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Effects of natural and anthropogenic processes in the distribution of marine litter in the deep Mediterranean Sea

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ABSTRACT

The distribution, type and quantity of marine litter accumulated on the bathyal and abyssal Mediterranean seafloor has been studied in the framework of the Spanish national projects PROMETEO and DOS MARES and the ESF-EuroDEEP project BIOFUN. Litter was collected with an otter trawl and Agassiz trawl while sampling for megafauna on the Blanes canyon and adjacent slope (Catalan margin, north-western Mediterranean) between 900 and 2700 m depth, and on the western, central and eastern Mediterranean basins at 1200, 2000 and 3000 m depth. All litter was sorted into 8 categories (hard plastic, soft plastic, glass, metal, clinker, fabric, longlines and fishing nets) and weighed. The distribution of litter was analysed in relation to depth, geographic area and natural (bathymetry, currents and rivers) and anthropogenic (population density and shipping routes) processes. The most abundant litter types were plastic, glass, metal and clinker. Lost or discarded fishing gear was also commonly found. On the Catalan margin, although the data indicated an accumulation of litter with increasing depth, mean weight was not significantly different between depths or between the open slope and the canyon. We propose that litter accumulated in the canyon, with high proportions of plastics, has predominantly a coastal origin, while litter collected on the open slope, dominated by heavy litter, is mostly ship-originated, especially at sites under major shipping routes. Along the trans-Mediterranean transect, although a higher amount of litter seemed to be found on the Western Mediterranean, differences of mean weight were not significant between the 3 geographic areas and the 3 depths. Here, the shallower sites, also closer to the coast, had a higher proportion of plastics than the deeper sites, which had a higher proportion of heavy litter and were often affected by shipping routes. The weight of litter was also compared to biomass of megafauna from the same samples. On the Blanes slope, the biomass of megafauna was significantly higher than the weight of litter between 900 and 2000 m depth and no significant differences were found at 2250 and 2700 m depth. Along the trans-Mediterranean transect, no significant differences were found between biomass and litter weight at all sites except in two sites: the Central Mediterranean at 1200 m depth, where biomass was higher than litter weight, and the Eastern Mediterranean at 1200 m depth, where litter weight was higher than biomass. The results are discussed in the framework of knowledge on marine litter accumulation, its potential impact on the habitat and fauna and the legislation addressing these issues.

1. Introduction

The deep sea is the largest and most remote ecosystem on Earth and, consequently, one of the least studied. What little we know provides evidence that the deep seafloor comprises one of the highest biodiversities of the Planet as well as valuable biological and mineral resources (Ramirez-Llodra et al., 2011a). However, because of their remoteness, deep marine habitats have long been out of sight – and therefore out of mind – for policymakers and society in general. This unawareness has facilitated waste and litter discard into the sea in the absence of regulations. In the framework of the Barcelona Convention (1976), the Mediterranean countries adopted, in 1980, a protocol for the protection of the Mediterranean Sea against pollution from land-based sources (UNEP, 2009). In the revised version of this protocol (1996), marine litter was defined as "any persistent, manufactured or processed solid material discarded, disposed of or abandoned in the marine and coastal environment" (UNEP, 2009).

Most studies on marine litter quantification have investigated floating debris (Aliani et al., 2003; Barnes, 2002; Barnes and Milner, 2005; Day and Shaw, 1987; Lecke-Mitchel and Mullin, 1992; Thiel and Haye, 2006) and coastal areas (Gabrielides et al., 1991; Gottfried et al., 1987; Hess et al., 1999; Katsanevakis and Katsarou, 2004; Pruter, 1987). Some information is also available from shelf habitats (Galgani et al., 1995a, 1995b, 2000; Stefatos et al., 1999),

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but very little has been done on deep slopes and basins (Spengler and Costa, 2008) because of the technical and financial limitations on sampling at great depths. Multidisciplinary and coordinated research in the last decades has provided evidence of accumulation of marine litter and insights into the impacts caused on bathyal and abyssal habitats and fauna (Bergmann and Klages, 2012; Galgani and Andral, 1998; Galgani et al., 1996, 2000, 2010; Galil et al., 1995; Miyake et al., 2011; Mordecai et al., 2011; Watters et al., 2010).

The first systematic disposal of anthropogenic waste reaching deep waters dates from the end of the 18th century, with the start of the use of steam engines. For 150 years, the residues of burnt charcoal (clinker) used to power ship engines were dumped overboard, sinking along shipping lines to the bottom of the sea. Because of its persistence, clinker is commonly found on the margins and abyssal plains of all oceans. Evidence is available, however, of human artefacts such as amphorae on the deep seafloor from much earlier times (see Section 3, below). Since the 20th Century, the main sources of marine litter include land-originated pollution, river discharges, lost fishing gear and illegal dumping from ships and offshore installations (Ramirez-Llodra et al., 2011a; UNEP, 2009). The London Convention on the Prevention of Marine Pollution by Dumping of Wastes has been in force since 1975. It was replaced by the London Protocol, which entered into force in 2006, but only four Mediterranean countries ratified it. However, illegal dumping of litter, together with the advection of waste from coastal areas and river discharges, are still a major problem, with an estimate of 6.4 million tonnes of litter entering the oceans each year (UNEP, 2009). Marine litter accumulates mainly close to main cities, along shipping lanes and, in the deep sea. Certain topographic features such as canyons facilitate the transport and deposition of litter in specific areas. The common marine litter types are plastics, glass and metal (UNEP-MAP-WHO-MEDPOL, 2011; UNEP, 2009). Since the mass production of plastics began in the 1950s, the use of plastics has increased continuously, and so has its waste. The result is that plastics are the most important type of marine litter worldwide (reviewed in (Derraik, 2002)), making up 60–80% of total marine litter (Gregory and Ryan, 1997) and with significant effects on the habitat and its fauna. Plastics are occasionally ingested by marine organisms including fish, marine mammals, marine turtles and seabirds, causing at times lethality (Gregory, 2009). Plastics can physically damage sessile and fragile fauna such as sponges or corals, and they constitute a major source of chemical pollutants such as polyethylene and polypropylene (Burgess-Cassler et al., 1991). The characteristics that have made the use of plastics ubiquitous (i.e. strong, light, durable and cheap) may harm the environment. The longevity of plastics, although still debated, ranges from hundreds to thousands of years (Barnes et al., 2009), and it is estimated that all conventional plastics that have entered the oceans to date still remain un-mineralised in the environment at different stages of fragmentation (Thompson et al., 2005). Because of their buoyancy, plastics may drift and disperse long distances and, when sinking to the seafloor, persist there for centuries (Goldberg, 1995; Goldberg, 1997). Plastic degrades to small particles down to microplastics (microscopic particles of eroded plastic) that are becoming more common in oceans, including the deep sea, and may be a source of chemical additives or hydrophobic waterborne pollutants to the fauna (Cole et al., 2011; O'Brine and Thompson, 2010; Thompson et al., 2009).

The Mediterranean is a closed sea with two deep basins separated by the strait of Sicily (400 m deep), reaching a maximal depth of 5121 m at the Matapan-Vavilov Trench (Vanney and Gennesseaux, 1985) and opened to the Atlantic through the shallow strait of Gibraltar (350 m deep) (Sardà et al., 2004b; Tyler, 2003). The Mediterranean geomorphology is characterised by a narrow shelf and high abundance of submarine canyons and gullies that may act as pathways for transportation of particles from the coast towards the bathyal and abyssal areas of the basin. The Mediterranean coast is densely inhabited and its waters have been used for millennia for the transportation of people and goods, as well as for fishing and resources exploitation. All these characteristics are key factors in the arrival and accumulation of marine litter on the Mediterranean seafloor, from the coast to abyssal depths. Although several local studies on the accumulation of marine litter on the deep seafloor have been conducted in the Eastern Mediterranean (Galil et al., 1995) and off the French coast (Galgani et al., 1996, 2000), little is known to date on the distribution, types and quantities of litter accumulated on most slopes and deep basins in the Mediterranean and no information is available at the basin scale. In this study, we analyse litter data collected in the framework of two ecological studies of bathyal and abyssal Mediterranean habitats with the final aim to provide new information on litter accumulation and distribution in the Mediterranean Sea. The first two surveys investigated in detail marine litter accumulation at a local scale, in the Blanes canyon and adjacent open slope (Catalan margin, NW Mediterranean) from 900 to 2700 m depth. The third survey investigated the accumulation of marine litter at the regional scale, from the Western to the Eastern Mediterranean Sea from 1200 to 3000 m depth. The overall goal of this study was to describe litter distribution by depth and geographic region, describe and quantify litter types and analyse potential relationships with depth and region in relation to natural processes (seafloor geomorphology, general hydrographical settings and main rivers) and anthropogenic processes (shipping routes and coastal population density).

