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Abstract

Abundance, composition, and distribution of macro-litter found on the seafloor of the Strait of Sicily between 10-800 m depth has been studied using data collected by bottom trawl surveys MEDITS from 2015 to 2019. Three waste categories based on the items use were considered: single-use, fishing-related and generic-use. Over 600 sampling sites, just 14% of these were litter-free. The five-years average density of seafloor litter was 79.6 items/km^2 and ranged between 46.8 in 2019 and 118.1 items/km^2 in 2015. The predominant waste type was plastic (58% of all items). Regardless of material type, single-use items were a dominant (60% of items) and widespread (79% of hauls) fraction of litter with a mean density of 48.4 items/km^2. Fishing-related items accounted for 12% of total litter items. Percentage of dirty hauls and litter density increased with depth. Analysis of the relation density-depth indicates a progressive increase of litter density beyond depth values situated within the interval 234-477 m depending on the litter category. A significant decrease in litter density by categories was observed over the period. Patterns of spatial distribution at the higher depths (200-800m) resulted stable over the years. Density hotspots of fishing-related items were found where the fishing activity that uses fish aggregating devices (FADs) is practised and in the proximity of rocky banks. Single-use and generic-use objects densities were greater on the seafloor along main maritime routes than other areas. Comparisons between the percentage of hauls littered with anthropic waste from the mid-1990s against those in 2018-19 highlighted an increase of about 12% and 15 % for single-use items and fishing-related items respectively, and a decrease of 13% for generic-use items. This study provides a snapshot of the current situation of littering in the central Mediterranean Sea and represents a solid baseline against which the effectiveness of current and future mitigation strategies of the litter impact on marine environment can be measured.

Keywords: baseline, plastics, single-use litter, fishing-related litter, Strait of Sicily

Main Findings

Higher density of litter distribution at deeper bottoms. Single-use and generic-use items accumulate along main shipping routes; fishing-related items are associated with specific fishing activities

Introduction

Accumulation of anthropogenic solid waste on the seafloor is a ubiquitous and increasing phenomenon that poses a serious threat to marine ecosystems health worldwide. Types and quantities of marine litter vary considerably across marine regions due to different hydrodynamics, geomorphologic and anthropic factors, being the enclosed seas such as the Mediterranean or the Black Sea the most affected areas in the world (UNEP/MAP, 2015). It is estimated that about 0.5 billion litter items are currently lying on the Mediterranean seafloor (UNEP/MAP, 2015) with densities locally reaching over 1000 items/km^2 (Ioakeimidis et al., 2014; Fortibuoni et al., 2019) and exceptionally exceeding 100000 items/km^2 (Galgani et al., 2000, 2015).

Despite the great variety of waste materials (plastics, metals, glass/ceramics, wood, rubber, textiles, paper, etc.) found in the marine environment, plastics are predominant worldwide (Derraik, 2002). The proportion of plastic consistently varies between 60% and 80% of the total marine litter, overcoming 90% in some regions (Derraik, 2002). According to a recent estimate, the annual input of plastic waste to ocean amounts to 4.8-12.7 million tons and could increase by an order of magnitude by 2025 (Jambeck et al., 2015). Metal and glass/ceramic also contribute significantly to marine litter and generally represent the highest percentage of waste after plastics, while other litter typologies contribute cumulatively with minor percentages (Ioakeimidis et al., 2014; Pham et al., 2014; Spedicato et al., 2019).

Solid waste enters the seas mostly from land-based sources (e.g. about the 80% of plastic waste is from terrestrial sources; Andrady, 2011; Bonanno and Orlando-Bonaca, 2018) and originates from accidental or intentional dumping and poor waste management systems in coastal regions. Nevertheless, marine-based sources play an important role too through unintentional or illegal unloading of waste from ships, including fishing boats, and accidental losses of fishing gear (Ryan, 2015; Bonanno and Orlando-Bonaca, 2018). It is estimated that derelict fishing gear on the seafloor accounts for about 10% of all marine litter in the world oceans (UNEP/MAP, 2015). Furthermore, in some areas, aquaculture can also be an important source of marine-based littering, especially given the continuous expansion of the aquaculture industry (Pasquini et al. 2016; Melli et al. 2017)

Different factors determine the fate of litter entering the sea (Bonanno and Orlando-Bonaca, 2018 and reference therein) and, in recent years, an increasing number of studies are focusing on the modeling of marine litter transport and its accumulation patterns (e.g. Liubartseva et al., 2018; Mansui et al., 2020). Heavy waste such as glass and metal probably sink very close to the place of discharge, light waste such as plastics can be dispersed over long distances for the effect of winds and currents causing degradation of the marine environment even in areas far away from the pollution sources (e.g. Bonanno and Orlando-Bonaca, 2018).

