. 2016).

However, the model proposed here recognizes that both bottom depth and slope are important drivers for the retention of plastic macro-litter. Looking at the density model smoothing terms, the depth effect shows the presence of four local maxima. The first corresponds to shallower waters, while the others are at approximately 200, 400 and 600 m depth. The maximum corresponding to the shallower depths is likely linked to the proximity to populated areas and human activities. This also appears quite evident from the effect of the distance from ports, which shows the highest levels of accumulation in the proximity of major port cities, where litter disposal very likely has the highest rates, such as in the areas of Valencia (GSA 6), Mar-

seille (GSA 7) and the Argo-Saronic region, where the most important Greek port is located (Lefkaditou et al. 2013). Other less prominent hotspots were identified in the Gulf of Salerno, on the Tyrrhenian side of the Strait of Messina (close to the ports of Messina and Gioia Tauro) and in the area of Limassol port in Cyprus. The effect is lower at intermediate distances (around 80 km) but increases again far from the port areas, as in the Gulf of Lions, because other factors also affect the litter distribution.

The slope has an interesting effect, and the accumulation is quite stable at lower slope steepness. However, when the slope increases and the litter cannot be retained by the seafloor, the accumulation is lower. Galgani et al. (1996, 2000) also reported evidence of the strong relation between the geomorphological characteristics of the seafloor, such as the presence of rocks, wrecks, depressions and channels, and the spatial distribution of marine litter.

The association of topographic and hydrodynamics components is also a pivotal factor influencing the dispersion or accumulation of marine macro-litter. Weak currents, for example, may facilitate deposition on shores, bays and lagoons more than in the open ocean (e.g. Dameron et al. 2007, Serena et al. 2011). Sinking macro-litter on continental shelves can be instead washed by bottom currents or by strong water flow from rivers towards deep submarine canyons, where it is tapped and accumulates, or even towards bathyal plains (Galgani et al. 1996, Lee et al. 2006, Cau et al. 2018). The bathymetric profile and the slope of the marine bottom are thus responsible, in combination with the local hydrography, for the peculiar descent of macro-litter. Investigating more complex topographies that are accessible only with other investigation tools (e.g. Angiolillo et al. 2015, Cau et al. 2017, Melli et al. 2017) might, in turn, provide further insights.

The GAM modelling highlighted the presence of hotspots of accumulation on the bottoms in the Strait of Gibraltar, the Gulf of Valencia, the Gulf of Lions, eastern Corsica, the eastern side of central-southern Adriatic Sea, the Argo-Saronic region, the eastern Aegean near the coasts of Asia Minor and the southern side of Cyprus. By analysing the geographic smooth term prediction of the model and mapping results, it is possible to identify the position of hotspots of plastic accumulation, mainly localized in the western and eastern parts of the Mediterranean, while the central part of the basin appears less affected. However, it should be considered that no data from the western part of the northern Adriatic Sea were available for the analysis. Strafella et al. (2015) and Pasquini et al. (2016) reported a high marine litter concentration in this area, showing that the northern part of the Adriatic basin must be one of the most polluted areas of the Mediterranean Sea.

The model proposed in this paper recognized the surface current effect as another relevant factor responsible for the dispersion of marine macro-litter in marine environments and influencing the formation of hotspots of plastic accumulation. The Atlantic current (AW) enters the Mediterranean Sea through the Strait of Gibraltar, also transporting floating plastic debris

in the western Alborán following the Western Anticyclonic Gyre (Renault et al. 2012) (Fig. 7). Conversely, the surface outflow current towards the Atlantic Ocean is insignificant, thus limiting the possibility of litter expulsion. The entering flow of Atlantic water determines a surface circulation describing along-slope anticyclonic gyres, which could facilitate the sinking of floating debris to the bottoms and be responsible for the western hotspot highlighted by the model close to the Strait of Gibraltar. Another important retention area was recognized in the northwestern Mediterranean basin (Galgani et al. 1996, Mansui et al. 2015), where the Western Gyre of the Northern Current flows along the slope from the Ligurian Sea up to the Catalan area, forming frontal systems mainly along the shelf break and anticyclonic eddies mostly during the warm season (Millot and Taupier-Letage 2005, Karimova 2017, Zambianchi et al. 2017). In addition, the canyons of the Gulf of Lions seem to show a trap effect on the dense water formed in the coastal zone, moving them towards deeper waters (Millot and Taupier-Letage 2005). Furthermore, the circulation pattern in the western basin generates in the eastern part of the Strait of Bonifacio a system of coupled cyclonic and anticyclonic eddies which could be responsible for the plastic debris accumulation observed along the eastern coasts of Corsica. By contrast, Sardinian waters remain quite unaffected by this local circulation.

The main circulation in the Adriatic Sea is guaranteed by the warm waters that move northward along the eastern coasts and the northern Adriatic current that moves in the opposite direction, conveying the fresh waters of the Po river towards the western-middle Adriatic current (Artegiani et al. 1997). There is, however, another component likely influencing the advection of the macro-litter and accumulation areas identified by the GAM to a larger extent on the eastern-southern side of the basin along the southern Croatian and Montenegrin coasts, i.e. the Middle Adriatic and Southern Adriatic cyclonic gyres (characterized by seasonal variations) (Artegiani et al. 1997, Millot and Taupier-Letage 2005). This advection has also been modelled by other authors (Liubartseva et al. 2016, Carlson et al. 2017), but using simulations for mimicking the trajectories of passive particles through Lagrangian modelling.