2. Materials and methods

2.1. Study area

Marine litter on the bathyal and abyssal Mediterranean seafloor was sampled in the framework of three projects. During the PROMETEO project (CYCIT, CTM2007-66316-C02/MAR) and the ongoing DOS MARES project (CTM2010-21810-C03-03), marine litter was sampled in the Blanes canyon and adjacent open slope (Catalan margin, NW Mediterranean) (Fig. 1). Samples were taken at 900, 1050, 1200, 1350, 1500, 1750, 2000, 2250 and 2700 m on the slope, and at 900, 1500 m in the canyon during 5 PROMETEO cruises. Further samples were collected in this area in the first DOS MARES cruise, extending the sampled depth range in the canyon down to 2250 m (Table 1). This study area comprises the Blanes canyon thalweg and the western adjacent open slope area. In the canyon, trawls were conducted at 3 depths: inside the deeper part along the thalweg at 900 m at the foot of the eastern canyon wall, in the middle canyon at 1500 m and in the lower bathyal part of the canyon at 2250 m (Table 1). None of the sites are directly related to a tributary draining channel. Morphologically, the canyon is most incised in the middle part and in the lower part it expresses a smooth topography. The sampling site at 900 m is located at the base of the steepest eastern flank of the canyon with slopes between 3° and 14° and is narrow (about 400 m width). At the 1500 m sampling site, slopes are as low as 1.5–2.5°. In the lower part, the incision is broad and smooth with slopes less than 1° and a width of over 6 km. The first two sites are found relatively close to the coastline and shelf, at 10 and 24 km off the coast respectively. The abyssal site is about 80 km from the coastline. Geologically, the Blanes canyon is a continuation of the Tordera River and drains the water over the shelf northeast of the canyon mouth, main thalweg and various tributary channels (Zúñiga et al., 2009). The open slope sampling sites are located south to south west and down current of the canyon. The slope gradients

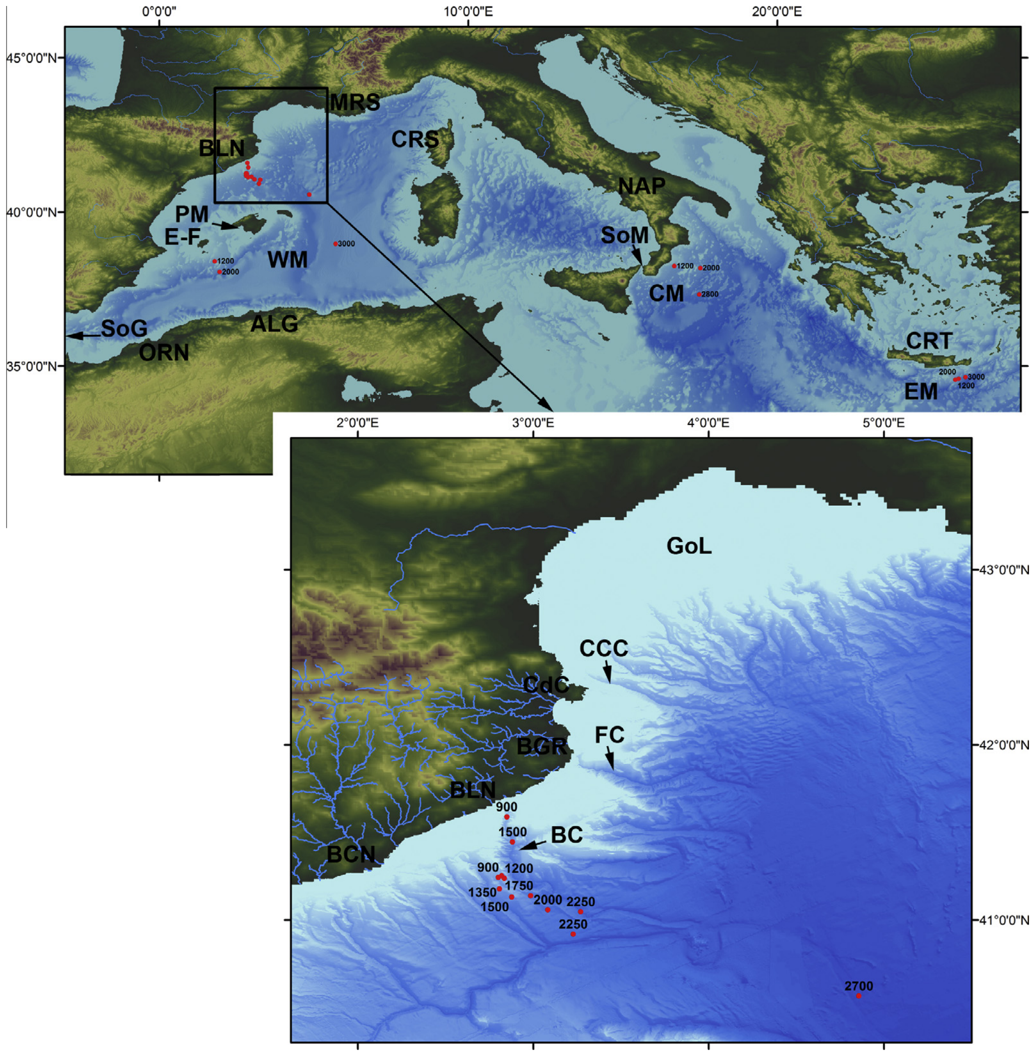

Fig. 1. Bathymetric map of the Mediterranean showing the sampling sites (red dots) with depths and main geographic locations. Main map: ALG, Alger; BCN, Barcelona, BLN, Blanes; CM, Central Mediterranean; CRT, Crete; CRS, Corsica; E-F, Eivissa-Formentera Balearic Islands; EM, Eastern Mediterranean; MRS, Marseille; NAP, Napoli; ORN, Oran; PM, Palma de Mallorca; SoG, Strait of Gibraltar; SoM, Strait of Messina; WM, Western Mediterranean. Insert: BC, Blanes Canyon; BCN, Barcelona; BLN, Blanes; BGR, Begur; CCC, Cap de Creus Canyon; CdC, Cap de Creus; FC, Fonera Canyon; GoL, Gulf of Lions. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.).

Table 1
Successful Otter Trawl Maireta System (M) and Agassiz (A) hauls conducted during the PROMETEO (PRO) and DOS MARES (DM) cruises in the Blanes canyon and adjacent open slope.

Cruise	Date	Open slope depth (m)									Canyon depth (m)		
		900	1050	1200	1350	1500	1750	2000	2250	2700	900	1500	2250
PRO1	30/10–03/11/2008	1M, 1A	1M	1M	1M	1M							
PRO2	28/02–09/03/2009	3M, 2A	2M, 1A	4M, 2A	3M, 1A	3M, 2A						1M	
PRO3	11/05–14/05/2009	2M, 1A	3M	3M	2M	3M, 1A							
PRO4	07/09–12/09/2009	3M, 1A	3M, 1A	3M, 1A	3M, 1A	3M, 1A					1M, 1A	3M, 1A	
PRO5	24/10–31/10/2009	3M, 1A	4M, 2A	4M, 2A	5M, 3A	6M, 2A	2M, 1A	2M, 1A		2M	1M, 1A	5M, 2A	
DM1	15/03–21/03/2012	1M		2M, 1A		2M	2M, 1A	3M, 2A	2M, 1A		1M		1M
Total		13M, 6A	13M, 4A	17M, 6A	14M, 5A	18M, 6A	4M, 2A	5M, 3A	2M, 1A	2M	2M, 2A	10M, 3A	1M

are between 4° and 5° at 900 and 1200 m and decrease towards the deeper locations, with about 2° at 1300 and 1500 m and 1.5–0.5° at 1750–2250 m depth. Distance to the coast varies between 42 and 90 km.

In the framework of the BIOFUN project (EuroDEEP Eurocores, ESF, CTM2007-402 28739-E), marine litter was sampled during one trans-Mediterranean cruise in the Western (southern Balearic), Central (western Ionian Sea) and Eastern (southern Cretan Sea) Mediterranean at 3 depths: 1200, 2000 and 3000 m (Table 2) on the margin and deep basins (Fig. 1). In the Western Mediterranean, an area south of the Eivissa-Formentera Balearic islands was sampled at 1200 m located at a featureless slope portion of the North-western margin of the Balearic promontory that is otherwise characterised by gullies and slopes of 2–6° (Acosta et al., 2003) and at 2000 m located at the base of the margin in a flat area with a slope gradient of less than 2 degrees. The abyssal station

Table 2
Successful Otter Trawl Maireta (M) and Agassiz (A) hauls conducted during the BIOFUN cruise in the Western, Central and Eastern Mediterranean at 1200, 2000 and 3000 m depth.

BIOFUN CRUISE 29/05–28/06 2009	Western Med DEPTH (m)			Central Med DEPTH (m)			Eastern Med DEPTH (m)		
	1200	2000	3000	1200	2000	3000	1200	2000	3000
OTMS (M)	2	2	2	3		1	3	1	0
Agassiz (A)	3	1	2		1		3	1	2

(3000 m) was located in the deep basin between the Balearic Islands and Sardinia. The site at 1200 m is at about 40 km off the coast of Formentera Island and 150 km off the city of Palma de Mallorca. All sample locations are distant of main cities and river outlets. In the Central Mediterranean, the Calabrian slope, an area containing various canyons and gullies and slopes of 2–6°, was sampled at 1200 and 2000 m depth. The deepest site is located in the Crotone-Spartivento Basin, a structural depression with a relatively flat seafloor with slope gradients below 2°. The shallowest sites are located 25 km from the coast and 40 km off the Italian city of Catanzaro. The deepest site is located at about 140 km from the coast. The Eastern Mediterranean basin was sampled in the region of the Crete-Rhodes ridge, south of Crete. The shallower site (1200 m) was sampled at the top of a local height in the margin. The 2000 m sites was located along the slope west to the shallow site, while the deepest site sampled was located east of the shallow site at 3000 m. This part of the Cretan margin is characterised by a narrow shelf and steep slope with several canyons and landslides. The complex seabed morphology is provoked by the tectonic setting and shows troughs and ridges and is shaped by mass wasting processes on the slopes. In particular, the seafloor south of Crete includes the Hellenic trench and active shearing (Strozyk et al., 2009). The nearest city is Lerapetra, a small town with about 23,000 inhabitants, located about 50 km away from the sampling sites.