The main concerns about the accumulation of anthropic waste on the seabed regard its persistence (e.g. plastic only degrades over the centuries) especially in the deep sea, and the potential harmful effects, direct and indirect, on ecosystems and organisms (Thompson et al., 2009; Galgani et al., 2013; Jambeck et al., 2015; Anastasopoulou & Fortibuoni, 2019 and reference therein). Direct damages to marine fauna may be due to the ingestion of large debris, such as plastic bags, or accidental entanglement in fishing gears lost or abandoned on the seafloor (Fossi et al., 2018 and reference therein; Consoli et al., 2019, 2020; Mancia et al., 2020). Another aspect is the potential risk associated to the degradation product of plastic items, i.e. microplastics (plastic fragments below 5 mm in size) which are ingested by zooplankton and may be transferred through the entire marine food web up to humans (Thompson et al., 2009; Cole et al., 2011; Lusher et al., 2017). Even social and economic damages are associated to marine litter mainly due to the loss of the aesthetic value and related ecosystem services of marine landscapes littered with anthropic waste (Xanthos & Walker, 2017; Maes et al., 2019). For all these reasons, marine litter and primarily plastic pollution are perceived worldwide as a critical environmental priority and an alarming threat to marine resources and blue growth.

In the last decade, the European Union (EU) has set up many complementing strategies to reduce and prevent the input of waste into the sea, as well as to take remedial action against waste already present in the marine environment. These include the Marine Strategy Framework Directive (MSFD; Council directive 2008/56/EC) which established a framework for the monitoring and achievement of Good Environmental Status (GES) for the marine environment through the assessment of 11 descriptors, with the descriptor 10 focusing specifically on the characteristics of litter in the marine and coastal environment and its impact on marine life. A similar framework was established, at regional level in the Mediterranean, with the Integrated Monitoring and Assessment Programme of the Mediterranean Sea Coast and Related Assessment Criteria (IMAP) which adopted the Common Indicator 23 "Trends in the amount of litter in the water column including microplastics and on the seafloor" under the Ecological Objective 10 (EO10) i.e. Marine Litter (IMAP Decision IG.22/7 of the 19th Meeting of the Contracting Parties of the Barcelona Convention). Most recently, the European Strategy for Plastics in a Circular Economy (EC 2018) was adopted, which proposes new EU-wide rules for modernising the plastics economy and modifying the way plastic goods are produced and recycled. In particular, the Council Directive (EU) 2019/904 is aimed at reducing the impact on the environment of single-use plastics, mainly plastic bottles, plates and food containers, and fishing gear containing plastic. According to the European Commission, taken together, these two broad categories constitute 70% of all marine litter items in Europe (https://ec.europa.eu/commission/presscorner/detail/en/IP_18_3927), so the proposed measures aim, among other, to reduce by 2025 the consumption of single-use food and drinks containers by at least 25 % and to reach a minimum collection rate of 50 % of fishing gear. In addition, a new Council Directive (EU) 2019/883 on port reception facilities (repealing Directive 2000/59/EC) introduced some new rules for the delivery of waste from ships, in line with requirements of the International Convention for the Prevention of Pollution from Ships (MARPOL). This new regulation, through a mix of incentive and enforcement measures, such as cost recovery systems based on indirect fee and targeted inspections, intends to ensure that waste generated on ships but also waste collected in nets during fishing operations is delivered to port reception facilities and adequately managed, instead of being discharged at sea. National law of Member States should comply with the adopted rules by 2021. Moreover, the European Maritime and Fisheries Fund (EMFF) provides financial support for the recovery of waste by fishermen from the sea as well as for the development of port facilities for waste collection.

The commitment of the EU to tackle the great challenges facing our oceans has also been strengthened in the new research and innovation programme Horizon Europe 2021-2027, where one of the five mission areas is "Healthy Oceans, Seas, Coastal and Inland Water". Specific goals of the mission are the development of solutions to prevent, mitigate and remove marine pollution (including plastics), the transition to a circular and blue economy and the development of biodegradable plastic substitutes.

However, according to Bonanno and Orlando-Bonaca (2018), current regulations are still not enough to address the real threat of massive amounts of plastics entering the oceans. The current knowledge gaps on waste distribution and accumulation in specific areas hinder the capacity of making progress towards mitigating marine pollution with particular regard to plastic (i.e. the real quantity, characteristics, sources and distribution of litter released into the sea, as well as the biological and ecological impacts on the marine ecosystems and the harmful effects on human health) and for these reasons, it is necessary to have a clear understanding of this process.

By focused on single-use, generic-use and fishing-related litter, in the present paper we used macro-litter data collected during scientific trawl surveys carried out in the northern part of the Strait of Sicily (central Mediterranean) during the 2015-2019 period to: 1) assess the composition and density of seafloor litter; 2) evaluate how the density varied with depth and time; 3) explore spatial distribution; 4) compare the current level of pollution with that in the mid-1990s. Our study provides a baseline for monitoring and assessing the application of European policies and relevant international initiatives on reducing the amount of litter in the marine environment.

Materials and methods

Investigated area

The investigated area (Fig. 1) is located in the northern part of the Strait of Sicily, an ecologically important area in the Mediterranean sea (Altobelli et al., 2017; Di Lorenzo et al. 2018), and corresponds to the Geographical Sub Area (GSA) 16 (GFCM 2009), covering about 34000 km^2. The area is subject to intense and varied human pressure with relative systemic impacts on the coastal and marine environment. Indeed, the south coast of Sicily is very urbanised with many important commercial and tourist ports, agricultural and industrial activities, aquaculture plants, oil refineries and offshore platforms (Buhl-Mortensen et al., 2017). In addition, the Strait of Sicily is one of the most important fishing areas in the Mediterranean with the large fishing fleet of Mazara del Vallo engaged in deep-sea fishing (Milisenda et al., 2017; Russo et al., 2019). Finally, due to its central position connecting the eastern and western Mediterranean basins, the Strait of Sicily represents an important crossroads for Mediterranean trade and touristic routes including the most important oil traffic lane (e.g. to have an idea of this intense traffic it is estimated that a total of 170,000 vessels passed through the Strait of Sicily in one year between 2016 and 2017; Deidun et al., 2018).

Data collection

Typology and abundance of macro-litter on the seafloor of GSA 16 were recorded from 2015 to 2019 during the MEDITS trawl surveys (MEDiterranean International bottom Trawl Surveys; Bertrand et al., 2002). A total of 120 hauls were sampled each year over the depth range 10-800 m and allocated to five bathymetrical strata (A:10–50 m; B:51–100 m; C:101–200 m; D:201–500 m; E:501–800 m) (Anonymus, 2017). Litter data in each haul were counted and classified into 9 categories of material type and 27 sub-categories according to the standardised MEDITS protocol (Fiorentino et al., 2013; Anonymus, 2017).
For the purposes of the present work, collected litter items were reclassified according to three general categories based on the items use (sensu Veiga et al., 2016 and references therein), i.e. the use durability to which items were designed for, and the items designed for professional or consumer use (see Supplement S1): single-use items i.e. objects that are discarded after having been used once such as plastic bags and bottles, cans, containers and a variety of food packaging items; fishing-related items such as lines, nets, and buoys; generic-use items which include objects of mixed material and generic use such as large plastic or metal containers, tyres, drums, electrical appliances, clothes, mattresses, etc.
Hence, the number of items per category in each haul was divided by the swept area (km^2) of the haul, producing geo-referenced standardised indices of density (DI, items/km^2) by categories of use. It was decided to not calculate mass indices, because very large and weight items may increase variability in measures and because density indices give more emphasis to the nature/category of litter (Galgani et al., 2013).

Data analysis

Temporal trend and relation to depth by categories of use

Generalised linear models (GLM) with Poisson distribution corrected for overdispersion were used to model the density of the litter categories as a function of depth and year. Because of the overdispersion, the standard error was corrected using quasi-Poisson GLMs (Zuur et al., 2009). Further, it was tested if the relationship obtained with the GLM between the response (density index) and the depth was piecewise linear, i.e. represented by two or more straight lines connected at an unknown value named breakpoint. The breakpoints identify abrupt changes in the relation and can be considered threshold values beyond or below which significant effects of the independent variable on the dependent variable occur. The R package 'segmented' (Muggeo, 2008) was used to perform the analysis. It applies an iterative procedure in which a breakpoint is estimated at each iteration until the algorithm converges when the distance between neighbouring straight lines is minimised (close to zero). The method was applied on the whole depth range 10-800 m, but even on pairs of neighbour strata (i.e. reducing and fixing the window of the observations) to assess the presence of structural changes in the relation density-depth at small range of variations of the explanatory variable (otherwise not detectable due to the litter items distribution along the whole depth range likely masking the presence of small variations). The analysis was performed using the R software (R Development Core Team, 2019).