The topography of the eastern basin of the Mediterranean Sea has a crucial role in influencing one of the most important components of the water movements in this area: the Mid-Mediterranean Jet (MMJ) of the Levantine basin (Robinson et al. 1992), which bifurcates into two branches. The northern branch of the MMJ, pointing to Cyprus and then northward to feed the Asia Minor Current, and the Cretan Cyclon (Robinson et al. 2001) might be responsible for hotspots of macro-litter accumulation in this part of the basin. The Asia Minor Current is also important because it reaches the waters around the Island of Rhodes, where the GAM predicts another noteworthy hotspot.

Considering the floating macro-litter, Mansui et al. (2015), simulating advection due to surface circulation, depicted the Tyrrhenian Sea, the northeast of the Balearic Islands and the Gulf of Sirte as possible litter

accumulation areas in the western Mediterranean and the whole coastal strip from Tunisia to Syria as the favourite destination in the eastern basin. The formation of deep waters in winter and the convergence caused by anticyclonic eddies (Pinaridi and Masetti 2000) should facilitate the sinking of light plastics from the more superficial levels to the bottoms. Dense plastic materials (e.g. vinyl chloride and polyethylene terephthalate) are negatively buoyant, falling down to the seafloor (Andrady 2011), but even low-density synthetic polymers may sink under the weight of fouling. Because of the inhibition of plastic degradation (e.g. UV-induced photo-degradation reactions; Cooper and Corcoran 2010, Andrady 2015) in the proximity of the seafloor, benthic litters are generally composed of near-intact items or their fragments. All these elements contribute additive factors to plastic accumulation on the seafloor.

The most important risk linked to the presence of plastic for living organisms is that of physical injuries, especially caused by ingestion (Camedda et al. 2014, Gall and Thompson 2015, Pellini et al. 2018) after fragmentation and entanglement in fishing gear litter (Consoli et al. 2018, Gall and Thompson 2015). This risk is increased by the high accumulation rate and ubiquity of macro-litter. However, damage can also affect operation of fishing gears—for example, when selection grids are used (Werner et al. 2016).

Policy strategies to contrast marine litter, such as incentivized responsible waste management, the Circular Economy Action Package, replacing non-biodegradable plastics with other biodegradable materials and schemes for cleaning, sustainable consumption and production, and extended producer responsibility need information on the characterization, quantification and location of existing amounts of plastic marine litter. These strategies also require regular monitoring of the marine environment against agreed threshold values (currently agreed in the Mediterranean in the framework of the Barcelona Convention, while a similar initiative is ongoing at a European Union level) to verify the effectiveness of the measures.

Regularly collecting data on the real presence and accumulation of macro-litter on the seafloor is a pivotal point. Different kinds of sampling methods have been reported in literature for the characterization and assessment of marine litter on the seafloor. Spengler and Costa (2008) reviewed 26 studies and identified bottom trawl surveys as the most used method. Trawl surveys indeed give the possibility of exploring large seafloor areas at a wide range of depths using a standardized approach. Thus, spatial and temporal trend analyses of the collected data can be essential for setting reference points, or baselines, and monitoring the progressive achievement of agreed targets. A reference direction suggested by Ecological Objective 10 of the UNEP Mediterranean Action Plan (UNEP 2016) is, for example, to reduce seafloor litter by 10% in 5 years, considering a baseline of 130-230 items km⁻² of marine macro-litter with a mean of 179 items. However, the availability of more detailed information at a wider geographical scale might suggest, for example, that baseline values should be revised in the future. In this

paper, using trawl survey data at a Mediterranean-wide scale, we have identified three thresholds of macroplastic distribution on the seafloor, which can be used as a benchmark for assessing the move towards ecological objectives.

So far, modelling marine litter distribution and accumulation at a Mediterranean (Lebreton et al. 2012, Liubartseva et al. 2018) or sub-basin level (Carlson et al. 2016, Liubartseva et al. 2016, Politikos et al. 2017) has used Lagrangian modelling to mimic the dispersion of floating items, thus requiring validation of the predictions. Future research could link surface advection patterns with sinking processes and accumulation on the seafloor. Spatially explicit modelling is a powerful tool for environmental and conservation planning. The results of this paper provide a focus on the distribution of plastic marine macro-litter on the seafloor at a northern Mediterranean scale. Due to the expected accumulation of floating macro-litter on the southern coasts of the eastern basin (Mansui et al. 2015), monitoring on bottoms off southern countries of the Mediterranean would be beneficial to increase our knowledge on macro-litter distribution.

The GAM modelling approach used here allowed us to assess, through multiple predictors, the contemporary effects of explanatory variables on the spatial distribution of plastic macro-litter and to localize, for the first time at a wide geographical scale, hotspots of plastic accumulation associated with specific density values (items per km²). This use of GAM modelling is likely only the starting point for further studies aimed at giving insight to the distribution and accumulation of other litter categories and sub-categories.

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