2.2. Sampling methods

Litter was collected as a by-catch of benthic megafauna sampling using two types of trawling equipment: an otter-trawl Maireta system (OTMS) and an Agassiz trawl. The OTMS has a 12.4 m spread by 1.4 m height of front opening, 40 mm mesh size at the cod end, covered by an outer net 12 mm in mesh size and a total net length of 25 m (Sardà et al., 1998). SCANMAR sensors were used down to 1200 m depth to estimate mouth opening dimensions and the arrival and departure times from the seafloor. Below 1200 m, the same values for mouth opening were used and bottom time was calculated as the time between the end of cable paying out and the start of cable hauling. The OTMS was trawled over the seafloor at 2.6–2.8 knots. The Agassiz trawl had a net mesh size of 12 mm, a 2.5 m horizontal opening and 1.2 m vertical opening. It was trawled at 2.0 knots.

2.3. Data analyses

All litter was separated on deck and classified into 8 categories: (1) hard plastic (e.g. bottles or buckets); (2) soft plastic (e.g. bags and bag pieces); (3) glass (e.g. bottles, broken glass); (4) metal (e.g. conserve tins, cans and metal pieces); (5) clinker; (6) fabric (e.g. clothes); (7) lost or discarded longlines, with and without hooks; and (8) lost or discarded fishing nets. Oil drums collected during the survey have been noted but they have not been included in the analyses as their weight is orders of magnitude higher than the rest of litter items collected. Excess of water and/or mud was removed from litter items and litter was weighed by category in each sample. Litter weight was standardised for trawled area as kg km^{-2} and data was entered in the litter data template of the EU-FP7 project HERMIONE (http://www.ub.edu/hermes/hermione/database_templates.html). This template was designed during a HERMIONE workshop on anthropogenic impact (Barcelona, October 2009) with the aim to provide a standardised method for litter data collection and sharing at the international level. The litter data has been archived in the open access Publishing Network for Geoscientific & Environmental Data (PANGAEA) information system PANGAEA (Ramirez-Llodra et al., 2012a, 2012b, 2012c, 2012d).

The standardised weight data for each litter category was grouped by depth and region and normalised against the number of trawls. This data was imported into a Geographic Information System (ESRI ARCGIS 9.3) and maps of litter quantity and distribution were produced for each of the study regions (the Catalan margin and trans-Mediterranean areas) in relation to natural and anthropogenic processes. Regarding natural processes, data on bathymetry (Catalano-Balearic Sea – Bathymetric chart, 2005, www.icm.csic.es/geo/gma/MCB; (IOC, IOH & BODC, 2003)), general current patterns (Malanotte-Rizzoli et al., 1997; Robinson et al., 2001) and river estuaries were included. Regarding anthropogenic impact, data on coastal population density and ship traffic density for the year 2011 (Halpern et al., 2008) were plotted in the spatial GIS analysis. Shipping activity is shown as density of commercial activities and excludes the nautical recreational activities, even though it is important to note that these are intense during the summer months in the Mediterranean coastal area.

Different litter types will have different transport patterns in the water column, with light litter such as plastic floating and drifting from the source, slowly sinking down to the seafloor, while heavy litter such as glass bottle sinking almost directly to the seafloor. Thus, to detect potential distribution patterns caused by the way litter is transported in the water column, data on the most abundant litter types (plastic, glass, metal and clinker) were grouped into light litter (soft and hard plastic) and heavy litter (glass, metal and clinker). Distribution patterns of light litter (plastics) and heavy litter (glass, metal and clinker) were compared between the Blanes canyon and open slope and amongst the different depths and areas on the trans-Mediterranean study. Longlines and fishing nets were not used in this analysis as the distribution of fishing-related litter is dependent on the fishing activity and known to vary in relation to other litter types (June, 1990; Keller et al., 2010).

Furthermore, because comparisons of the accumulation of the different litter types cannot be conducted using weight units, the percentage of trawls (OTMS and Agassiz) where each litter category was found was calculated and plotted in order to identify the most abundant litter types. Finally, total litter weight in each site was compared with total biomass of megafauna (data from (Tecchio et al., 2011) and (Tecchio et al., this issue).

The non-parametric Kruskal–Wallis statistics were used to test for significant differences in the mean litter weight at different depths on the Blanes slope and to compare biomass of megafauna with litter weight at each sampling site. Data on litter from the Blanes canyon and adjacent slope were analysed using the multivariate permutational analysis of variance analysis (PERMANOVA, v. 6, PRIMER-E Ltd., Plymouth, UK) with a factor with two levels for habitat (Blanes canyon and open slope) and a factor with two levels for depth (900 m and 1500 m). Moreover, a 2-factorial analysis using both habitats (with two levels) and depth (with two levels) was performed with the Blanes data from the Catalan margin. In addition, a one-factorial analysis with three levels for basin (Western, Central and Eastern Mediterranean) and at 3 depths (1200 m, 2000 m and 3000 m) was performed with the trans-Mediterranean data, while a 2-factorial analysis using both depth and basin was also performed. This method calculates a *pseudo-F* statistic directly analogous to the traditional *F*-statistic for multifactorial univariate ANOVA models, but which uses permutation procedures to obtain *p*-values for each term in the model (Anderson et al., 2008).

3. Results

3.1. General observations

Litter was collected in all OTMS and Agassiz samples together with the megafauna. The most abundant litter types found in the deep Mediterranean Sea at bathyal and abyssal depths were plastic, glass, metal and clinker (Fig. 2A–E). Domestic and industrial objects, such as shoes, toothbrushes, 3 oil drums and tires were collected in lower quantities (Fig. 2F). Longlines were common (Fig. 2F and G) and lost or discarded fishing nets were also collected, in one case with 9 dead or moribund *Geryon* crabs entangled (Fig. 2H). Among the unusual objects retrieved from the seafloor were a chair, a porcelain toilet bowl, the box of the survival raft of an F15 aircraft (Fig. 2I–K) and two amphorae, from the first century and from the Late Roman period (5–7th AC) (Fig. 2L and M). The standardised weight data of all litter collected for this study is available through PANGAEA (http://www.pangaea.de).

3.2. Litter distribution

On the Blanes open slope (Fig. 3) and trans-Mediterranean transect (Fig. 4), variation in abundance and weight of the different litter types was high amongst samples. All sampled sites provided a wide range of litter objects. On the Blanes open slope, the minimum total litter (0.02 kg km^{-2}) was collected in a sample from 1750 m depth, while the maximum total litter (3264.6 kg km^{-2}) was collected in a sample from 2250 m depth. This sample contained over 20 kg of clinker. All samples on the slope contained high quantities of clinker and other heavy litter (Fig. 3A). A particularly high quantity of clinker and heavy litter was found at the 1500 m and 1750 m sites. These sites are found about 60 km away from the coast, but are situated under the major shipping route that links the port of Marseille to Oran (Alger) and the main shipping corridor from Suez Canal to the Strait of Gibraltar (Fig. 3B). The results from two trawls conducted at the deepest and outermost site (2700 m) indicate that the site contained a small amount of litter composed mainly by plastics. This site is 81 km away from the coast at the end of the canyon and away from major shipping routes (Fig. 3A and B). The shallower sites (900 and 1050 m) contained relative high quantities of longlines. Overall, in the Blanes slope, soft plastics, mainly composed by whole and broken plastic bags, were present in 93.3% of the samples. Clinker was present in 68.3% of the samples (Fig. 5A) and was often colonised by the brachiopod *Grypheus vitreus.* Fabric and hard plastics were also abundant (45.2% and 39.4%, respectively), while glass and metal were found in 21% of the samples (Fig. 5A). In the Blanes canyon, the shallower site (900 m), found at only 10 km from the coast, had a variety of plastics, glass and clinker. The 1500 m site, also close to the coast (24 km), contained litter mostly composed by plastics, both hard and soft (Fig. 3A). Finally, the deeper site (2250 m), at a distance of 80 km from the coast but under the Marseille to Suez-Gibraltar shipping corridor, contained a variety of litter types, mostly clinker, metal and soft plastics (Fig. 3B).

Fig. 2. Examples of marine litter collected at bathyal and abyssal depths in the Mediterranean. A, Plastic material from the Central Mediterranean at 1200 m; B, plastic bags and piece of longlines from the Western Mediterranean at 1200 m; C, Plastics, glass bottles and tins from the Western Mediterranean at 2000 m; D, plastics, a can and clinker from the Blanes open slope at 1500 m; E, a bucket with remains of engine oil change from the Western Mediterranean at 3000 m; F, oil drum, longline and tyre collected from the Central Mediterranean at 1200 m depth; G, longline collected from the Blanes open slope at 1200 m; H, example of ghost fishing showing dead or moribund *Geryon* crabs in a fishing net collected from 1200 m depth on the Western Mediterranean; I, a potty collected from 2000 m on the Blanes open slope; J, a chair collected in the Western Mediterranean at 1200 m; K, the box of an F15 plane survival raft collected from 1500 m on the Blanes open slope; L, an amphora from the 1st Century collected in the Eastern Mediterranean; M, an amphora from the Late Roman (5–7th AC) collected from the Eastern Mediterranean.