Spatial distribution by categories of use

For each of the three litter categories, two spatial indicators were computed to summarise the characteristics of the distribution of density values within the depth strata of GSA 16: 1) the centre of gravity (CG) that measures the mean geographic location of the distributions and 2) the global index of collocation (GCI) which served to assess whether distributions were geographically distinct or overlapped over the years (Woillex et al., 2009). Specifically, GCI allowed quantifying the extent to which each litter category was found mainly at the same geographic places over the different years. To achieve this, a GCI was computed for each depth stratum (from A, 10-50 m to E, 501-800 m) and all possible pairs of consecutive years. GCI varied from 0 to 1, where 1 indicated a complete overlap between the spatial distributions in two consecutive years. The mean GCI (± s.e.) by depth stratum was plotted for each category of litter. CG and GCI were computed using the geostatistical R Package RGeostats (Version 11.2.11).
Global and local spatial autocorrelation analyses was conducted to investigate the spatial distribution of the three litter categories and to identify the areas of high densities and accumulation. Firstly, Incremental Spatial Autocorrelation analysis was applied to identify the appropriate scale for spatial analysis. The method computes spatial autocorrelation for a series of increasing distances applying the global Moran's I statistic (Moran, 1950), and gives an index of the intensity of spatial clustering (z-score) for each distance. Peaks of the index reflect distances at which clustering is most pronounced. Once selected, the peak distance was successively used as an appropriate distance threshold to compute Anselin local Moran's I statistic (Anselin, 1995). The statistic measured how similar each location was to its neighbours within the threshold distance and based on the inverse distance. Z-score and p-value were the final results of the analysis which allowed to single out statistically significant "spatial clusters" (high values surrounded by high values or high-high clusters) and "outliers" (outstanding values with respect to the neighbourhoods or high-low clusters) of high litter density. ArcGIS software by ESRI (ESRI, 2012) was used to perform spatial autocorrelation analyses and create maps. Drawings of main maritime traffic lanes (modified from Fiorentino et al., 2015) and of areas where fish aggregating devices (FADs) (modified from Sinopoli et al., 2020) are employed for fishing, were superimposed on litter distribution maps. All the sampling sites were assigned to two regions: 'IN' if they were within the maritime traffic route and 'OUT' otherwise. Poisson GLMs corrected for overdispersion were developed to assess how density levels of single-use, fishing-related and generic-use items varied across the two regions (factor with two levels, IN and OUT).

Comparison with data from the mid-1990s

A series of historical data on seafloor litter in the northern sector of the Strait of Sicily collected during bottom trawl surveys in the mid-1990s (GRUND surveys - GRUppo Nazionale Demersali;

Relini, 2000) were recovered for comparative purpose with the present assessment. In the GRUND surveys, litter data collection was realized at a high degree of detail (e.g. Cannizzaro et al., 1995), so the allocation of items to the specific categories of use adopted in this work was simple and straightforward (Supplementary S1). Then, historical data collected in spring 1994 and 1995 were reclassified on the basis of the category of uses to make the two data series comparable. The percentage of dirty hauls for each category was calculated and matched with those over the two years 2018-19.

The rationale of comparing the two series of surveys despite the investigated area and the number of hauls in each depth stratum was slightly different, was that of not changing the allocation of the hauls proportionally to surface of depth strata as in the original sampling scheme. However, in order to make the comparison of the two time series more robust a further analysis was carried out using bootstrapping. Specifically, we selected for both surveys only the hauls within the GSA16 and subsequently we extracted using bootstrapping (n=99 per stratum) an equal number of hauls per depth stratum between the two surveys, set based on the minimum number of hauls between the two surveys. Finally, the percentage of dirty hauls for each litter category was compared between the two time series.

Results

Quantity and composition by categories of material type and use

On average, 727 items per year were found at the 120 hauls carried out yearly, for a total of 600 hauls during the 2015-2019 period (Fig. 1). Overall, the percentage of dirty hauls increased with depth, reaching 97% (Tab. 1) at the deepest stratum (501-800 m). Particularly, the 22% (813 items) of litter was found at the first three strata (between 10 and 200 m) and the 78% (2824 items) at the deepest strata (201-800 m). Analysing the type of waste material, plastic (58% of all items) was the dominant category in all the depth strata, resulting more abundant in shallower water (10-50 m) (Supplement S2). The other most abundant categories were metal (18%), textile/natural fibres (8%) and glass/ceramic (7%) (Supplementary S2). Items classified as ‘‘other’’ accounted for about 5% of the litter items and often included limestone blocks i.e. anchorage weights of FADs. Considering the classification based on the category of use, single-use items (2190 items) were found in the 79% of hauls and represented on average the 64% of seafloor litter items up to 500 m deep, decreasing to 57% in the deepest stratum (501-800 m) (Tab. 1). Fishing-related items (443 items) occurred in the 37% of hauls and accounted for 12% of total litter items, showing the minimum percentage occurrence at a depth between 101 and 500 m (Tab. 1). Objects of generic-use (1004 items) represented about 28% of waste. Plastic items made up most of the single-use and fishing-related categories, reaching values of ca. 67 and 91 % respectively (Fig. 2), while in the generic-use category, they represented about 23%.

The highest densities of seafloor litter have mostly been found on the bathyal bottoms (Fig. 1). Overall, the mean density of seafloor litter collected in the surveyed area throughout the five years was 79.6 (± 3.6 s.e.) items/km^2 with values relative to the single hauls ranging from a minimum of 9 items/km^2 observed in 2019 to a maximum of 618 items/km^2 in 2015. The average density of single-use items resulted globally 48.4 (± 2.4 s.e.) items/km^2 (Fig. 2) and varied from the minimum average value of 23.9 (± 3.8 s.e.) items/km^2 in stratum B (51-100 m) to the maximum average value of 69.2 (± 4.8 s.e.) items/km^2 in the deepest stratum E (501-800 m). Fishing-related items with an average value of 9.2 (± 0.7 s.e.) items/km^2 across the investigated area (Fig. 2), showed a mean density (12.3 ± 1.2 s.e. items/km^2) more than double on the strata belonging to the slope (201-800 m) compared to the mean density (5.6 ± 0.7 s.e. items/km^2) observed on the strata of the continental shelf (10-200 m). Overall, the density of generic-use items was 22.1(± 1.5 s.e.) items/km^2 (Fig. 2).

Time trend and relation to depth by categories of use

The Poisson GLMs corrected for overdispersion showed that for each litter category, albeit slightly, the densities decreased significantly (p=0.0001) during the period considered (Fig. 3; Supplement S3) and structural changes in the relation with depth (i.e. statistically significant breakpoints) occurred in the upper slope. Specifically, considering the whole depth profile, a clear progressive increase of litter density was observed for single-use and generic-use categories beyond 445 m and 477 m respectively (Fig. 3), while no clear depth effect below these threshold values was detected. For the fishing-related items, a significant breakpoint occurred at 234 m beyond which densities significantly increased (Fig. 3). Performing the same analysis on a smaller subset of observations, i.e. considering pairs of depth strata, a change in the slope of the density-depth relation (a change from positive to negative slope indicating a local maximum) was observed for single-use and generic-use categories when considering the pair of strata B, 51-100 m and C, 101-200 m (Fig. 3) with the breakpoints located at 120 m and 138 m respectively (see Supplement S3). For fishing-related and single-use items, a breakpoint (i.e. a change from negative to positive slope in the density-depth relation indicating a local minimum) was also observed at 153 m and 161 m depth respectively when considering the pair of strata C, 101-200 m and D, 201-500 m. (Fig. 3; Supplement S3).

Spatial distribution by categories of use

The mean GCI per depth stratum provided insights into the degree of similarity through time of the litter spatial distributions (Fig. 4). For the single-use category, the overlap of the spatial distribution between consecutive years was high (values higher than 0.8) in all strata (Fig. 4), but more stable (low s.e.) for the depth strata from C (101-200 m) to E (501-800 m). A similar result was found for generic-use items which showed very high permanence of the distribution in the three deepest strata (Fig. 4). For both categories, the CG of the distributions relating to these three strata was located in the area subject to intense maritime traffic (Deidun et al., 2018) (Fig. 4).

Considering fishing-related litter category, mean GCI showed high overlap in the deepest strata (201-500 m and 501-800 m) over the years, and also high stability as indicated by very small standard errors (Fig. 4). For these two strata, the centre of gravity of the litter distributions was inside the area where fishing activity using FADs is practised during the autumn and winter seasons (Sinopoli et al., 2020) (Fig. 4).

Global spatial autocorrelation analysis revealed that appropriate spatial scale of analysis to single out clusters and outliers was 25, 54 and 38 km respectively for single-use, fishing-related and generic-use litter categories (see Supplement S4). Local autocorrelation analysis allowed to highlight the presence of clusters and outliers of high densities of single-use and generic-use litter mainly located along the maritime traffic lanes (Fig. 4). For single-use items, density values of hauls classified as clusters (High-High points) ranged from 84 to 387 items/km^2 while the two outliers (high-density values surrounded by low-density values or High-Low points) showed values of 205 and 333 items/km^2. Mean value of density hotspots of generic-use items amounted to 127.4 (± 14.7 s.e.) items/km^2. Regarding fishing-related materials, clusters of high densities (ranging from about 20 to 101 items/km^2) were found on deepest bottoms west and north-west of Maltese archipelago (mainly within FADs areas), while outliers, with density values of 43, 57 and 67 items/km^2, were found in proximity to rocky banks of the Adventure Bank (Fig. 4). ANOVA results showed that for single-use and generic-use objects, densities were significantly higher (p=0.001) in the region IN compared to the region OUT (see Supplement S5 for ANOVA results) while the difference was not significant for fishing-related items.

Comparison with data from the mid-1990s

The comparisons between the percentage of dirty hauls by categories of use observed in 1994-95 against the percentage from 2018-19 showed an increase of about 12% and 15% of the number of hauls in which single-use items and fishing-related materials were found respectively (Fig. 5). On the other hand, the "generic-use" category appeared less spread with a reduction of impacted hauls from 62% (1994-95) to 49% (2018-19) (Fig. 5). The comparisons achieved considering the hauls extracted by bootstrap were very similar (Supplement S6), thus supporting the previous results (Fig. 5).

Discussion

Monitoring of anthropogenic waste on the seafloor in the Strait of Sicily has been conducted during scientific bottom trawl surveys MEDITS carried out from 2015 to 2019. At least one item of litter was found in the 86% of sampling sites suggesting that pollution is rather ubiquitous in the area. Single-use litter (e.g. bags, bottles, food wrappers and cans) and waste originated from fishing activity (constituted by lost or dumped fishing gear) accounted for the 72% of total litter collected (60% and 12% respectively). Plastic was the dominant material within these two broad litter categories and contributed more than 50% of the total litter collected, in agreement with data reported by relevant literature in the Mediterranean (Galgani et al., 2015; Spedicato et al., 2019 and references therein).

