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Research Paper

Fishing for litter, accidental catch in bottom trawl nets along the Catalan coast, Northwestern Mediterranean

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ABSTRACT

The seafloor of the Mediterranean Sea accumulates marine litter (ML), an area where bottom trawlers operate and can accidentally catch the litter from the seafloor. This study aims to describe and quantify the ML caught by bottom trawlers along the Catalan coast (NW Mediterranean Sea) and estimate the potential of the bottom trawl fleet to extract ML from the area as a Fishing for Litter (FFL) initiative to tackle the ML issue. Marine litter was collected from commercial trawlers and was classified as metal, plastic, rubber, textile, wood, and other waste and weighed (kg) from 305 hauls performed during three years (2019–2021) from 9 different ports at 3 different depths. ML was present in 97 % of the hauls, with plastic being the most abundant material. The composition varied according to zone, port and depth, with the highest densities found in highly urbanized areas (13.75 ± 3.25 kg km^{-2}), which mainly contained plastics (74.3 %). The port of Barcelona had the highest presence of plastics (23.62 ± 6.49 kg km^{-2}), mainly wet wipes. Regarding depth, the continental shelf had the highest density of ML, with 12.24 ± 2.40 kg km^{-2}. The potential ML removal (t year^{-1}) was calculated using fishing effort (hours). It is estimated that the bottom trawlers may potentially remove 237 ± 36 t year^{-1} of ML in the Catalan coast. FFL initiatives should be part of a multidisciplinary approach to tackle marine litter, which must include prevention, monitoring, and cleaning actions.

1. Introduction

Marine litter is a worldwide problem found in all areas of the ocean, from the deepest depths of the Mariana trench to the most isolated continent, Antarctica (Barnes et al., 2010; Peng et al., 2020). It is calculated that between 19 and 23 Mt of plastic ended in aquatic ecosystems in 2016 but predictions estimate that up to 90 Mt could enter these ecosystems by 2030 (Borrelle et al., 2020). Once accumulated in the marine environment, marine litter is associated with multiple impacts on marine biodiversity (Li et al., 2016). Between 1997 and 2015 the number of species known to have become entangled in or ingested marine litter doubled from 267 to 557 species (Kühn et al., 2015). Globally, the analysis of gastrointestinal contents, have revealed plastic ingestion in a wide variety of marine species, from deep-sea invertebrates to large marine mammals, inhabiting both pelagic and demersal habitats (Alomar and Deudero, 2017; Anastasopoulou et al., 2013; Deudero and Alomar, 2015; Lusher et al., 2013; Taylor et al., 2016). Whilst entanglement and plastic ingestion are direct impacts affecting individual organisms, their effects can reach more complex ecological levels as species populations and ecosystems (Browne et al., 2015). Furthermore, even in the absence of biotic damage, ecosystem services can be affected by the increase of marine litter pollution and socioeconomic losses reported due to its negative effects and removal efforts (Bergmann, 2015). Approaches to tackle the marine litter global issue are many and should address different stages of the waste cycle such as prevention, monitoring and cleaning, using all available and innovative technologies (Bellou et al., 2021). This is especially critical in the Mediterranean Sea, which is described as one of the most polluted

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seas regarding marine litter (Rios-Fuster et al., 2019).

Enclosed seas, including the Mediterranean, may have the highest amounts of waste including both floating and benthic litter items (Eriksen et al., 2014; Galgani et al., 2000; Lambert et al., 2020). The size, composition, and environment, among other causes, will determine whether the litter will drift or sink and accumulate on the seafloor (Williams and Rangel-Buitrago, 2019). For example, the densest particles will sink faster than those with lower densities (Soto-Navarro et al., 2020). Concentration of benthic marine litter vary with area and depth, among other factors, and values as high as 393 kg km^{-2} have been reported in the Mediterranean Sea (Alomar et al., 2020; Galimany et al., 2019). From the different types of items that compose the marine litter, i.e. plastic, metal, rubber, textile, or processed wood, plastics are the most abundant reported in several Mediterranean areas, with percentages varying from 59.4 % in Sardinia, Italy (Alvito et al., 2018), to 90 % reported in Israel (Pasternak et al., 2017). Plastics represent a special threat to the ecosystems because, in addition to their deleterious effects, their degradability is extremely slow remaining on the seafloor for many decades, even centuries (Williams and Rangel-Buitrago, 2019). Several innovative approaches have been proposed to tackle marine litter, including strategies on prevention, monitoring, cleaning, and the multiple use of these methods at the same time (Bellou et al., 2021). For example, a multiuse strategy combining monitoring and cleaning would be Fishing for Litter (FFL) initiatives, which tackle the negative problems that marine litter is causing in the ecosystems through the removal of waste by clean up actions and retrieval programs (Chen, 2015; Ronchi et al., 2019).

The seafloor is, in most cases, the last destination of marine litter. This waste, which has been accumulated for decades, is commonly captured by the nets of bottom trawlers. They are important actors in FFL initiatives offering several benefits, such as engaging fishers in marine litter problems, improving waste management practices, and retrieving waste from the seafloor which, otherwise, would remain unextracted (KIMO, 2015). The Mediterranean Sea has a broad social, cultural, and economic fishing sector extracting 0.8 Mt of catch in 2018 (FAO, 2022). These highly active fleet can be key to promote FFL strategies in a basin that is being considered one of the most polluted in the world (Rios-Fuster et al., 2019).

Bottom trawlers in the Mediterranean are constrained to fish within the depth of 50–1000 m although the minimum depth may be exchanged for 3 nautical miles where this depth is reached at a shorter distance from the coast (EC 1626/1994; EC 1967/2006). In the Catalan continental margin (NW Mediterranean Sea), this fleet is composed by 222 fishing vessels and landed 7854 t of commercial catch in 2019 (Blanco et al., 2023). Considering the large fleet and wide depth range that they cover, the daily catches of the bottom trawl fleet have a great potential to study the magnitude of the marine litter and implement effective FFL strategies. Marine litter assessment is of international importance to understand the fate and effects of terrestrial waste and provide data for policy makers to prevent and mitigate this type of pollution (Löhr et al., 2017). However, these data are yet to be studied in the area, where only occasional research in time or space provide some insights of what might be on the seafloor (Galimany et al., 2019; Pham et al., 2014; Ramirez-Llodra et al., 2013; Sánchez et al., 2013). Then, this study aims to elucidate the type and amount of marine litter accidentally caught by bottom trawlers along the Catalan coast from 20 to 700 m depth. Moreover, the study estimates the potential of the bottom trawl fleet to extract marine litter from the area. This research aligns with the Ocean Decade challenge “Understand and beat marine pollution” (UNESCO-IOC, 2022) and highlights the role of fisheries in tackling this global issue.

2. Materials and methods

2.1. Study site

The study was carried out along the Catalan coast, in the NW Mediterranean Sea (Fig. 1). This area has been traditionally inhabited and hosts one of the largest cities in Europe, Barcelona, with 4.9 million of people including their commuting zone (EU, 2019), where human activities generate considerable quantities of waste, potentially polluting the marine environment. The coast is 580 km long and stratified sampling was designed by dividing the area in three zones, according to their province borders. From each zone, purposive sampling was adopted as three different ports were selected, according to their importance in terms of catches and economic incomes: i) north zone, including the ports of Roses, Palamós, