What is in our seas? Assessing anthropogenic litter on the seafloor of the central Mediterranean Sea

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36

Abstract

38
39 Abundance, composition, and distribution of macro-litter found on the seafloor of the Strait of
40 Sicily between 10-800 m depth has been studied using data collected by bottom trawl surveys
41 MEDITS from 2015 to 2019. Three waste categories based on the items use were considered:
42 single-use, fishing-related and generic-use. Over 600 sampling sites, just 14% of these were litter-
43 free. The five-years average density of seafloor litter was 79.6 items/km^2 and ranged between 46.8
44 in 2019 and 118.1 items/km^2 in 2015. The predominant waste type was plastic (58% of all items).
45 Regardless of material type, single-use items were a dominant (60% of items) and widespread (79%
46 of hauls) fraction of litter with a mean density of 48.4 items/km^2. Fishing-related items accounted
47 for 12% of total litter items. Percentage of dirty hauls and litter density increased with depth.
48 Analysis of the relation density-depth indicates a progressive increase of litter density beyond depth
49 values situated within the interval 234-477 m depending on the litter category. A significant
50 decrease in litter density by categories was observed over the period. Patterns of spatial distribution
51 at the higher depths (200-800m) resulted stable over the years. Density hotspots of fishing-related
52 items were found where the fishing activity that uses fish aggregating devices (FADs) is practised
53 and in the proximity of rocky banks. Single-use and generic-use objects densities were greater on
54 the seafloor along main maritime routes than other areas. Comparisons between the percentage of
55 hauls littered with anthropic waste from the mid-1990s against those in 2018-19 highlighted an
56 increase of about 12% and 15 % for single-use items and fishing-related items respectively, and a
57 decrease of 13% for generic-use items. This study provides a snapshot of the current situation of
58 littering in the central Mediterranean Sea and represents a solid baseline against which the
59 effectiveness of current and future mitigation strategies of the litter impact on marine environment
60 can be measured.
61
62 **Keywords:** baseline, plastics, single-use litter, fishing-related litter, Strait of Sicily
63

