Scattered accumulation hotspots of different seafloor macro-litter categories: first guidelines for the optimization of mitigation actions

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Abstract

Marine litter is an ever-increasing problem that demands immediate reduction plans and mitigation actions that should act synergically to efficiently meet ambitious goals. Since the seafloor has been recognized as a major sink for marine debris, the study of litter accumulation dynamics underlies future plans of removals. We analysed a 7 years (2013-2019) standardized data series collected along Sardinian fishing grounds through MEDiterranean International Trawl Survey, for which estimates of density and abundance of seafloor macro-litter were calculated over 707 hauls. Results emphasize the absence of any temporal trend in seafloor macro-litter abundance and density, but rather a spatial and bathymetric segregation of different litter categories. Our data showed how different sources and physical features of macro-litter items (*i.e.*, plastic and fishing gears, rubber, glass, metals and textile) led to spatially segregated accumulation hotspots, often at shallower depths and closer to coastlines, so that litter removal action could prioritize more accessible hotspots that could represent a solid benchmark for developing more challenging activities to be performed in deeper waters. We point here how the identification of seafloor macro-litter hotspots using aggregated data could be indeed be blurred by the dominance of plastic items and thus hide the presence of less abundant but yet detrimental litter categories accumulated in the marine environment.

Keywords: Marine litter; Single-use Plastic; Mitigation strategies; Seafloor macrolitter hotspots; litter removal.

1. Introduction

Poorly managed waste is contaminating the world's oceans and human-made marine litter is continuously entering the marine environment, with significant impacts on marine ecosystems (Canals et al., 2021; Chiba et al., 2018). It is estimated that plastic alone account for ca. 8 million tons of the solid waste that enters into the marine environment, constituting ca. 60-80% of the whole amount of marine litter (Jambeck et al., 2015), so that the terms plastic and marine litter are used almost as synonyms.

A global commitment aimed at reducing waste and plastic emissions into the environment is urgently needed, both from communities, authorities (*e.g.*, the United Nations Environment Assembly Resolutions Marine Litter and Microplastics and Goal 14.1 of the United Nations Sustainable Development Goals, among others), non-governmental organizations and several businesses that are generally promoting more sustainable lifestyles.

Activities of beach clean-up are efficient initiatives to raise awareness of the extent of litter pollution; however, the ocean seafloor is out of sight to most of society. As such, its vulnerability remains largely unknown to the general public (Canals et al., 2021). This perception does contrast evidence from recent scientific reports devoted to seafloor litter, which strongly supports the hypothesis by which the seafloor represents the ultimate sink for the great majority of items that enter into the marine environment (Cau et al., 2018; Peng et al., 2019; Woodall et al., 2014), especially plastic items, which include the well-known microplastics (1µm to 5 mm in size) (Frias and Nash, 2019).

Within the European Union, Marine litter has been recognized as a major issue in European seas since the entering into force of the Marine Strategy Framework Directive (MSFD; 2008/56/EC), within which marine litter quantification is the 10th of 11 descriptors proposed for evaluating the environmental status of European seas (Galgani et al., 2013). The Mediterranean is among the worlds' oceans exhibiting the most considerable accumulation of marine litter (Eriksen et al., 2014; Pham et al., 2014; Ramirez-Llodra et al., 2011) and, indeed, thousands of items (up to 20,000 km^{-1}; Pierdomenico et al., 2019) have been estimated to sit on its seafloor. However, these *scenarios* could be even more prominent in other areas, for which no data exist. The assessment of the abundance, distribution, and effects of marine litter on the ocean floor is primarily challenged by our limited knowledge of this environment. Indeed, studies carried out so far have investigated benthic litter abundance, composition, and distribution mainly on continental shelves and slope, whereas data from deeper habitats such as adjacent bathyal plains (Bergmann and Klages, 2012; Galgani et al., 2000, 1996; Pham et al., 2014; Ramirez-Llodra et al., 2013) are far less abundant, primarily due to the difficulties and associated costs of deep-sea sampling (Barnes et al., 2009).

As unfortunately reported, the concept of seas litter-free has proved to be utopian, while more realistic targets of reduction are foreseen, only if multiple mitigation measures will act synergically against the global plastic problem (Borelle et al., 2020; Lau et al., 2020); one of these is to potentially reduce harm by removing marine litter that is already in the ocean (Rochman, 2016). In the past decade, a remarkable effort has been put into the identification areas of the sea where floating plastic and microplastic removal could be more effective (Sherman and Van Sebille, 2016). However, this sort of effort doesn't have a 'benthic' counterpart, despite the availability of numerous studies dealing with the identification of seafloor litter hotspots (Franceschini et al., 2019; Garofalo et al., 2020).

The distribution, abundance, and composition of benthic litter in the Mediterranean Sea have patchy documentation, further scattered by the use of different sampling techniques. Over the last decade, the necessity to standardize protocols over wide geographical scales and assess the baseline of seafloor litter's abundance and composition has been recognized. These information were identified as vital to implement litter reduction policies and adequate monitoring schemes. While recognizing a still limited knowledge on the topic, much effort has been put into assessing these two abovementioned points (Spedicato et al., 2019).

What could be considered the 'second step' of the process is the evaluation of multiple years, standardized data series, which are pretty rare (Canals et al., 2021; Galgani et al., 2021; Parga Martínez et al., 2020). Indeed, it has been recently documented how difficult it is to provide a solid answer to whether seafloor macro-litter amount into marine environments is increasing or not due to the scatteredness of data and the lack of continuous standardized surveys (Galgani et al., 2021). These kinds of data would allow to identify seafloor macro-litter 'hotspots', which are defined as those areas where macro-litter accumulates (Tubau et al., 2015) and, pragmatically, where eventual mitigation actions should be prioritized.

In this perspective, this work aims at analyzing the spatial and temporal variability of seafloor litter in the Food and Agriculture Organization (FAO) Geographical Sub-Area 11 (Sardinian seas, western Mediterranean), taking advantage of the MEDiterranean International Trawl Survey (MEDITS) (Spedicato et al., 2020) standardized protocol of surveys conducted for 7 years (from 2013 to 2019).

The present work also aims to test whether different litter categories (according to the MEDITS protocol) may result in geographically segregated seafloor litter hotspots, thus providing useful guidelines for prioritizing remedial action foreseen in the framework of plastic reduction policies.

2. Materials and methods

2.1. Data collection

Data used in the present study were collected in the MEDITS survey framework conducted from 2013 to 2019 in the FAO GSA 11. Spatial patterns of data collected between 2013 and 2015 have been described in Alvito et al. (2018), while the present study focuses on the entire temporal range between 2013 and 2019, including the analysis of accumulation hotspots.

A total of 707 hauls, pre-positioned following a random stratified sampling design, were carried out, from a minimum of 100 to a maximum of 102 hauls year^{-1}(see Tab. 1), distributed over a depth range comprised between 10 and 800m, grouped according to five bathymetrical *strata,* namely: A (0-50m); B (51-100m); C (101-200); D (201-500) and E (501-800) and seven zone, comprised within GSA11 (see Fig. 1).

Once onboard, seafloor macro-litter data was classified according to nine major categories (i.e., L1: Plastic; L2: Rubber; L3: Metal; L4: Glass/Concrete; L5: Clothes; L6: Processed wood; L7: Paper and cardboard; L8: Other; L9: Unspecified), and relative sub-categories (see Alvito et al., 2018; Spedicato et al., 2019 for more details). To obtain standardized abundance and density indices, the total weight and the number of items collected per each sub-category were standardized according to the swept area, expressed in km^2.

2.2 Data processing and statistical analysis

To test for significant spatio-temporal differences in seafloor litter density (items km^{-2}) and abundance (kg km^{-2}), a non-parametric permutational analysis of variance (PERMANOVA; software PRIMER 7+) was performed. The statistical routine was based on Euclidean distance-based resemblance matrixes, built used untransformed data on density and abundance. The PERMANOVA was ran in Uni- and Multivariate environments using the total density or abundance of seafloor macro-litter and its composition, respectively. The analysis was conducted using a design based on three fixed orthogonal factors and their interactions; in detail: i) Year (7 levels); ii) Zone (7 levels); iii) Depth (5 levels), with a variable number of replicates. Differences in seafloor macro-litter abundance across years were also tested singularly using the five most representative macro-litter categories (*i.e.*, from L1 to L5) density and abundance data.

2.3 Seafloor macro-litter hotspots

In order to highlight seabed hotspots of litter accumulation, abundance data from the MEDITS survey were interpolated, and then areas of high densities were selected. For each category, interpolated values were evaluated by 2D interpolating via Inverse Distance Weighting (IDW) (Falivene et al., 2010) on a grid of 1x1 km, thereby obtaining an extended map of the potential zones where plastic litter tends to sink and accumulate according to the historical series. Input variables taken into account for interpolation were longitude, latitude, and depth, while estimation errors were assessed using cross-validation techniques (CV) (Wise, 2011). *Hotspots* of recurrent litter accumulation were evidenced by selecting the 90th percentile of the interpolated distribution.

3. Results

The total swept area covered by the survey was ca. 44 km^2. Among the 707 hauls conducted between 2013 and 2019, 246 showed the absence of seafloor macro-litter (35%). More in detail, the lowest number of macro-litter free hauls (18) was recorded in 2015, corresponding to 17% of the hauls conducted that year; on the contrary, the highest (45) was recorded in 2016 (44% of the year' hauls). Overall, a raw total of 1908 items were collected from 2013 to 2019, corresponding to a total of 531 kg of seafloor litter (Fig. 3).

3.1. Spatio-temporal trends

During the study period, the average number of collected items was 107.3 ± 30 items km^{-2}, with a maximum of 151.1 ± 44.8 items km^{-2} (average ± standard error) in 2014 and a minimum of 70.8 ± 26.4 items km^{-2} recorded in 2016. With respect to the amount of seafloor macro-litter, the average abundance recorded in the study period was 35.06 ± 20.8 kg km^{-2}, with a maximum of 85.4 ± 66.9 kg km^{-2} in 2019 and a minimum of 10 ± 2.6 kg km^{-2} in 2013.