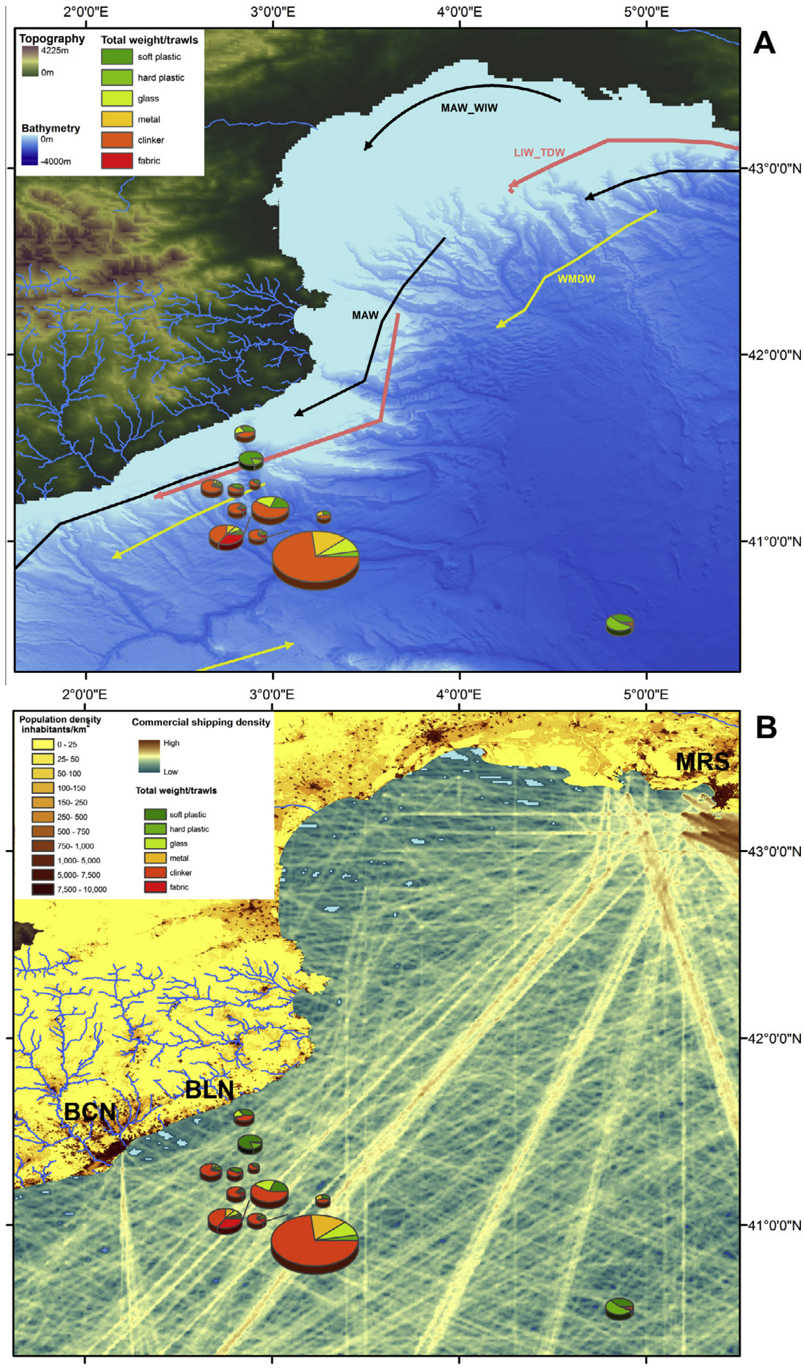

Fig. 3. GIS map showing the distribution of different litter types on the Blanes canyon and adjacent slope in relation to (A) natural processes (bathymetry, main rivers and major currents) and (B) anthropogenic processes (population density and commercial shipping routes). Water circulation: LIW, Levantine Intermediate Water; MAW, Modified Atlantic Surface Water; TMW, Transitional Mediterranean Water; WIW, Winter Intermediate Water; WMDW, Western Mediterranean Deep Water. Geographic locations: BCN, Barcelona; BLN, Blanes; MRS, Marseille.

Along the trans-Mediterranean transect, the minimum total litter (14.7 kg km^{-2}) was collected in a sample from the Central Mediterranean at 1200 m depth and the maximum (1536.6 kg km^{-2}) in a sample from the Western Mediterranean at 1200 m depth. In the three geographic areas, soft plastics and clinker were the most abundant litter types (Fig. 4A). In the Western Mediterranean, the two shallower sites (1200 and 2000 m), situated under the major shipping route from Marseille to Oran and the Suez-Gibraltar corridor, had large quantities of clinker (Fig. 4B). The 1200 m site is the closest to the coast (40 km from Formentera Island and 150 km from Palma de Mallorca) and had a higher proportion of plastics than the 2000 m site. The abyssal site (3000 m) is located in the middle of the basin and under the Western Mediterranean Deep Water mesoscale gyres (Fig. 4A). Although shipping traffic is moderated, high shipping density is found about 25 km west (Marseille to Skikda (Alger) shipping route) and 40 km south (Napoli and Corsica to Strait of Gibraltar routes) of the site. This abyssal site contained a high proportion of clinker, metal and fabric, as well as hard and soft plastics (Fig. 4B). The Central Mediterranean is a complex topographic area (Fig. 4A), which limited the number of successful trawls that could be made (Table 1). The 1200 m site is closest to the coast and contained mainly plastics and longlines.

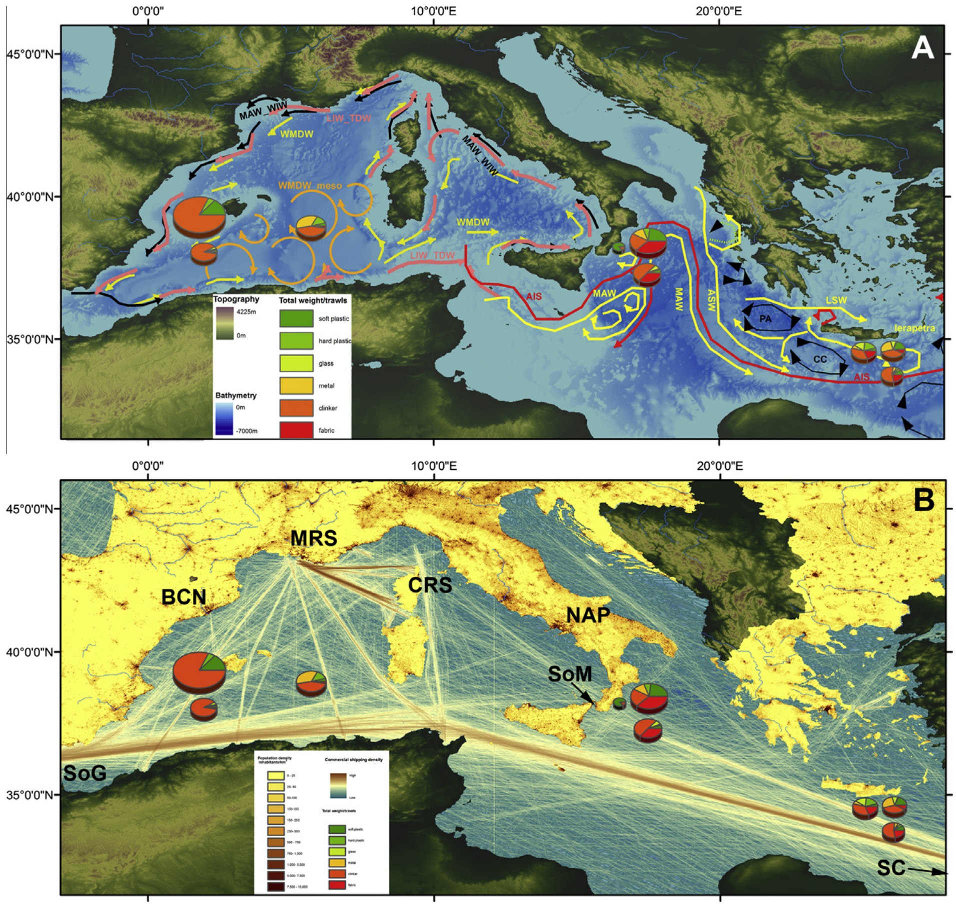

Fig. 4. GIS map showing the distribution of different litter types along the Western, Central and Eastern Mediterranean Sea in relation to (A) natural processes (bathymetry, main rivers and major currents) and (B) anthropogenic processes (population density and commercial shipping routes). Water circulation: AIS, Atlantic-Ionian Stream; CC, Cretan Cyclone; IA, Ionian Anticyclones; LDW, Levantine Deep Water; LIW, Levantine Intermediate Water; LSW, Levantine Surface Water; MAW, Modified Atlantic Surface Water; PA, Pelops Anticyclone; TMW, Transitional Mediterranean Water; WIW, Winter Intermediate Water; WMDW, Western Mediterranean Deep Water. Geographic locations: BCN, Barcelona; CRS, Corsica; MRS, Marseille; NAP, Napoli; SC, Suez Canal; SoG, Strait of Gibraltar; SoM, Strait of Messina.

The 2000 m site had a higher variety of litter types, including a high proportion of fabric. Shipping density is relatively low to moderate in the area, with the exception of the deepest site (3000 m), which is located under the shipping line connecting the Suez Canal with the Strait of Messina. This site contained large quantities of clinker and fabric (Fig. 4B). The Eastern Mediterranean, south of Crete is also a complex topographic area. The 3 sites are separated from the coast by the Hellenic trench followed by a height and, additionally, the abyssal site (3000 m) is close to a submarine canyon (Fig. 4A). All sites are located at about 60 km north of the major shipping route that connects the Suez Canal with the southern Italian harbours (Fig. 4B). The 3 sites contained similar quantities of litter of similar types, mostly composed by clinker, metal, fabric and plastics (Fig. 4A). Overall along the Mediterranean Sea, soft plastics were present in all samples in the Western and Central Mediterranean areas and in 80% of the samples in the Eastern Mediterranean (Fig. 5B–D). Clinker was present in all samples from the Central Mediterranean, in 90.9% of samples from the Western and 80% of samples from the Eastern Mediterranean (Fig. 5B–D). As on the Blanes slope, clinker was often colonised by the brachiopod *Grypheus vitreus*. Hard plastics were also abundant in the Western (81.8%) and Central (71.4%) regions, followed by metal also in the Western (63.6%) and Central (57.1%) Mediterranean (Fig. 5B–D).