Main Findings

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

67

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

218 index) and the depth was piecewise linear, i.e. represented by two or more straight lines connected
219 at an unknown value named breakpoint. The breakpoints identify abrupt changes in the relation and
220 can be considered threshold values beyond or below which significant effects of the independent
221 variable on the dependent variable occur. The R package 'segmented' (Muggeo, 2008) was used to
222 perform the analysis. It applies an iterative procedure in which a breakpoint is estimated at each
223 iteration until the algorithm converges when the distance between neighbouring straight lines is
224 minimised (close to zero). The method was applied on the whole depth range 10-800 m, but even on
225 pairs of neighbour strata (i.e. reducing and fixing the window of the observations) to assess the
226 presence of structural changes in the relation density-depth at small range of variations of the
227 explanatory variable (otherwise not detectable due to the litter items distribution along the whole
228 depth range likely masking the presence of small variations). The analysis was performed using the
229 R software (R Development Core Team, 2019).
230
231
232 **Spatial distribution by categories of use**
233
234 For each of the three litter categories, two spatial indicators were computed to summarise the
235 characteristics of the distribution of density values within the depth strata of GSA 16: 1) the centre
236 of gravity (CG) that measures the mean geographic location of the distributions and 2) the global
237 index of collocation (GCI) which served to assess whether distributions were geographically
238 distinct or overlapped over the years (Woillex et al., 2009). Specifically, GCI allowed quantifying
239 the extent to which each litter category was found mainly at the same geographic places over the
240 different years. To achieve this, a GCI was computed for each depth stratum (from A, 10-50 m to E,
241 501-800 m) and all possible pairs of consecutive years. GCI varied from 0 to 1, where 1 indicated a
242 complete overlap between the spatial distributions in two consecutive years. The mean GCI (± s.e.)
243 by depth stratum was plotted for each category of litter. CG and GCI were computed using the
244 geostatistical R Package RGeostats (Version 11.2.11).
245 Global and local spatial autocorrelation analyses was conducted to investigate the spatial
246 distribution of the three litter categories and to identify the areas of high densities and accumulation.
247 Firstly, Incremental Spatial Autocorrelation analysis was applied to identify the appropriate scale
248 for spatial analysis. The method computes spatial autocorrelation for a series of increasing distances
249 applying the global Moran's I statistic (Moran, 1950), and gives an index of the intensity of spatial
250 clustering (z-score) for each distance. Peaks of the index reflect distances at which clustering is
251 most pronounced. Once selected, the peak distance was successively used as an appropriate distance
252 threshold to compute Anselin local Moran's I statistic (Anselin, 1995). The statistic measured how
253 similar each location was to its neighbours within the threshold distance and based on the inverse
254 distance. Z-score and p-value were the final results of the analysis which allowed to single out
255 statistically significant "spatial clusters" (high values surrounded by high values or high-high
256 clusters) and "outliers" (outstanding values with respect to the neighbourhoods or high-low clusters)
257 of high litter density. ArcGIS software by ESRI (ESRI, 2012) was used to perform spatial
258 autocorrelation analyses and create maps. Drawings of main maritime traffic lanes (modified from
259 Fiorentino et al., 2015) and of areas where fish aggregating devices (FADs) (modified from
260 Sinopoli et al., 2020) are employed for fishing, were superimposed on litter distribution maps. All
261 the sampling sites were assigned to two regions: 'IN' if they were within the maritime traffic route
262 and 'OUT' otherwise. Poisson GLMs corrected for overdispersion were developed to assess how
263 density levels of single-use, fishing-related and generic-use items varied across the two regions
264 (factor with two levels, IN and OUT).
265
266 **Comparison with data from the mid-1990s**
267 A series of historical data on seafloor litter in the northern sector of the Strait of Sicily collected
268 during bottom trawl surveys in the mid-1990s (GRUND surveys - GRUppo Nazionale Demersali;

269 Relini, 2000) were recovered for comparative purpose with the present assessment. In the GRUND
270 surveys, litter data collection was realized at a high degree of detail (e.g. Cannizzaro et al., 1995),
271 so the allocation of items to the specific categories of use adopted in this work was simple and
272 straightforward (Supplementary S1). Then, historical data collected in spring 1994 and 1995 were
273 reclassified on the basis of the category of uses to make the two data series comparable. The
274 percentage of dirty hauls for each category was calculated and matched with those over the two
275 years 2018-19.
276 The rationale of comparing the two series of surveys despite the investigated area and the number of
277 hauls in each depth stratum was slightly different, was that of not changing the allocation of the
278 hauls proportionally to surface of depth strata as in the original sampling scheme. However, in order
279 to make the comparison of the two time series more robust a further analysis was carried out using
280 bootstrapping. Specifically, we selected for both surveys only the hauls within the GSA16 and
281 subsequently we extracted using bootstrapping (n=99 per stratum) an equal number of hauls per
282 depth stratum between the two surveys, set based on the minimum number of hauls between the two
283 surveys. Finally, the percentage of dirty hauls for each litter category was compared between the
284 two time series.
285
286
287 **Results**
288 **Quantity and composition by categories of material type and use**
289
290 On average, 727 items per year were found at the 120 hauls carried out yearly, for a total of 600
291 hauls during the 2015-2019 period (Fig. 1). Overall, the percentage of dirty hauls increased with
292 depth, reaching 97% (Tab. 1) at the deepest stratum (501-800 m). Particularly, the 22% (813 items)
293 of litter was found at the first three strata (between 10 and 200 m) and the 78% (2824 items) at the
294 deepest strata (201-800 m). Analysing the type of waste material, plastic (58% of all items) was the
295 dominant category in all the depth strata, resulting more abundant in shallower water (10-50 m)
296 (Supplement S2). The other most abundant categories were metal (18%), textile/natural fibres (8%)
297 and glass/ceramic (7%) (Supplementary S2). Items classified as ''other'' accounted for about 5% of
298 the litter items and often included limestone blocks i.e. anchorage weights of FADs. Considering
299 the classification based on the category of use, single-use items (2190 items) were found in the 79%
300 of hauls and represented on average the 64% of seafloor litter items up to 500 m deep, decreasing to
301 57% in the deepest stratum (501-800 m) (Tab. 1). Fishing-related items (443 items) occurred in the
302 37% of hauls and accounted for 12% of total litter items, showing the minimum percentage
303 occurrence at a depth between 101 and 500 m (Tab. 1). Objects of generic-use (1004 items)
304 represented about 28% of waste. Plastic items made up most of the single-use and fishing-related
305 categories, reaching values of ca. 67 and 91 % respectively (Fig. 2), while in the generic-use
306 category, they represented about 23%.
307 The highest densities of seafloor litter have mostly been found on the bathyal bottoms (Fig. 1).
308 Overall, the mean density of seafloor litter collected in the surveyed area throughout the five years
309 was 79.6 (± 3.6 s.e.) items/km^2 with values relative to the single hauls ranging from a minimum of 9
310 items/km^2 observed in 2019 to a maximum of 618 items/km^2 in 2015. The average density of
311 single-use items resulted globally 48.4 (± 2.4 s.e.) items/km^2 (Fig. 2) and varied from the minimum
312 average value of 23.9 (± 3.8 s.e.) items/km^2 in stratum B (51-100 m) to the maximum average value
313 of 69.2 (± 4.8 s.e.) items/km^2 in the deepest stratum E (501-800 m). Fishing-related items with an
314 average value of 9.2 (± 0.7 s.e.) items/km^2 across the investigated area (Fig. 2), showed a mean
315 density (12.3 ± 1.2 s.e. items/km^2) more than double on the strata belonging to the slope (201-800
316 m) compared to the mean density (5.6 ± 0.7 s.e. items/km^2) observed on the strata of the continental
317 shelf (10-200 m). Overall, the density of generic-use items was 22.1(± 1.5 s.e.) items/km^2 (Fig. 2).
318
319 **Time trend and relation to depth by categories of use**

320

321 The Poisson GLMs corrected for overdispersion showed that for each litter category, albeit slightly,
322 the densities decreased significantly (p=0.0001) during the period considered (Fig. 3; Supplement
323 S3) and structural changes in the relation with depth (i.e. statistically significant breakpoints)
324 occurred in the upper slope. Specifically, considering the whole depth profile, a clear progressive
325 increase of litter density was observed for single-use and generic-use categories beyond 445 m and
326 477 m respectively (Fig. 3), while no clear depth effect below these threshold values was detected.
327 For the fishing-related items, a significant breakpoint occurred at 234 m beyond which densities
328 significantly increased (Fig. 3). Performing the same analysis on a smaller subset of observations,
329 i.e. considering pairs of depth strata, a change in the slope of the density-depth relation (a change
330 from positive to negative slope indicating a local maximum) was observed for single-use and
331 generic-use categories when considering the pair of strata B, 51-100 m and C, 101-200 m (Fig. 3)
332 with the breakpoints located at 120 m and 138 m respectively (see Supplement S3). For fishing-
333 related and single-use items, a breakpoint (i.e. a change from negative to positive slope in the
334 density-depth relation indicating a local minimum) was also observed at 153 m and 161 m depth
335 respectively when considering the pair of strata C, 101-200 m and D, 201-500 m. (Fig. 3;
336 Supplement S3).

337

338 **Spatial distribution by categories of use**
339 The mean GCI per depth stratum provided insights into the degree of similarity through time of the
340 litter spatial distributions (Fig. 4). For the single-use category, the overlap of the spatial distribution
341 between consecutive years was high (values higher than 0.8) in all strata (Fig. 4), but more stable
342 (low s.e.) for the depth strata from C (101-200 m) to E (501-800 m). A similar result was found for
343 generic-use items which showed very high permanence of the distribution in the three deepest strata
344 (Fig. 4). For both categories, the CG of the distributions relating to these three strata was located in
345 the area subject to intense maritime traffic (Deidun et al., 2018) (Fig. 4).
346 Considering fishing-related litter category, mean GCI showed high overlap in the deepest strata
347 (201-500 m and 501-800 m) over the years, and also high stability as indicated by very small
348 standard errors (Fig. 4). For these two strata, the centre of gravity of the litter distributions was
349 inside the area where fishing activity using FADs is practised during the autumn and winter seasons
350 (Sinopoli et al., 2020) (Fig. 4).
351 Global spatial autocorrelation analysis revealed that appropriate spatial scale of analysis to single
352 out clusters and outliers was 25, 54 and 38 km respectively for single-use, fishing-related and
353 generic-use litter categories (see Supplement S4). Local autocorrelation analysis allowed to
354 highlight the presence of clusters and outliers of high densities of single-use and generic-use litter
355 mainly located along the maritime traffic lanes (Fig. 4). For single-use items, density values of
356 hauls classified as clusters (High-High points) ranged from 84 to 387 items/km^2 while the two
357 outliers (high-density values surrounded by low-density values or High-Low points) showed values
358 of 205 and 333 items/km^2. Mean value of density hotspots of generic-use items amounted to 127.4
359 ($\pm$ 14.7 s.e.) items/km^2. Regarding fishing-related materials, clusters of high densities (ranging from
360 about 20 to 101 items/km^2) were found on deepest bottoms west and north-west of Maltese
361 archipelago (mainly within FADs areas), while outliers, with density values of 43, 57 and 67
362 items/km^2, were found in proximity to rocky banks of the Adventure Bank (Fig. 4). ANOVA results
363 showed that for single-use and generic-use objects, densities were significantly higher (p=0.001) in
364 the region IN compared to the region OUT (see Supplement S5 for ANOVA results) while the
365 difference was not significant for fishing-related items.

366

367 **Comparison with data from the mid-1990s**
368 The comparisons between the percentage of dirty hauls by categories of use observed in 1994-95
369 against the percentage from 2018-19 showed an increase of about 12% and 15% of the number of
370 hauls in which single-use items and fishing-related materials were found respectively (Fig. 5). On

371 the other hand, the "generic-use" category appeared less spread with a reduction of impacted hauls
372 from 62% (1994-95) to 49% (2018-19) (Fig. 5). The comparisons achieved considering the hauls
373 extracted by bootstrap were very similar (Supplement S6), thus supporting the previous results (Fig.
374 5).
375
376
377 **Discussion**
378
379 Monitoring of anthropogenic waste on the seafloor in the Strait of Sicily has been conducted during
380 scientific bottom trawl surveys MEDITS carried out from 2015 to 2019. At least one item of litter
381 was found in the 86% of sampling sites suggesting that pollution is rather ubiquitous in the area.
382 Single-use litter (e.g. bags, bottles, food wrappers and cans) and waste originated from fishing
383 activity (constituted by lost or dumped fishing gear) accounted for the 72% of total litter collected
384 (60% and 12% respectively). Plastic was the dominant material within these two broad litter
385 categories and contributed more than 50% of the total litter collected, in agreement with data
386 reported by relevant literature in the Mediterranean (Galgani et al., 2015; Spedicato et al., 2019 and
387 references therein).
388 Higher pollution, both in terms of percentage of dirty hauls and litter density, was observed at
389 deeper bottoms compared to the depths belonging to the continental shelf (10-200m). The mean
390 density over the study area amounted to 79.6 items/km^2, but most observations of litter with
391 densities >300 items/km^2 were found between 200 and 800 m depth. Previous studies showed a
392 positive correlation between litter abundance and depth in the study area (Ragonese et al., 1994;
393 Fiorentino et al., 2015) and a similar correlation, but limited to plastic only, was observed in the
394 nearby Maltese archipelago (Mifsud et al., 2013). Studying in detail the relation between the density
395 of litter (by categories) and depth (using fixed depth windows, i.e. pairs of depth strata), a local
396 peak was found at 120 m and 138 m for single-use and generic-use categories respectively
397 (breakpoint between strata 51-100 m and 101-200 m). While for single-use and fishing-related
398 categories there was a local minimum at a depth limit (breakpoint at 161 m and 153 m respectively)
399 corresponding approximately to the shelf-break (i.e. the depth at which a distinct change in the
400 steepness of the seafloor and hence of the bottom currents speed occur). A relatively low steepness
401 of the seafloor characterises the continental shelf up to the shelf-break and may favour the
402 accumulation of waste originated mainly from land or coastal activities. At the shelf-break, when
403 the seafloor steepness increases, the accumulation is lower because the currents increase
404 considerably favouring the washing up of the seafloor and the transport of waste toward the deep-
405 sea bottoms. A similar pattern was observed in the French waters where the seafloor was clean at
406 the shelf/slope break, between 150 and 200 m depth in the Gulf of Lion and from 200 to 250 m
407 depth in the Corsica Channel (Gerigny et al., 2019). Overall, the relation between litter density and
408 depth displayed a structural change in the upper continental slope, showing a progressive increase
409 of litter density beyond depth values within the interval 234 - 477 m depending on the litter
410 category (234 m for fishing-related litter, 445 m and 477 m for generic-use and single-use items
411 respectively). Similar results were found at Mediterranean scale (Spedicato et al. 2019) where no
412 clear effect of depth (presence of local peaks) on plastic density was detected up to about 350 m
413 depth, while a sudden increasing trend beyond this depth occurred. In the Sardinian waters, recent
414 studies showed that, regardless of the material type, a large dominant fraction of litter was
415 represented by single-use items in the bathyal plain at a depth greater than 750 m (Cau et al., 2018),
416 while in the upper slope derelict fishing gear derived from artisanal fisheries were predominant
417 (Cau et al., 2017).
418 Our study shows that the relationship between litter density and depth does not translate into a
419 defined spatial gradient from the coast to offshore in the Strait of Sicily, suggesting that other
420 hydrodynamic, geomorphologic and anthropic factors, such as shipping lanes and fishing, may be
421 important (Galgani et al., 2000). In fact, the observed patterns of the spatial distribution of each

422 litter category resulted permanent over the years on the deepest bottoms (200-800m) and showed a
423 strong association to specific anthropic activities. The densities of single-use and generic-use
424 objects were significantly higher on the seafloor along the intense maritime route that crosses the
425 Strait of Sicily in a west-east direction (Deidun et al., 2018) compared to other areas. Density
426 hotspots of fishing-related items were found mainly on the deepest international waters west of
427 Maltese bank (fishing grounds exploited by bottom trawlers and fleets using FADs), and in the
428 proximity of rocky banks in the Sicilian continental shelf. Very recently, predictive models have
429 been developed to estimate marine litter abundance and distribution at the Mediterranean or local
430 spatial scale, and investigate the driving factors for its accumulation on the seafloor. According to
431 Spedicato et al. (2019), variables that play a major role for plastics accumulation on the seafloor in
432 the Mediterranean basin are depth and slope of the sea bottom, surface currents and distance from
433 the ports. Applying Artificial Neural Networks approaches to data from the Strait of Sicily,
434 Franceschini et al. (2019) showed that depth, fishing pressure, distance from cities and maritime
435 traffic are the most important variables in predicting marine litter quantities on the seafloor. In
436 particular, the highest abundances (in weight) of seafloor litter were observed at deeper bottoms
437 (400-800 m), characterised by intense maritime traffic and fishing activities. The hypothesis of a
438 relationship between the waste accumulation areas and the main shipping routes in the Strait of
439 Sicily had already been put forward by Fiorentino et al. (2015), analysing data collected in 2013,
440 and by Cannizzaro et al. (1995) who showed, in the mid-1990s, that the distribution of certain types
441 of waste such as metal bins, cans of paint, bits of tar, etc., could be related to maritime traffic
442 routes. Similarly, in the Adriatic sea, litter hotspots in deep waters were associated with the
443 presence of most congested shipping lanes (Pasquini et al., 2016). Results from the present study
444 highlight a general and persistent accumulation of single-use items in the deeper areas which are
445 situated under intense shipping routes, with average density twice the average density in other areas.
446 Obviously, caution is needed in interpreting this distribution because the transport and waste
447 sinking processes are not well known and it is presumable that light single-use items, because of
448 their buoyancy, can be dispersed over long distances via surface currents, so the sinking place could
449 be far from the dumping site. In addition, once litter is deposited on the seafloor, bottom trawl
450 fishing can act as a displacement and transport mechanism on the seabed (Franceschini et al., 2019).
451 Therefore, the high concentration of single-use items observed on the slope is probably due to the
452 combined effect of land sourced waste transported toward the deep-sea bottom and direct dumping
453 into the sea from commercial and fishing vessels. However, the hypothesis of high ship-originated
454 waste pollution on the seafloor along the major maritime route that crosses the Strait of Sicily in a
455 west-east direction is strengthened by the persistent occurrence in the same area of generic-use
456 objects (including large plastic or metal containers, drums, electrical appliances, textiles, etc.) with
457 densities values more than double compared to other bottoms. Since these objects sink quickly, it is
458 likely that they were recovered near the dumping location and therefore originated mainly from
459 merchant ships. Similarly to our results, other studies in the Mediterranean described a correlation
460 between ship-originated litter dominated by heavy objects and main shipping routes (Ramirez-
461 Llodra et al., 2013; Garcia-Rivera et al., 2017).
462 High densities of single-use items were also found along the highly anthropised shallow coastal area
463 of the south-eastern Sicily, while considering the entire Sicilian coast, plastic items were found in
464 the 79% of sampled sites at shallower depths (up to 50 m depth). Our results are in agreement with
465 recent data collected in the same area using Remotely Operated Vehicle (ROV) (Consoli et al.,
466 2018b) which showed that general waste, mainly plastics, was the dominant type of litter (68%)
467 followed by lost or abandoned fishing gears (32%). In the whole Mediterranean basin, the shallower
468 areas closer to the coast have a higher proportion of plastics with a probable coastal origin
469 (Ramirez-Llodra et al., 2013).
470 As far as the waste originated from fishing activity is concerned, consistently over time, clusters of
471 high-density values have been observed on the deepest bottoms (200-800 m) in the central part of
472 the Strait of Sicily, west and north-west of Maltese archipelago. These sites of litter accumulation

473 are mainly located inside or near some areas where the FADs are deployed for the traditional
474 dolphinfish (*Coryphaena hippurus*) fishery during the autumn and winter seasons (Cannizzaro et
475 al., 1995; Sinopoli et al., 2020). Here, litter found includes very long synthetic ropes and limestone
476 or concrete blocks which are used as anchorage weights of FADs. As reported in the literature
477 (Cannizzaro et al., 1995; Fiorentino et al., 2015; Sinopoli et al., 2020), often these materials are
478 abandoned on the sea bottom at the end of the fishing season (1.6 million FADs were abandoned in
479 the Mediterranean Sea between 1961 and 2017; Sinopoli et al., 2020) creating, beyond the impact
480 on the environment and the risk of entanglement of marine species, serious problems to trawl
481 fishing. In fact, they represent an obstacle to bottom trawling and can cause the damage or loss of
482 fishing gear, the recovery of which can be difficult when working in deep water. This could explain
483 the relatively high density of fishing nets found in the FADs area which overlaps the fishing
484 grounds of giant red shrimp (an economically important species in the area) located on the west of
485 Maltese islands (Russo et al., 2019; Lauria et al., 2020). These fishing grounds are exploited by
486 distant trawlers belonging to the Mazara del Vallo port, which generally undertake long fishing trips
487 (15–30 days) and hence may be responsible for dumping other typologies of litter.
488 Hotspots of dumped or lost fishing gears have also been found close to rocky banks of the
489 Adventure Bank. This finding is comparable with ones from other studies which investigated
490 offshore rocky substrata by means of ROV (Bo et al., 2014; Angiolillo et al., 2015; Consoli et al.,
491 2018a; Melli et al., 2017). For example, fishing lines represented the 79% of analysed waste in eight
492 rocky areas (at depths ranging between 30 and 270 m) located in the north-west of Sicily
493 (Angiolillo et al., 2015). Similar results were obtained by Consoli et al. (2018a) on the rocky
494 offshore banks of the Adventure Bank (at depths ranging between 20 and 220 m), where mixed
495 fishing material (fishing lines, ropes and set net) was the dominant litter category (98%) and the
496 litter presence was positively correlated to habitat complexity. More generally, it has been observed
497 that seamounts and rocky banks are hotspots of derelict fishing gear because they are highly
498 productive areas supporting high aggregations of commercially valuable species that attract intense
499 professional and recreational fishing activities (Bo et al., 2014; Pham et al., 2014). Since bottom
500 trawling operates exclusively on soft bottoms, it can be argued that the relative abundance of
501 fishing-related items measured in this study is underestimated.
502 The average density of litter found on the seafloor of the Strait of Sicily decreased significantly,
503 although slightly, from 2015 to 2019. Data on time trend of anthropogenic litter in the
504 Mediterranean are scanty and contrasting, with a signal of increase, decrease or no change
505 depending on locations (Galgani et al., 2015). The rare case of a study analysing a long time series
506 (24 years) of litter density in the French Mediterranean Sea (including the Gulf of Lion and Corsica
507 Island) (Gerigny et al., 2019) showed a significant increase of total litter and plastics over the entire
508 time series (1994-2017) but some contrasting trends over shorter periods (two periods of increase
509 and one period of decrease). Interestingly, the results of the study show a decrease in the densities
510 of total litter and plastic from 2015 to 2017 (Gerigny et al., 2019) in agreement with our finding.
511 Comparing the litter occurrence in the Strait of Sicily in the mid-1990s against the current situation
512 has shown that the percentage of dirty hauls has decreased for generic-use objects (less 13%), while
513 it has moderately increased for single-use items (plus 12%) and practically doubled for fishing-
514 related items (which however remain much less frequent than the other two categories). The
515 moderate increase of single-use items can likely be related to the fact that, despite their massive
516 dumping into the sea, they degrade or are transported offshore due to sea bottom currents and
517 probably accumulate in the deep trenches (> 800 m) of the Strait of Sicily, which may represent the
518 ultimate sink of marine litter but have not been investigated in the present study. Regarding fishing-
519 related litter, while it is obvious that fishermen have high economic motivation to retrieve lost
520 fishing gear (explaining the lowest relative occurrence of this litter category), on the other hand, the
521 difficulties in recovery operations, especially in deep waters, and the lack of port facilities for
522 effective management of discarded fishing gear can explain the increase of fishing-related littering
523 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.

Research Data
Data will be made available on request

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840 Table 1. Occurrence of litter items (overall and individual categories) at different depth intervals in
841 the Strait of Sicily during 2015-2019. For each stratum, the total swept area (km^2), the overall
842 number of hauls and the percentage of dirty hauls are reported.
843

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**

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