The highest macro-litter density was recorded in zones 6 and 7 (Fig. 1), showing an average density of 180 ± 39.5 and 140 ± 23.7 items km^{-2}, respectively, while the lowest density was in zone 1 (32 ± 5.5 items km^{-2}).

According to the PERMANOVA routine, there was a lack of significant differences in seafloor macro-litter density, abundance and composition across years (Tab. 2). The absence of significance was also confirmed when each of the 5 major categories of macro-litter was considered singularly.

While the interaction of the three factors considered simultaneously (*i.e.* 'year', '*strata*' and 'zone') was not significant, the interaction of the factors' *strata*' and 'zone' was statistically significant ($p<0.001$; Tab. 2), emphasizing a significant variability in the spatial and bathymetric distribution and composition of seafloor macro-litter.

3.2. Seafloor macro-litter composition

Concerning the seafloor macro-litter composition in terms of abundance, plastic was the most abundant component, with an average value of 82% across the investigated period (2013-2019). The highest relative abundance was measured in 2019 with 94%, followed by 2014 and 2017, where plastic accounted for 90% and 86% of the total amount of seafloor macro-litter, respectively (Fig. 2). Despite the absence of a temporal trend, the macro-category of plastic that includes Derelict Fishing Gears was consistently the dominant category in relative abundance, followed by rubber, metal and others, that showed an average percentage of ca. 4% and clothes (3%) (Fig. 2). The mean relative abundance of plastic collected from the seven different zones of the Sardinian grounds was 82%, followed by rubber, metal, and 'other', all accounting for ca. 4%. The highest values were observed in zone 4, where plastic items accounted for 96% of the total, followed by zone 5 (94%) and zone 6 (72%) (Supplementary Fig. 1). Concerning the relative abundance in weight calculated for all the five bathymetric *strata* (A-E), plastic occupied the major portion with 82%, followed by metal, glass, and clothes with ca. 4%. The deepest stratum (E) and stratum (C) generally showed the highest values for weight abundance with 85% of plastic debris followed by the shallowest strata (i.e., A and B), showing values of 84% of plastic debris each. The lowest value for plastic was observed in stratum (D); which showed a higher relative abundance of ‘Other’ category and Clothes (26% and 13%, respectively; Supplementary Fig. 2).

With respect to the density of items collected throughout the study period, plastic debris represented the dominant category, which was on average accounting for ca. 84% of the total number of items (Fig. 2). The highest record was observed in 2019 (90%), followed by 2017, 2018 and 2016, where items belonging to the plastic category accounted for 88%, 87%, and 86%, respectively (Fig. 2). As per the relative abundance in terms of weight, plastic remained the dominant category over metal, glass & clothes, which showed a mean density percentage of 4%. The spatial analysis revealed how collected items were numerically dominated by the plastic category, with a maximum value of 93% recorded for zone 5, followed by zone 6 (88%) and zone 4 (83%). The mean density was 84% across all zones, followed by metal, glass, and clothes, accounting for 4% (Supplementary Fig. 3). The average relative density calculated for the study period in all the five bathymetric *strata* (A-E) showed how plastic constituted 84% of collected material, followed by metal, glass, and clothes, all accounting for 4%. The remaining categories accounted cumulatively for 4%. *Stratum* (B) showed the highest values of plastic macro-litter (89%); followed by *strata* E and A, where plastic always accounted for more than 80% (i.e., 87% and 82%, respectively); whereas stratum (C) recorded the lowest values of 74% plastic debris (Supplementary Fig. 4). The second most representative category of macro-litter were Glass and

Clothes, with variable percentages through different bathymetric *strata*, ranging between 2 and 12% and between 3 and 7% respectively (Supplementary Fig. 4).

3.3. Seafloor macro-litter hotspot

Seafloor macro-litter hotspots for the whole set of categories and segregated for each category are shown in Fig. 4. Results showed that for the Plastic category, which was split in fishing-related (e.g., fishing nets, lines, etc.) and not fishing-related (all other plastic items), major concentrations of items recur in the south-west area of the island. Hotspots for rubber items showed a reasonably homogeneous distribution around the Sardinia coast, with the highest peaks in the south-eastern area. Similar values were found for the Metal debris. Glass category showed a consistent hotspot in the north-western area of the island, while the highest values of fiber and clothes are more likely to occur in the south-eastern area (Fig. 4).

4. Discussions

Environmental recovery (*i.e.*, clean-up actions and restoration of highly contaminated sites) is recognized as one of the mitigation strategies that should act synergically with other measures to reduce seafloor litter and plastic contamination in the future (Borelle et al., 2020). Removal of litter contamination is desirable, but in many cases, it lacks a detailed consideration of the possible effectiveness, costs, and benefits of such solutions and without acknowledging a basic lack of data (Falk-Andersson et al., 2020). Such strategies will surely be most effective when guided by best-available science (Rochman, 2016). What is the best science on the topic is a still-opened debate that will unlike find a proper answer in the near future; however, trying to identify the *best-available* science is a more affordable task. In this perspective, standardized data that take advantage of well-established protocols currently represent the most reliable option to study seafloor macro-litter's temporal trends (Spedicato et al., 2019), while acknowledging the intrinsic drawback that campaigns designed for other purposes might present (Canals et al., 2021).

Based on regular surveys conducted over a 7 years' time series, our results confirm the absence of a significant temporal trend in seafloor macro-litter quantities, regardless of the litter category, as already observed and commented in a recent review proposed by Galgani et al. (2021). The absence of any trend is likely related to the oscillatory pattern of plastic macro-litter, which represents the most conspicuous fraction of collected items (*i.e.*, always >60% over the study period, both in terms of density and abundance per km^2), regardless of the geographical area or the bathymetric *stratum* considered.

The plastic fraction is of particular concern due to the detrimental effects that its persistence in the environment can possibly trigger, such as: i) the introduction of artificial substrates that can locally enhance benthic biodiversity (the so-called 'plastic benefits paradox'; Carugati et al., 2021; Song et al., 2021); ii) the accidental ingestion and possible fragmentation into smaller particles mediated by *biota* that can ideally become more and more bioavailable to multiple levels of the trophic web (Cau et al., 2020, 2019a; Courtene-Jones et al., 2019; Fossi et al., 2018); iii) compromise the biogeochemistry and alter microbial communities in sediments (Seeley et al., 2020); iv) provide physical damage to structuring fauna, in case of Derelict Fishing Gears (Angiolillo and Fortibuoni, 2020; Cau et al., 2017; Galgani et al., 2018). Nonetheless, beside the enormous attention of the scientific community on the plastic problem, other undocumented yet detrimental effects of other litter categories to the ecosystem could likely be discovered.

The observation of a decreasing trend can be possibly observed for few specific types of plastics subject to societal reduction measures (e.g., certain categories of single-use plastic), even though the time required might be within decades (Maes et al., 2019); on the contrary, other sub-categories of plastic items (e.g., fishing gears) do not follow the same trend. However, the urgency to remove seafloor macro-litter and consequently plastic already accumulated in the marine environment for long periods (Cau et al., 2019b) is crucial to reduce the detrimental effects mentioned above.

Fishing For Litter (FFL) initiatives are among the most effective strategies for removing seafloor-litter from oceans, although many difficulties arise in their execution and implementation (Ronchi et al., 2018); this is due to the wide spatial coverage of trawling activities, often in remote areas where fishermen are the only operators capable of providing this type of social service, nonetheless during their regular working routine.

Focusing specifically on DFGs, their removal appears very demanding in terms of tools and skills required to perform such remedial action, which additional difficulties to the low accessibility of sea-bottom environment below certain depths. Bottom trawling vessels using hooks and ropes are the cheapest way for removing DFGs, but it strongly impacts mechanically the seabed (Cho, 2011). Additionally, it could also be ineffective since nets and ropes are often lost due to their entanglement in small geomorphologies of the seabed or structuring communities (Angiolillo et al., 2015), that would be likely ripped out. In order to tackle this issue, a synergic, sustainable action that might involve diverse parties and technologies (such as professional divers and remote sensing) should be adopted (Cho, 2011; Madricardo et al., 2020; Morishige and McElwee, 2012).

The study of seafloor macro-litter as a whole could be blurring if the aim is identifying areas where mitigation strategies should be prioritized. The accumulation hotspot analysis, performed separately per each category identified in the MEDITS protocol, showed segregated distribution for the 5 major categories investigated (Fig. 3). This segregation pattern is ascribable to the macro-litter's intrinsic features, which, depending on material and dimensions, can float on the sea surface before sinking due to changes in specific weight enhanced by biofouling, or reach the seafloor directly once discarded. While the former case is the one that mostly relates to plastic items (Ryan, 2015), the latter relates the most with heavier objects such as rubber, glass, metal. Heavier objects hotspots were generally closer to the coastline, mostly in the proximity of the larger ports (Cagliari, Oristano and Olbia) or, in the case of glass objects, far from the coast but close to the most trafficked maritime routes such as the one those across the Gulf of Bonifacio or the port of Olbia, which suggests how this sort of object can possibly result from local dumping activities.

As recently reported (Scotti et al., 2021), according to available information extrapolated by Maritime State Property Concessions (Italian Ministry of Infrastructure and Transports), the hotspot area for glass the seafloor category could be related to both intense tourism and shipping activity that occurs most intensely along the north-western coastline. Also, hydrodynamic drivers such as the Northern Tyrrhenian Cyclone (east of the Strait of Bonifacio), could be invoked as a driver of local accumulation pattern by predictive model studies (Mansui et al., 2020). Similarly, the highest density of plastic litter found in the southwestern waters, could be related not only to the inefficient waste management of the coastline, but even to the mesoscale instabilities belonging to the Algerian currents, with the latter being one of the most evident feature of swift currents (Zambianchi et al., 2017).

Plastic objects can be transported and accumulated far from the sources and over long distances following marine currents and in proximity of peculiar geomorphologies of the seafloor (Galgani et al., 2000; Spedicato et al., 2019). Thus, the distribution of plastic hotspots resulted in few delimited areas, mainly on the northern, western, and southern coasts, while they were absent on the eastern shore. The western coast, in particular, is one of the most dynamic areas of the Mediterranean Sea (Olita et al., 2013). It is characterized by strong northwest winds (Mistral and Tramontane) and by the presence of a southeastward current coming from the Balearic island, that around 40°N separates into two branches flowing northward and southward when approaching the coast (Hernandez-Lasheras and Mourre, 2018). The northward flow branch may be one of the factors that enhanced the accumulation of plastic and rubber categories in the gulf of Alguer (north-western corner), together with high tourism activities to which this area is subject especially in the summer; while the southward branch, also known as the Western Sardinian Current (WSC), might be one of the leading transport pathways contributing to the accumulation of plastic objects, but also of all the other categories, in the south-western corner. In this area, the presence of two minor Sardinian islands, Carloforte and Sant'Antioco, represents a physical barrier to the flow of WSC at its maximum intensity (Olita et al., 2013), favoring the formation of macro-litter hotspots washed up from the western continental shelf. Additionally, the presence of mesoscale anticyclonic eddies observed in this area (Knoll et al., 2017) could be another hydrological contributor to the accumulation of seafloor litter as they could facilitate the collection and sinking of floating macro-litter to the sea bottom (Spedicato et al., 2019).

Coupled with this highly dynamic hydrological *scenario*, the geomorphology of the seafloor is another critical feature that acts synergically to the spatial distribution of seafloor macro-litter hotspots (Galgani et al., 2000). Along the western Sardinian coast, the presence of a large continental shelf, characterized by extensive areas of outcropping and sub-outcropping rocky volcanic substrates (Conforti et al., 2016; Deiana et al., 2021), could possibly facilitate the entangling and thus the accumulation of drifting objects on the seafloor. In contrast, along the eastern Sardinian coast, a short continental shelf, incised by numerous submarine canyons with their heads at a short distance from the shoreline (Harris and Whiteway, 2011), favors the transport of seafloor macro-litter, especially for lighter objects such as plastic items, towards deeper sea bottoms (Cau et al., 2017; Tubau et al., 2015; Zhong and Peng, 2021), explaining the absence of plastic hotspots along the eastern continental shelf.

Land-sourced macro-litter can be a major fraction of the total litter retrieved, which may flow from distant inland sources (Meijer et al., 2021; Pierdomenico et al., 2019). Moreover, such input can be exacerbated by heavy rainfalls, river floods, sewage overflow, or can carry large amounts of debris to beaches and coastal waters in a matter of a few hours or days, part of which subsequently spreads seawards and settles to the seafloor (Canals et al., 2021). Four of the largest Sardinian's rivers (i.e., Flumini Mannu, Rio Mannu, Coghinas and Tirso; Alvito et al., 2018) discharges their water, together with all the land-based litter accumulated along their path, in proximity of highlighted hotspots in the southern (Gulf of Cagliari), northern (Gulf of Asinara) and western (Gulf of Oristano) Sardinian coasts. All these rivers pass near by the highest populated Sardinian cities, Cagliari, Oristano, and Sassari, and they outflow in distinct gulfs, which, for their hydrological dynamics, tend to accumulate litter debris instead of washing them away by currents (Katsanevakis and Katsarou, 2004). A fifth big Sardinian river, the Flumendosa river, discharge its water on the island's south-eastern coast. However, the San Lorenzo canyon's presence in front of the Flumendosa rivers mouth might favor the convey pathway of litter objects from the continental shelf down to the submarine canyons, as already documented by Tubau et al., (2015) in the north western Mediterranean.

Conclusions

Despite the almost exponential increase in the number of studies dealing with seafloor macro-litter over the past decade, our knowledge on the topic remains still limited when coping with the necessity to develop sound removal actions for the fraction of macro-litter already accumulated in the marine environment. Data collection is nowadays capable of providing relatively limited information when considering the deep-sea as the major sink for macro-litter. Indeed, it can be assumed that some major accumulation areas, have yet to be identified.

Numerous surveys have shown that litter can accumulate more likely in some locations rather than in others, often showing concentrations comparable to those observed in landfills (Pierdomenico et al., 2019). This warrants reflections on the urgency to schedule, whenever possible, *in situ* removal activities, which should be carefully assessed.

In this perspective, our results are the first to document a scattered distribution of different macro-litter categories, which likely depend on their sources and mobility through the marine environment. Such analysis pointed how the identification of macro-litter hotspots performed using aggregated density data might actually blur the identification of smaller yet considerable macro-litter hotspots, due to the unequivocal dominance of plastic related categories, both numerically and in terms of abundance. Moreover, our analyses also highlighted how in GSA11, hotspots for numerically minor but yet detrimental for the environment macro-litter categories dwell closer to the coastlines compared to other litter categories. Considering this, and also considering how removal activities are still in their infancy, prioritizing such closer and more accessible areas could represent a solid benchmark for developing more challenging remediation activities, to be performed in the deep-sea.