Higher pollution, both in terms of percentage of dirty hauls and litter density, was observed at deeper bottoms compared to the depths belonging to the continental shelf (10-200m). The mean density over the study area amounted to 79.6 items/km^{2,} but most observations of litter with densities >300 items/km^2 were found between 200 and 800 m depth. Previous studies showed a positive correlation between litter abundance and depth in the study area (Ragonese et al., 1994; Fiorentino et al., 2015) and a similar correlation, but limited to plastic only, was observed in the nearby Maltese archipelago (Mifsud et al., 2013). Studying in detail the relation between the density of litter (by categories) and depth (using fixed depth windows, i.e. pairs of depth strata), a local peak was found at 120 m and 138 m for single-use and generic-use categories respectively (breakpoint between strata 51-100 m and 101-200 m). While for single-use and fishing-related categories there was a local minimum at a depth limit (breakpoint at 161 m and 153 m respectively) corresponding approximately to the shelf-break (i.e. the depth at which a distinct change in the steepness of the seafloor and hence of the bottom currents speed occur). A relatively low steepness of the seafloor characterises the continental shelf up to the shelf-break and may favour the accumulation of waste originated mainly from land or coastal activities. At the shelf-break, when the seafloor steepness increases, the accumulation is lower because the currents increase considerably favouring the washing up of the seafloor and the transport of waste toward the deep-sea bottoms. A similar pattern was observed in the French waters where the seafloor was clean at the shelf/slope break, between 150 and 200 m depth in the Gulf of Lion and from 200 to 250 m depth in the Corsica Channel (Gerigny et al., 2019). Overall, the relation between litter density and depth displayed a structural change in the upper continental slope, showing a progressive increase of litter density beyond depth values within the interval 234 - 477 m depending on the litter category (234 m for fishing-related litter, 445 m and 477 m for generic-use and single-use items respectively). Similar results were found at Mediterranean scale (Spedicato et al. 2019) where no clear effect of depth (presence of local peaks) on plastic density was detected up to about 350 m depth, while a sudden increasing trend beyond this depth occurred. In the Sardinian waters, recent studies showed that, regardless of the material type, a large dominant fraction of litter was represented by single-use items in the bathyal plain at a depth greater than 750 m (Cau et al., 2018), while in the upper slope derelict fishing gear derived from artisanal fisheries were predominant (Cau et al., 2017).

Our study shows that the relationship between litter density and depth does not translate into a defined spatial gradient from the coast to offshore in the Strait of Sicily, suggesting that other hydrodynamic, geomorphologic and anthropic factors, such as shipping lanes and fishing, may be important (Galgani et al., 2000). In fact, the observed patterns of the spatial distribution of each litter category resulted permanent over the years on the deepest bottoms (200-800m) and showed a strong association to specific anthropic activities. The densities of single-use and generic-use objects were significantly higher on the seafloor along the intense maritime route that crosses the Strait of Sicily in a west-east direction (Deidun et al., 2018) compared to other areas. Density hotspots of fishing-related items were found mainly on the deepest international waters west of Maltese bank (fishing grounds exploited by bottom trawlers and fleets using FADs), and in the proximity of rocky banks in the Sicilian continental shelf. Very recently, predictive models have been developed to estimate marine litter abundance and distribution at the Mediterranean or local spatial scale, and investigate the driving factors for its accumulation on the seafloor. According to Spedicato et al. (2019), variables that play a major role for plastics accumulation on the seafloor in the Mediterranean basin are depth and slope of the sea bottom, surface currents and distance from the ports. Applying Artificial Neural Networks approaches to data from the Strait of Sicily, Franceschini et al. (2019) showed that depth, fishing pressure, distance from cities and maritime traffic are the most important variables in predicting marine litter quantities on the seafloor. In particular, the highest abundances (in weight) of seafloor litter were observed at deeper bottoms (400-800 m), characterised by intense maritime traffic and fishing activities. The hypothesis of a relationship between the waste accumulation areas and the main shipping routes in the Strait of Sicily had already been put forward by Fiorentino et al. (2015), analysing data collected in 2013, and by Cannizzaro et al. (1995) who showed, in the mid-1990s, that the distribution of certain types of waste such as metal bins, cans of paint, bits of tar, etc., could be related to maritime traffic routes. Similarly, in the Adriatic sea, litter hotspots in deep waters were associated with the presence of most congested shipping lanes (Pasquini et al., 2016). Results from the present study highlight a general and persistent accumulation of single-use items in the deeper areas which are situated under intense shipping routes, with average density twice the average density in other areas. Obviously, caution is needed in interpreting this distribution because the transport and waste sinking processes are not well known and it is presumable that light single-use items, because of their buoyancy, can be dispersed over long distances via surface currents, so the sinking place could be far from the dumping site. In addition, once litter is deposited on the seafloor, bottom trawl fishing can act as a displacement and transport mechanism on the seabed (Franceschini et al., 2019). Therefore, the high concentration of single-use items observed on the slope is probably due to the combined effect of land sourced waste transported toward the deep-sea bottom and direct dumping into the sea from commercial and fishing vessels. However, the hypothesis of high ship-originated waste pollution on the seafloor along the major maritime route that crosses the Strait of Sicily in a west-east direction is strengthened by the persistent occurrence in the same area of generic-use objects (including large plastic or metal containers, drums, electrical appliances, textiles, etc.) with densities values more than double compared to other bottoms. Since these objects sink quickly, it is likely that they were recovered near the dumping location and therefore originated mainly from merchant ships. Similarly to our results, other studies in the Mediterranean described a correlation between ship-originated litter dominated by heavy objects and main shipping routes (Ramirez-Llodra et al., 2013; Garcia-Rivera et al., 2017).