Total litter was compared between depths on the Blanes slope and between depths and geographic regions along the trans-Mediterranean transect. On the Blanes slope, a high peak of total litter weight was observed at 2250 m depth (Fig. 6A). However, this peak was caused by one Agassiz sample that contained over 20 kg of clinker (equivalent to 3264.6 kg km^{-2}), while the other 3 OTMS trawls and 1 Agassiz trawl contained between 0.26 and 12.5 kg of clinker. Excluding this exceptional sample of clinker at 2250 m depth from the analysis, a higher weight of litter was observed in general in the Blanes slope at 1500 and 1750 m depth (Figure 6A). However, the variation amongst samples was high and differences in mean weight of litter were not significant (Kruskal–Wallis: K-W = 13.696, 8df, $P > 0.05$). Total weight of litter was also compared between the Blanes canyon and open slope habitats at 900 and 1500 m depth (Figure 6B). The mean weight of total litter was not significantly different between habitats, depths or the interaction (PERMANOVA: Pseudo-$F_{habitat}$ = 0.079737, Pseudo-F_{depth} = 4.0269, Pseudo-$F_{interaction}$ = 0.15113, $P > 0.05$). In the trans-Mediterranean transect, a highest amount and weight of litter was collected, in general, from the Western Mediterranean site at 1200 m (Fig. 7). However, the variation amongst samples was high, especially in the Western Mediterranean, and differences in mean weight of litter were not significant between depths, areas or the interaction (PERMANOVA: Pseudo-F_{depth} = 0.085327, Pseudo-F_{area} = 1.6608, Pseudo-$F_{interaction}$ = 1.5308, $P > 0.1$).

When comparing the accumulation of light litter (plastics) and heavy litter (glass, metal and clinker) in the Blanes open slope (Fig. 8A), a higher amount of light litter was observed at 1500–1750 m and 2250–2700 m depth. The peak of light litter at 2700 m was caused by the high amount of soft plastics caught in

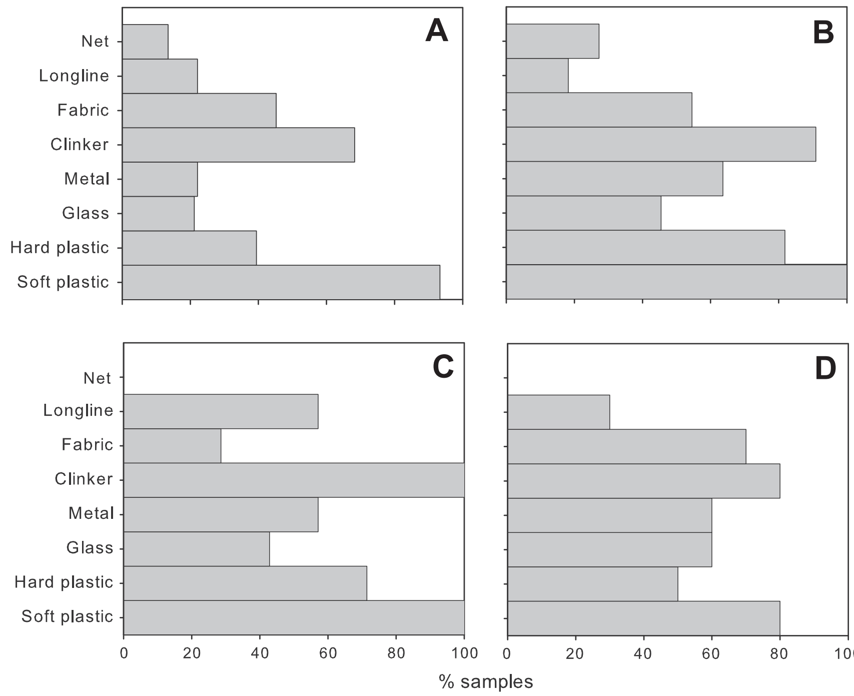

Fig. 5. Percentage of samples that contained each of the different litter types collected on the Blanes margin (A) and the Western (B), Central (C) and Eastern (D) Mediterranean regions.

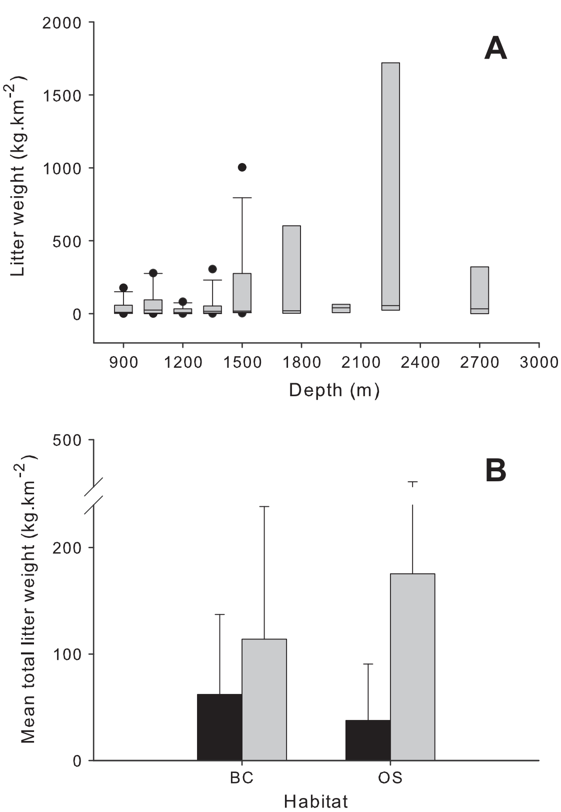

Fig. 6. Distribution of total litter. A, Box plot of total litter on the Blanes open slope at the different sampled depths; B, Mean total litter weight (and standard deviation) in the Blanes canyon (BC) and open slope (OS) at 900 m depth (black) and 1500 m depth (grey).

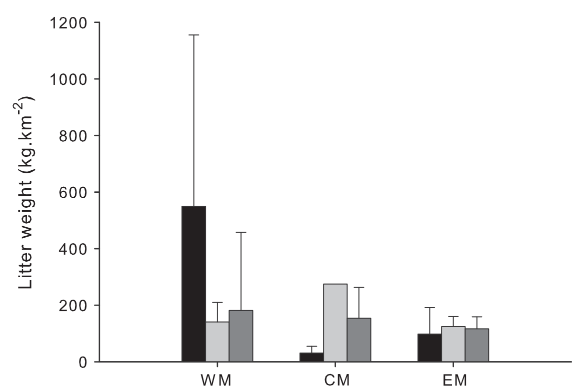

Fig. 7. Mean weight and standard deviation of total litter on the Western (WM), Central (CM) and Eastern (EM) Mediterranean at 3 depths: 1200 m (black), 2000 m (light grey) and 3000 m (dark grey).

all trawls conducted at this depth. However, the differences in mean weight of light litter were not significant (Kruskal–Wallis, K–W = 9.559, 8df, $P > 0.1$). Heavy litter followed a similar trend, with accumulation at depth (1500–1750 m) and a large peak at 2250 m. This peak was caused by a large sample of clinker caught on one Agassiz trawl at this depth. However, the differences in mean weight of heavy litter were not significant (Kruskal–Wallis, K–W = 9.532, 8df, $P > 0.1$). When comparing the Blanes canyon and open slope, we observed an accumulation of light litter in the Blanes canyon at 1500 m depth and of heavy litter on the Blanes open slope also at 1500 m depth (Fig. 8B). Differences in weight of light litter were significant between the canyon and slope habitats (PERMANOVA: Pseudo-$F_{habitat} = 13.645$, $P < 0.001$), but not between depths or the interaction (PERMANOVA: Pseudo-$F_{depth} = 0.86787$, Pseudo-$F_{interaction} = 3.568$, $P > 0.05$). Differences in weight of heavy litter were not significant between habitats, depth or the interaction (PERMANOVA: Pseudo-$F_{habitat} = 1.9662$, Pseudo-$F_{depth} = 1.6512$, Pseudo-$F_{interaction} = 2.0155$, $P > 0.05$). Along the trans-Mediterranean transect (Fig. 9), there were no significant differences in the weight of light litter amongst

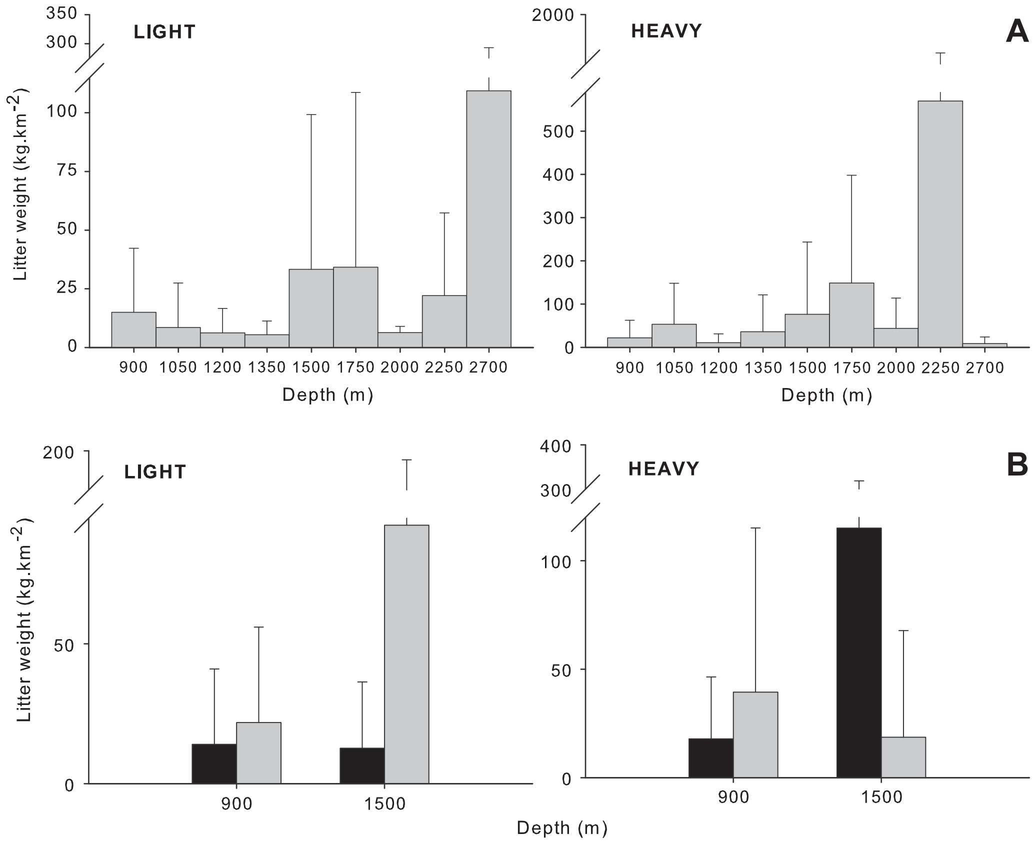

Fig. 8. Accumulation of light and heavy litter on the Blanes slope. A, light and heavy litter on the Blanes open slope by depth; B, light and heavy litter on the Blanes open slope (black bars) and Blanes canyon (grey bars).

areas, depth or the interaction (PERMANOVA: Pseudo-F_{area} = 0.77492, Pseudo-F_{depth} = 0.54564, Pseudo-$F_{interaction}$ = 2.3041, $P > 0.05$), nor in the weight of heavy litter (PERMANOVA: Pseudo-F_{area} = 1.2872, Pseudo-F_{depth} = 0.078106, Pseudo-$F_{interaction}$ = 0.56455, $P > 0.1$).

3.3. Litter and biomass

Total standardised litter weight at each site was compared to total standardised biomass of megafauna collected in the same trawls (OTMS). In the Blanes slope, the biomass of megafauna was significantly higher than the weight of litter between 900 and 2000 m depth (Kruskal–Wallis, $P < 0.001$) (Fig. 10A). At the deeper stations, however, the decrease in megafaunal biomass and increase in accumulated litter caused a reverse in the trend, with no significant differences in mean biomass and mean litter weight at 2250 and 2700 m depth (Kruskal–Wallis, $KW_{2250} = 0.0$, $P > 0.5$; $KW_{2700} = 0.333$, $P > 0.5$) (Fig. 10A). Along the trans-Mediterranean transect, the proportion of biomass *vs* litter weight varied with area and depth (Fig. 10B), but in most cases there were no significant differences between mean biomass and mean litter weight (Kruskal–Wallis, $P > 0.1$). The only marginally significant differences were found in the Central Mediterranean at 1200 m depth, where biomass was higher than litter weight (Kruskal–Wallis , $KW = 3.857$, $P = 0.05$), and in the Eastern Mediterranean at 1200 m depth, where litter weight was higher than biomass (Kruskal–Wallis , $KW = 3.857$, $P = 0.05$).

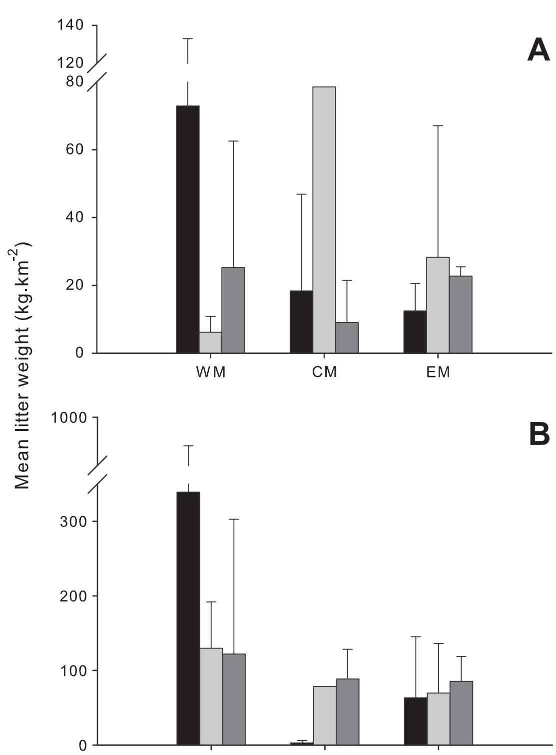

Fig. 9. Accumulation of light (A) and heavy (B) litter in the Western (WM), Central (CM) and Eastern (EM) Mediterranean Sea at 1200 (black bars), 2000 (light grey bars) and 3000 (dark grey bars) m depth.

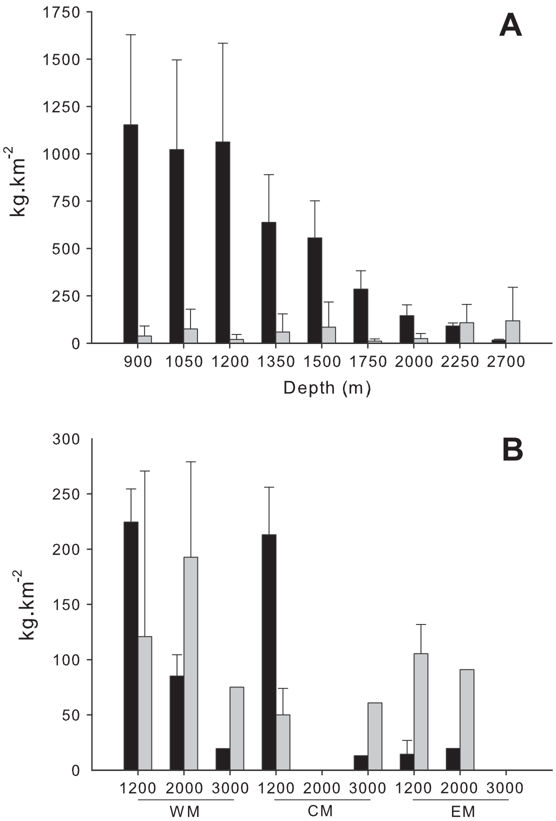

Fig. 10. Mean (and Standard Deviation) biomass of megafauna (black bars) and mean total litter weight (grey bars) on the Blanes slope (A) and along the trans-Mediterranean transect (B). WM, Western Mediterranean; CM, Central Mediterranean; EM, Eastern Mediterranean.

4. Discussion

4.1. Litter types

The Mediterranean basin is considered a hotspot of marine biodiversity, with 7.5% of known marine species (Bianchi and Morri, 2000), but these data relate mostly to coastal systems and little information is available from deep waters (Coll et al., 2010; Danovaro et al., 2010; Ramirez-Llodra et al., 2010). Biodiversity in the Mediterranean is currently under threat by climate change and human impact (Bianchi and Morri, 2000; Coll et al., 2012), including the accumulation of marine litter if we consider results from this study. The Mediterranean coast is home to 7% of the world's human population, with the region attracting 25% of international tourism and 30% of shipping traffic. Marine litter in the Mediterranean is a result of intense urbanisation and increasing economic activities in parallel to limited infrastructures and policies (UNEP, 2009). Recently, UNEP / MAP MED POL published a report on the assessment of the status of marine litter in the Mediterranean region (UNEP-MAP-WHO-MEDPOL, 2011). This report assessed mainly marine litter on beaches and floating on the sea surface, mostly from the northern Mediterranean. The study indicated that most of the marine litter on beaches and sea surface in the Mediterranean has a land origin rather than ship origin, composed mainly by plastics, aluminium and glass on beaches and plastics (83%) floating on the surface. Our study of deep-water marine litter has shown that debris is present in all sampled locations, from 900 to 3000 m depth across the Mediterranean. The most abundant litter types were plastics, metal and glass, similarly to what is described in the UNEP/MAP/MEDPOL survey and in other studies in the Mediterranean (Galgani et al., 1996, 2000, 2010; Galil et al., 1995). Plastics were present in 92.8% of the samples collected in the trans-Mediterranean study and in 93.5% of the samples collected on the Catalan margin, showing similar proportions to those reported for floating plastics (UNEP-MAP-WHO-MEDPOL, 2011). Plastics are found from the equator to the poles and from the shore to the deep sea. Recent studies have shown that densities are particularly high near densely populated areas (Galgani et al., 2000; Mordecai et al., 2011), in enclosed seas such as the Mediterranean and at water fronts (Barnes et al., 2009).

Clinker was also conspicuous in most samples (in 89.3% of trans-Mediterranean samples and 68.2% of Catalan margin samples). Clinker, the burnt residue of charcoal from steam ships, is a characteristic deep-sea human-produced residue that accumulated on the seafloor for 150 years, when sailing ships were replaced by steam ships at the end of the 18th Century (Ramirez-Llodra et al., 2011b). In the abyssal Atlantic, clinker composes over 50% of the hard substratum and is often colonised by the anemone *Phelliactis robusta*, although no other sessile species seem to use clinker for attachment (Kidd and Huggett, 1981). In our Mediterranean survey, clinker was very abundant and often colonised by the brachiopod *Grypheus vitreus*. A very high amount of clinker (over 20 kg) was collected during one trawl on the Blanes open slope at 2250 m depth. This site was sampled 3 times, each time producing relatively high amounts of clinker (2257, 12,470 and 20,850 kg respectively). Without direct observations, however, it is difficult to provide an explanation for this accumulation of clinker. Potential causes include topographic features (small elevation or depression) where clinker may accumulate or, most probably, a massive disposal of clinker in the area by a passing steam ship.

Lost or discarded fishing gear (longlines and nets) were commonly found in our study. In the Catalan margin, fishing gear was found at all depths, both in the canyon and margin. Longlines were found in 22.5% of samples, while 12.4% of samples collected parts of fishing nets. Across the Mediterranean, 32% of the samples contained longlines, mostly in the Central Mediterranean, while 10.7% of samples (all in the Western Mediterranean) included parts of fishing nets. Intense fisheries targeting deep-sea organisms have affected the Mediterranean Sea since the 1930s, with a particular fishing pressure in the Western Mediterranean (Sardà et al., 2004b). One of the most valuable natural resources in this region is the red shrimp *Aristeus antennatus*, with a population distribution from 80 to 3000 m depth (Sardà et al., 2004a). This resource has been fished intensively during the last 6 decades, to the point of changing dramatically the seafloor morphology at certain places (Puig et al., 2012), and the fishery reaches now 900 m depth in the Western Mediterranean. This high fishing intensity in the area could partially explain the relatively high abundance of nets in the northwestern Mediterranean in comparison with the Central and Eastern basins. Although trawling and drift net fishing have been banned below 1000 m in the whole Mediterranean Sea since 2004 (WWF/IUCN, 2004), this ban is not enforced. A study trammel nets ghost fishing conducted off Portugal (to 30 m depth) (Baeta et al., 2009) estimated that the net's fishing lifetime (i.e. when catching efficiency falls below 1%) varies between 8 months on sandy seafloor to 10–11 months in rocky seafloor. In the deep sea, however, the lack of sun irradiation, relative stable physical conditions (when compared to the shallow coastal area) and low temperatures (although the deep Mediterranean waters are relatively stable around 13 °C) will delay the degradation of the materials, most probably extending the fishing lifetime of nets. Evidence of ghost fishing was found here in one sample from 1200 m in the Western Mediterranean, where several *Geryon* crabs were observed dead or moribund in a broken fishing net (Fig. 3H).

4.2. Litter distribution

The overall results of our study showed that the accumulation and distribution of marine litter is highly variable within and between sites, both at the local scale (Blanes slope and canyon, Catalan margin) and the regional scale (Mediterranean Sea). Although no clear patterns of accumulation of total litter with geographic area or depth were found, patterns of distribution of the different litter types seem to emerge from our data. Here, we discuss the effect of both natural (seafloor bathymetry, circulation and rivers) and anthropogenic (coastal population density and shipping density) in shaping the observed distribution of litter.

Hydrographical patterns and seafloor bathymetry, and in particular the presence of major submarine canyons, play an important role in the transportation and distribution of marine litter (Galgani et al., 2000; Mordecai et al., 2011). The main general circulation setting of the North-western Mediterranean has a south-west direction over the shelf (Modified Atlantic Water), at intermediate depths (Levantine Intermediate Water) and over the seafloor (Western Mediterranean Deep Water) (Fig. 3A) (Robinson et al., 2001). The north-western Mediterranean margin is also characterised by the presence of canyons. Submarine canyons are pathways for transportation of both sediment and material in suspension (Puig et al., 2003; Vetter and Dayton, 1999). In the Catalan margin, canyons are known to have periodically enhanced peak currents caused by dense and cold water cascading that is produced in the Gulf of Lions at certain winter wind conditions, which transport large quantities of material from the shelf to the deep basin and can re-suspend settled particles. These cascading processes have been well documented at the Cap de Creus and Fonera canyon (Canals et al., 2006; Company et al., 2012; Puig et al., 2008). South from Cap de Creus canyon, the main processes driving the transport of particles down canyon are major storms (Martín et al., 2006; Sanchez-Vidal et al., 2012; Zúñiga et al., 2009). A detailed study of particle fluxes dynamics in the Blanes canyon and adjacent slope (Zúñiga et al., 2009) has shown that the canyon acts as a conduit for particles from the shelf to bathyal depths, with fluxes in the canyon 3 orders of magnitude higher than on the adjacent slope. The transport of particles in the canyon is furthermore event-dominated, with maximum fluxes related to high river discharges from the Tordera River in winter, cascading events and intensification of the Northern Current flowing over the shelf (Sanchez-Vidal et al., 2012; Zúñiga et al., 2009). Our samples from the Blanes canyon, and in particular litter collected at 1500 m depth, contained large quantity of plastics in comparison with the open slope sites. On the contrary, the open slope sites had a higher variability of litter, with significant quantities of clinker and other heavy litter such as metal, glass and fabrics. We suggest that litter in the canyon (with high proportion of plastics) is predominantly of coastal origin, as plastics can be transported easily downwards by canyon enhanced currents, whereas most litter sampled on the slope (mostly heavy litter) is ships' discards, including fishing vessels. The shallower sites are located under moderate shipping traffic, mostly passenger ferries and fishing vessels, where a variety of litter types and a significant presence of fabric and longlines were found. The 2250 m site on the slope is located under the major shipping route connecting Marseille with Oran (Alger) and the Strait of Gibraltar (Fig. 3B) (Halpern et al., 2008) where large quantities of litter, mostly clinker, metal and glass were collected. The accumulation of clinker is closely related with modern shipping routes (Figs. 3B and 4B), indicating that the main shipping corridors have not been altered in the last two Centuries. Main cities and ports are not directly related to the Blanes slope and canyon sites, with Marseille located about 250 km up-current and Barcelona located about 100 km down-current. In relation to rivers, the Blanes canyon is a continuation of the small Tordera River, but the study area is not directly related to major rivers, with the Rhone River near Marseille northern of our study area, the Ebro Delta about 230 km south of Blanes, and the smaller Besòs and Llobregat Rivers at each side of Barcelona. Therefore, we suggest that the litter from the Rhone River and the heavily populated city and region of Marseille (Fig. 3B) is transported southwards over the shelf, sinking to deep waters channelled by the Gulf of Lions canyons and not arriving in our study area. The Costa Brava, between Cap de Creus and Blanes, though not heavily populated, draws a large transient population to its beaches during the summer months. We suggest that litter produced in the northern Costa Brava (Cap de Creus to Begur) is transported southwards and can be channelled to the deep basin through the large Fonera canyon. Therefore, we propose that most litter entering the Blanes canyon has been produced between the towns of Begur and Blanes, as well as a significant input of litter through discharges of the Tordera River. Litter entering the marine system from Barcelona and its associated rivers or from the major Ebro River will not reach the Blanes area, as the main currents affecting the Catalan margin flow south and Barcelona and the Ebro Delta are situated downstream from Blanes. Galgani et al. (2000) observed increased amounts of litter at lower depths in the Bay of Biscay and Mediterranean canyons, suggesting a washing down effect caused by the enhanced currents occurring in the upper part of these canyons. Because of the high variability found amongst samples in our study, a stronger sampling effort is needed, with emphasis on the lower part of the margin (i.e. 2500–2800 m depth), to confirm potential accumulation zones.

Along the trans-Mediterranean transect, the rough topography of the deep-seafloor limited the number of trawls that could be conducted successfully and, therefore, the results need to be interpreted cautiously. From our observations (Fig. 4A and B), we suggest that the shallower sites, closer to the coast have a higher proportion of plastics than the deeper sites, which contain a larger proportion of heavy litter dumped from ships. It is worth noting that sites with higher amount of clinker often had a higher amount of fabric and are situated under main shipping routes. The fabrics collected were mostly of industrial material (e.g. security ropes, tissues embedded in engine oil) with a probable ship origin. An early study of the National Academy of Sciences study (National Academy of Sciences, 1975) quantified the composition of ship-originated litter and showed that the most abundant types were paper, metal, fabric and glass, with plastics being only a small component of the litter. This is similar to our suggestion here that areas affected mostly by coastal-originated litter have a higher proportion of plastics, while areas affected mostly by ship-originated litter have a higher proportion of heavy litter with a significant increase of fabric and metal. In the Western Mediterranean, the Balearic islands triple their population during the touristic season (Salvà-Tomàs, 2002). The 1200 m site is the closest to the coast of Formentera Island, but it is also influenced by the major shipping route linking Marseille to Oran (Fig. 4B). We suggest that this site is affected both by coastal litter (mostly plastics) and dumping from ships (historically clinker, but also hard plastic, glass and metal). The relative high abundance of plastics in the deeper station situated in the middle of the basin and therefore far away from coastal influence could be caused by the retention of plastics in the mesoscale gyres of the Western Mediterranean Deep Water (Fig. 4A). In the Central Mediterranean area, dense populations are found along the southern Italian coast, which has also a strong touristic industry, but less intense than the Balearic Islands or Costa Brava on the Spanish sites in the Western Mediterranean. Here again, the shallower area had a higher proportion of plastics, with a probable coastal origin, while the deeper areas, which are situated under moderate to intense shipping routes, had a higher proportion of heavy litter, mostly clinker, fabric and metal

(Fig. 4B), suggesting a ship origin of the litter. The study sites in the Eastern Mediterranean are close to the southern coast of Crete. Although Crete is an important touristic destination, the population density along that coast is low (Fig. 4B). Additionally, the sites are separated from the shelf by a trench and elevation, causing a natural barrier to the transportation of litter from the coast, in particular to litter with short floatation periods. The combination of this topographic isolation, moderate shipping intensity over the shallower sites (mostly ferries), high shipping intensity over the abyssal site (Suez Canal to Southern Italy corridor) and the significant presence of clinker, fabric, glass and metal, as well as plastics in all sites, suggests that most litter in this area originates from shipping. The general ocean circulation over the sites is influenced by the Ieopetra current, which makes a clockwise gyre with a north-western component over the sites. This circulation could explain the retention and accumulation of plastics. A previous study of litter in the Eastern Mediterranean (Galil et al., 1995), which sampled a site south of Crete, also collected a variety of litter types, including plastic, glass and paint chips, and concludes that vessel-originated refuse is a major source of litter in the deep Mediterranean Sea.