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Table 1. Summary of the MEDITS survey conducted in Sardinian sea, reporting the number of hauls and the swept area per year, geographical sub-area within GSA11, and bathymetric *stratum*. Also, the average density and abundance of items per km^2 (± st. error) are reported per category.

			n. items km^{-2}		Kg km^{-2}	
Years	**Hauls**	**Swept Area (km^2)**	**Average**	**St. Error**	**Average**	**St. Error**
2013	101	6.2	75.5	20.8	10.0	2.6
2014	102	5.7	151.1	44.8	44.6	23.7
2015	101	6.4	141.3	29.7	41.0	14.0
2016	100	6.2	70.8	26.4	13.5	4.3
2017	100	5.8	106.4	38.3	37.4	14.6
2018	102	6.4	84.1	22.7	13.6	5.6
2019	101	7.2	121.3	26.2	85.4	66.9
TOTAL	**707**	**43.9**				

		n. items km^{-2}		Kg km^{-2}	
Zones	**Hauls**	**Average**	**St. Error**	**Average**	**St. Error**
1	63	31.8	5.5	10.4	4.5
2	126	44.7	6.2	8.2	2.5
3	70	90.9	19.7	26.0	7.9
4	68	81.1	20.1	140.9	104.3
5	80	87.7	16.4	39.3	16.3
6	184	180.1	39.5	26.7	6.7
7	116	139.8	23.7	31.3	12.1

		n. items km^{-2}		Kg km^{-2}	
Strata	**Hauls**	**Average**	**St. Error**	**Average**	**St. Error**
A	142	101.5	19.1	32.3	11.7
B	131	221.5	55.2	48.9	18.4
C	168	82.3	10.5	64.9	40.8
D	148	73.5	8.6	10.4	2.8
E	118	65.6	12.4	11.4	5.4

Table 2. Output from the PERMANOVA analysis (main test). Significant Monte Carlo procedure p-values [P(MC)] are reported in bold.

UNIVARIATE density (n. items km^{-1})

Source	df	MS	Pseudo-F	P(MC)
Year	6	1153	0.691	0.762
Zone	6	4094	2.4541	**0.003**
Stratum	4	4136	2.4791	**0.009**
Year*Zone	36	1485	0.8899	0.730
Year*Stratum	24	1275	0.7639	0.885
Zone*Stratum	24	2550	1.5282	**0.013**
Year*Zone*Stratum	116	1267	0.7596	0.996
Res	247	1668		
Total	463			

MULTIVARIATE density (n. items km^{-1})

Source	df	MS	Pseudo-F	P(MC)
Year	6	3462.8	1.328	0.098
Zone	6	5967.1	2.288	**0.001**
Stratum	4	5883.2	2.256	**0.004**
Year*Zone	36	2608	1	0.485
Year*Stratum	24	2732.5	1.048	0.335
Zone*Stratum	24	3925.8	1.505	**0.002**
Year*Zone*Stratum	116	2464	0.945	0.796
Res	247	2607.3		
Total	463			

UNIVARIATE abundance (Kg km^{-1})

Source	df	MS	Pseudo-F	P(MC)
Year	6	2251.8	0.8915	0.601
Zone	6	3914.2	1.5497	**0.050**
Stratum	4	7820.5	3.0963	**0.001**
Year*Zone	36	2082.7	0.8246	0.898
Year*Stratum	24	2293.3	0.9079	0.694
Zone*Stratum	24	4085.7	1.6176	**0.004**
Year*Zone*Stratum	116	2348.7	0.9299	0.791
Res	247	2525.7		
Total	463			

MULTIVARIATE abundance (Kg km^{-1})

Source	df	MS	Pseudo-F	P(MC)
Year	6	4124.7	1.225	0.138
Zone	6	5848.7	1.738	**0.007**
Stratum	4	8317.9	2.471	**0.001**
Year*Zone	36	3563.3	1.058	0.256
Year*Stratum	24	3533.4	1.049	0.322
Zone*Stratum	24	4937.5	1.467	**0.001**
Year*Zone*Stratum	116	3520.8	1.046	0.189
Res	247	3365.8		
Total	463			