High densities of single-use items were also found along the highly anthropised shallow coastal area of the south-eastern Sicily, while considering the entire Sicilian coast, plastic items were found in the 79% of sampled sites at shallower depths (up to 50 m depth). Our results are in agreement with recent data collected in the same area using Remotely Operated Vehicle (ROV) (Consoli et al., 2018b) which showed that general waste, mainly plastics, was the dominant type of litter (68%) followed by lost or abandoned fishing gears (32%). In the whole Mediterranean basin, the shallower areas closer to the coast have a higher proportion of plastics with a probable coastal origin (Ramirez-Llodra et al., 2013).

As far as the waste originated from fishing activity is concerned, consistently over time, clusters of high-density values have been observed on the deepest bottoms (200-800 m) in the central part of the Strait of Sicily, west and north-west of Maltese archipelago. These sites of litter accumulation are mainly located inside or near some areas where the FADs are deployed for the traditional dolphinfish (*Coryphaena hippurus*) fishery during the autumn and winter seasons (Cannizzaro et al., 1995; Sinopoli et al., 2020). Here, litter found includes very long synthetic ropes and limestone or concrete blocks which are used as anchorage weights of FADs. As reported in the literature (Cannizzaro et al., 1995; Fiorentino et al., 2015; Sinopoli et al., 2020), often these materials are abandoned on the sea bottom at the end of the fishing season (1.6 million FADs were abandoned in the Mediterranean Sea between 1961 and 2017; Sinopoli et al., 2020) creating, beyond the impact on the environment and the risk of entanglement of marine species, serious problems to trawl fishing. In fact, they represent an obstacle to bottom trawling and can cause the damage or loss of fishing gear, the recovery of which can be difficult when working in deep water. This could explain the relatively high density of fishing nets found in the FADs area which overlaps the fishing grounds of giant red shrimp (an economically important species in the area) located on the west of Maltese islands (Russo et al., 2019; Lauria et al., 2020). These fishing grounds are exploited by distant trawlers belonging to the Mazara del Vallo port, which generally undertake long fishing trips (15–30 days) and hence may be responsible for dumping other typologies of litter.

Hotspots of dumped or lost fishing gears have also been found close to rocky banks of the Adventure Bank. This finding is comparable with ones from other studies which investigated offshore rocky substrata by means of ROV (Bo et al., 2014; Angiolillo et al., 2015; Consoli et al., 2018a; Melli et al., 2017). For example, fishing lines represented the 79% of analysed waste in eight rocky areas (at depths ranging between 30 and 270 m) located in the north-west of Sicily (Angiolillo et al., 2015). Similar results were obtained by Consoli et al. (2018a) on the rocky offshore banks of the Adventure Bank (at depths ranging between 20 and 220 m), where mixed fishing material (fishing lines, ropes and set net) was the dominant litter category (98%) and the litter presence was positively correlated to habitat complexity. More generally, it has been observed that seamounts and rocky banks are hotspots of derelict fishing gear because they are highly productive areas supporting high aggregations of commercially valuable species that attract intense professional and recreational fishing activities (Bo et al., 2014; Pham et al., 2014). Since bottom trawling operates exclusively on soft bottoms, it can be argued that the relative abundance of fishing-related items measured in this study is underestimated.

The average density of litter found on the seafloor of the Strait of Sicily decreased significantly, although slightly, from 2015 to 2019. Data on time trend of anthropogenic litter in the Mediterranean are scanty and contrasting, with a signal of increase, decrease or no change depending on locations (Galgani et al., 2015). The rare case of a study analysing a long time series (24 years) of litter density in the French Mediterranean Sea (including the Gulf of Lion and Corsica Island) (Gerigny et al., 2019) showed a significant increase of total litter and plastics over the entire time series (1994-2017) but some contrasting trends over shorter periods (two periods of increase and one period of decrease). Interestingly, the results of the study show a decrease in the densities of total litter and plastic from 2015 to 2017 (Gerigny et al., 2019) in agreement with our finding.