A high variability of litter concentration has also been observed on the shelves and slopes of the European continental margin (Galgani et al., 2000) and in the NW Mediterranean slope and bathyal plain (Galgani et al., 1996). Galgani et al. (2000), however, report the presence of accumulation zones related to the proximity of large cities, topographic features such as canyons or depressions and areas of high sedimentation rates. In our study, the sampling effort might not have been strong enough to detect such accumulation zones and dedicated sampling aiming at quantifying litter accumulation in more affected areas such as regions under major shipping routes or river outflows in front of large cities would be necessary. Nevertheless, subsequent ROV (Remote Operated Vehicles) observations on the NW Mediterranean Sea have shown that litter accumulates in seafloor depressions and litter is abundant in canyons (JB Company, pers. obs). Because trawling integrates information across a large area, the use of *in situ* observations with ROVs or submersibles is essential to better understand the small-scale distribution and accumulation of litter on the seafloor (Galgani and Andral, 1998; Galgani et al., 2000), as well as to provide insights of its effects on the habitat and fauna. Therefore, to progress towards a robust description of litter distribution on the Mediterranean deep seafloor and understand accumulation trends, additional data is needed and should be analysed in relation to sedimentological rates, hydrodynamics and anthropogenic factors such as proximity of large cities, fishing grounds and shipping routes.

4.3. Impact on habitat and fauna

The full spread of effects that litter has on deep-sea habitats and their fauna is still poorly understood, but several impacts have been documented in different studies. For example, evidence is available on the physical damage caused by longlines to fragile fauna such as cnidarians, sponges or echinoderms (Baco et al., 2010; Clark et al., 2007). Plastics can cause suffocation and starvation of fauna and lead to anoxic conditions on the sediment, as well as become a significant source of persistent organic pollutants on the seafloor (Barnes et al., 2009; Burgess-Cassler et al., 1991). Studies in the last decade show that decomposing plastics result in the accumulation of microplastics in sediment with yet unknown effects on the fauna (Barnes et al., 2009; Thompson et al., 2004, 2009). Furthermore, litter items have been shown to more than double the dispersal of alien species in comparison to the natural dispersal of species (Barnes, 2002). Litter provides also substrate for settlement to alien and invasive species (Barnes et al., 2009), potentially changing the structure and function of the autochthonous communities (Galil, 2007). Although the data obtained in our study do not allow us providing details of impact of litter on the fauna or habitat, some observations are worth noting. Firstly, we documented ghost fishing by lost or discarded nets collected from the bathyal north-western Mediterranean (Fig. 3H), where several dead or moribund *Geryon* crabs were found. Secondly, paint pots where collected in the Central and Eastern Mediterranean, which could be a long-term source of chemical contamination, including persistent organic pollutants, which have been found to accumulate in deep Mediterranean species (Koenig et al. 2013, 2012).

When comparing total biomass of megafauna (data from Tecchio et al., 2011) and total litter weight collected in the same samples along the Mediterranean transect, it was notorious to observe that litter weight was often equivalent to biomass and, in some cases (i.e. deep Central Mediterranean and the sampled 3 depths in the Eastern Mediterranean), litter weight was higher than biomass collected in the same sample. The pattern observed on the Catalan margin was also interesting. Here, biomass of megafauna (data from Tecchio et al. 2013) was higher than litter weight from 900 to 1750 m depth, while, at the deeper stations, the decrease in megafaunal biomass and increase in accumulated litter causes a reverse in the trend, with similar amounts of litter and biomass observed from 2000 to 2700 m depth. The Mediterranean has a marked oligotrophic gradient increasing from west to east (Coll et al., 2010; Danovaro et al., 1999). Also, the relatively constant high (13–14 °C) temperature below 200 m depth accelerates the degradation of organic matter by pelagic microbes, further decreasing the quantity and quality of food reaching the deep seafloor (Tyler, 2003). These characteristics result in an impoverished bathyal and abyssal megafauna (in terms of abundance) when compared to the Atlantic Ocean, with a significant decrease in biomass from the Catalan margin eastwards to the Eastern Mediterranean and from bathyal to abyssal depths (Tecchio et al., 2011). These longitudinal and bathymetric trends in megafauna biomass can explain the differences observed in the proportion of litter and megafauna in the more productive Catalan margin, especially above 1500 m, compared to the other studied areas. It is important to note that we are using weight data (biomass and weight of litter) instead of abundance, and therefore we do not have an exact idea of the coverage of litter on the seafloor that is affecting the habitat and the fauna. Our data, however, may be indicative of the level of exposure to litter in different Mediterranean deep-sea habitats. Further studies are nevertheless necessary to assess the real impact of accumulated litter in the communities to understand if the fauna from the Eastern Mediterranean is exposed to higher amounts of litter, or if the lower densities of fauna result in a lower interaction with the litter. The growing evidence of litter accumulation in deep-sea habitats, together with the scarce availability of data on impact, call for urgent studies dedicated to assessing the effect of different litter types in the habitat and fauna.

4.4. Contribution to policy

Our data showing equivalent or even higher amounts of litter than megafauna in several deep Mediterranean areas provide evidence that marine litter is a major issue in the deep Mediterranean Sea, needing urgent attention by policy makers, managers and society. The European Council and Parliament issued, in June 2008, the Marine Strategy Framework Directive (MSFD) for the establishment of a framework for community action in the field of marine environmental policy (EU-MSFD, 2008). This directive requires that the European Commission defines criteria and methodological standards to allow consistency in the approaches to evaluate the extent to which Good Environmental Status (GES) is being achieved. Eleven qualitative descriptors for determining GES have been defined, including marine litter (Annex 1 of the MSFD). Task group 10 addressed the issues related to marine litter and a report was published in 2010 (Galgani et al., 2010) concluding that all member states should undertake an initial evaluation on the current state of research on marine litter and its impacts, to define knowledge gaps and priority research areas as well as to provide the scientific and technical basis for monitoring. The research and monitoring to be undertaken under a coordinated and standardised effort will result in new data from which to develop recommendations and guidelines to assess GES both at the regional and European scales (Galgani et al., 2010). At the global scale, UNEP's Global Marine Litter Initiative is being developed by the Regional Seas Programme and the Global Programme of Action (GPA). In 2009, UNEP published a review on current knowledge on marine litter (UNEP, 2009), which includes regional assessments of litter distribution and activities being undertaken in several regions. Although most regions focused on litter on coastal areas and beaches, the Mediterranean assessment did include two deep-sea studies, one conducted in Greece by the University of Patras in collaboration with fishermen (down to 300 m depth), and one on the continental margin and bathyal plain of the NW Mediterranean (Galgani et al., 1995b; UNEP, 2009). Our study provides valuable new data on deep-sea litter in the Mediterranean, both at the local (Blanes slope and canyon) and basin scales.

In the Mediterranean, the UNEP Mediterranean Action Plan report (see Section 4.1; UNEP/MAP/WHO/MEDPOL, 2011) assessed current knowledge on the status of marine litter in the Mediterranean, describes the actions being undertaken by the different countries and makes practical recommendations for action. The report highlighted that, although useful data is available, it is scattered geographically and there is an urgent need for standardization of data collection. This needs for standardization and further studies on deep-sea litter have been addressed by the HERMIONE programme (http://www.eu-hermione.net/). Within HERMIONE, a unique logging template for litter data was created. Several deep-sea litter data, including ROV observations and trawl samples, have been gathered in the framework of HERMIONE and associated projects (e.g. BIOFUN and PROMETEO) and are now available in the open access data archive PANGAEA (http://www.pangaea.de/) (Alt and Daniel, 2012; Boetius, 2012; Huvenne, 2012; Ramirez-Llodra et al., 2012a; Ramirez-Llodra et al., 2012b; Ramirez-Llodra et al., 2012c; Ramirez-Llodra et al., 2012d). Data and analyses such as presented in this study provide baseline information from which to build a detailed picture of the distribution and impact of marine litter on European Seas, contributing to the efforts of the MSDF and UNEP's Global Marine Litter Initiative. Further dedicated studies investigating areas of potential accumulation of litter on essential habitats (e.g. canyons, seamounts, cold-water corals, bathyal plains) are necessary if we are to understand the real impact of litter in deep-sea ecosystems. These studies are crucial for undertaking policy reforms and to assess the economic impact of marine litter.

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