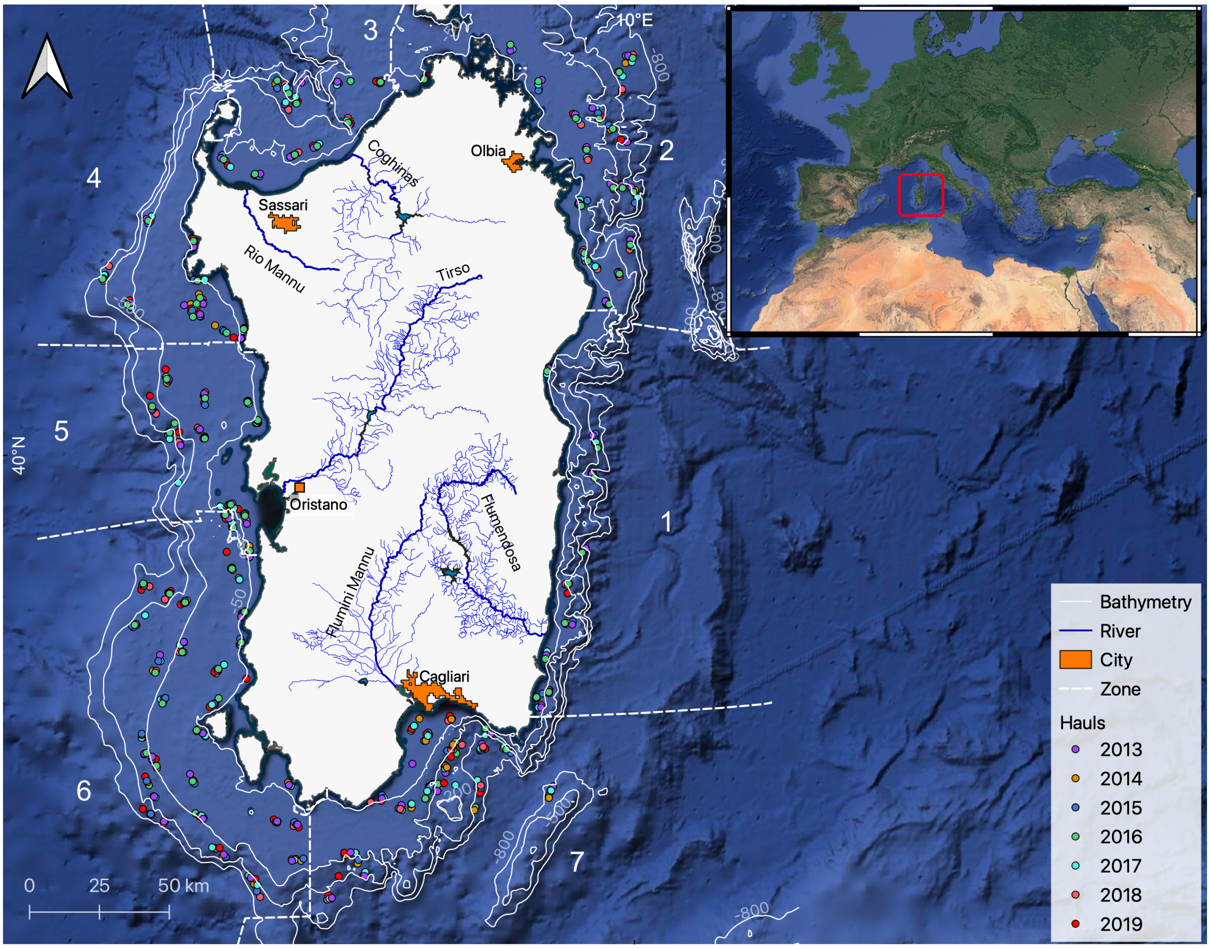

Figure 1. Map of the hauls performed during the study period (2013-2019). The map shows the main rivers in the study area, as well as the major cities in the region.

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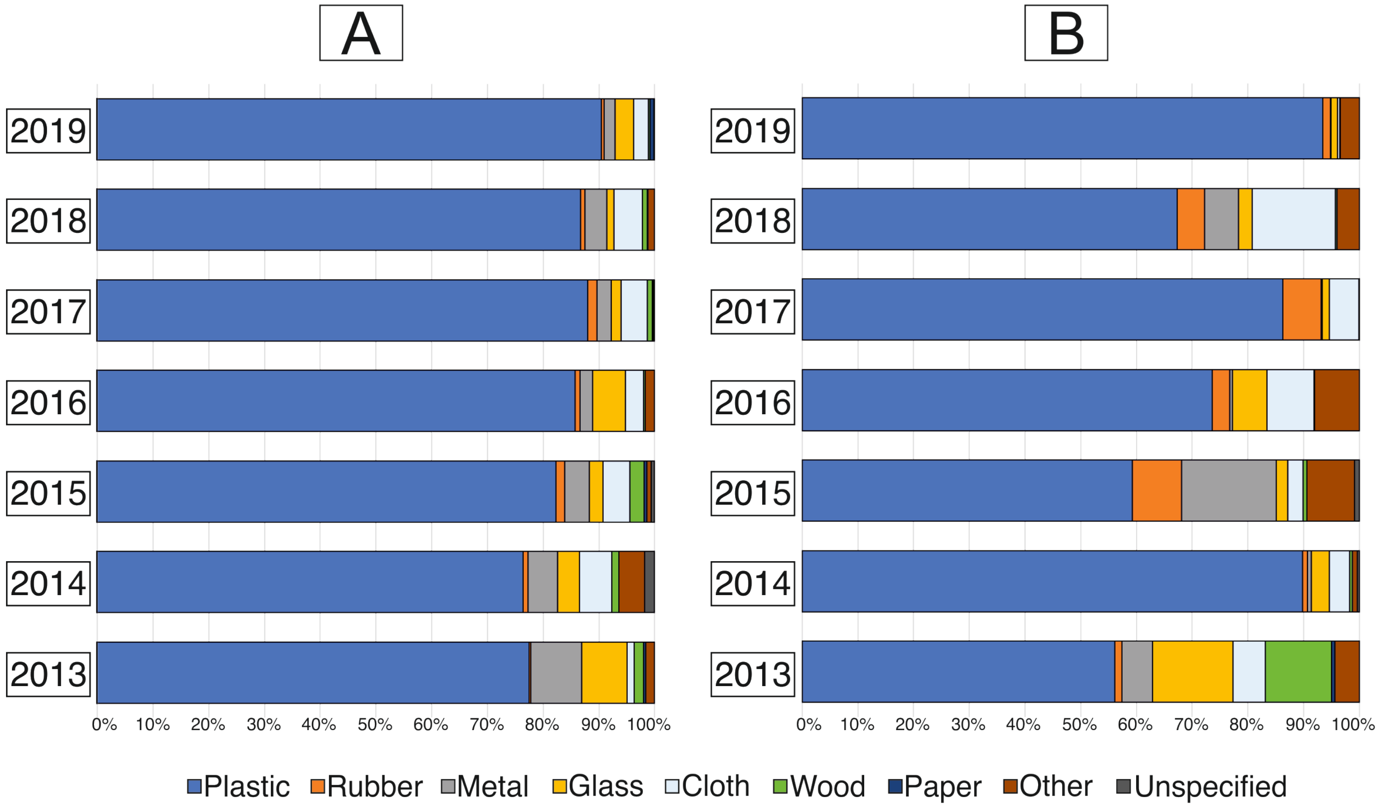

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605 **Figure 2.** Percentage composition in terms of (A) density (n. items km^{-2}) and (B) abundance (Kg km^{-2})
606 of seafloor macro-litter during the study period, comprised between 2013 and 2019.
607

Figure 3. Multipanel showing different macro-litter categories collected through the MEDITS trawl survey in the study period

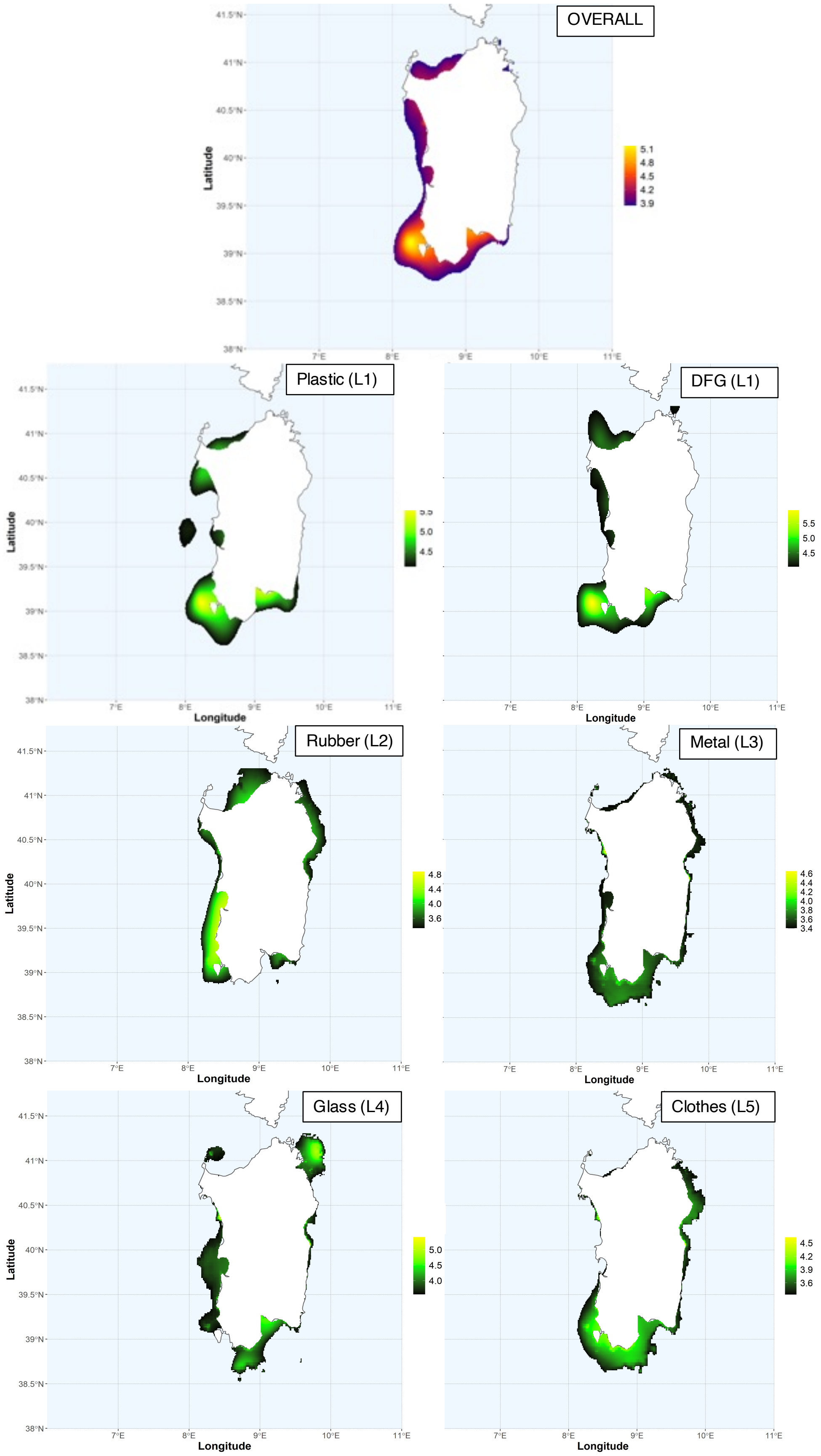

Figure 4. Map of seafloor macro-litter hotspot identified in GSA11, represented as results of the five litter categories merged (Overall) and divided according to each of the most representative seafloor macro-litter categories. The scale at the right of the figures is reported as logarithmic weighted n. of items.