Comparing the litter occurrence in the Strait of Sicily in the mid-1990s against the current situation has shown that the percentage of dirty hauls has decreased for generic-use objects (less 13%), while it has moderately increased for single-use items (plus 12%) and practically doubled for fishing-related items (which however remain much less frequent than the other two categories). The moderate increase of single-use items can likely be related to the fact that, despite their massive dumping into the sea, they degrade or are transported offshore due to sea bottom currents and probably accumulate in the deep trenches (> 800 m) of the Strait of Sicily, which may represent the ultimate sink of marine litter but have not been investigated in the present study. Regarding fishing-related litter, while it is obvious that fishermen have high economic motivation to retrieve lost fishing gear (explaining the lowest relative occurrence of this litter category), on the other hand, the difficulties in recovery operations, especially in deep waters, and the lack of port facilities for effective management of discarded fishing gear can explain the increase of fishing-related littering over twenty years. In particular FADs fishery may have played a major role by generating every year, at least from 30 years, a high quantity of abandoned FAD components (polypropylene and polyethylene cables, limestone or concrete blocks) which accumulate on the seafloor west and north-west of Maltese archipelago (Cannizzaro et al., 1995; Sinopoli et al., 2020). A reduction in the number of FADs deployed at sea together with the use of innovative and sustainable materials is considered an effective strategy to mitigate the impact of FAD litter in the Mediterranean (Sinopoli et al., 2020).

Conclusion

Much attention has been devoted in the last decade to study the abundance and distribution of plastics deposited on the seafloor worldwide, and this is because the increasing abundance of plastics in the marine environment is considered an alarming environmental problem (Ostle et al. 2019). However, precisely because of its pervasiveness, studying plastic litter distribution as a whole could be not suitable for identifying targeted mitigation strategies. There is a wide consensus in the scientific literature about the need of more detailed classification of marine litter on the basis of its use and potential sources (Veiga et al., 2016) in order to be most easily linked to reduction measures. In our study, seafloor litter originally catalogued according to the MEDITS material categories, was reclassified on the basis of the items use and use durability awith the aim to find better interpretation keys about its source and distribution and help to establish appropriate reduction measures. Indeed, it has been shown that the different categories of use have distinct distributions in the Strait of Sicily and that particular processes are associated with defined locations. Particularly, high densities of single-use and generic-use litter items were associated to the presence of major maritime traffic lanes while sites of accumulation of fishing-related items were mainly located within areas exploited by distant trawlers and fleets using FADs or in proximity to rocky bottoms.

The comparison of anthropic litter on trawlable bottoms of the Strait of Sicily in the mid-1990s with that found in the late 2010s showed an increase of the percentage of sites littered with single-use and fishing-related waste. This finding is not surprising considering that the production of plastic materials, in particular disposable plastics, has continued to rise significantly since the 1950s, fueled by the packaging market and the global shift from reusable to single-use containers (Worm et al., 2017; Ostle et al., 2019). Once reaching the ocean, plastics persist and accumulate on the seafloor over long time (Worm et al., 2017). In addition, regulations for limiting single-use plastics, reducing illegal dumping, and encouraging fishermen to get derelict gear back to port reception facilities have only been introduced relatively recently. It has been shown that the effects of behavioural and legislative changes could be evident within decades (Maes et al., 2018). However, an encouraging result is the observed decreasing trend in the density of both categories of waste on the bottom of the Strait of Sicily over the past 5 years. It is too early to make definite conclusions about this trend, but certainly our study provides a baseline for monitoring and evaluating the effectiveness of current and future policies to mitigate the impact of solid waste on marine ecosystems.

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Research Data

Data will be made available on request

Author contributions

Garofalo Germana: Conceptualization; Methodology; Formal analysis; Project administration; Writing - original draft
Quattrocchi Federico: Investigation; Methodology; Formal analysis; Writing - original draft
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Table 1. Occurrence of litter items (overall and individual categories) at different depth intervals in the Strait of Sicily during 2015-2019. For each stratum, the total swept area (km^2), the overall number of hauls and the percentage of dirty hauls are reported.

Depth strata	Swept area (km^2)	No. hauls	% dirty hauls	Total items	% single-use items	% fishing – related items	% generic-use items
A, 10-50 m	2.39	55	84	148	64	14	22
B, 51-100 m	5.24	115	63	201	62	13	25
C, 101-200 m	4.98	105	87	464	65	5	31
D, 201-500 m	13.21	136	92	692	64	9	27
E, 501-800 m	17.86	189	97	2132	57	15	28
Total (10-800 m)	**43.68**	**600**	**86**	**3637**	**60**	**12**	**28**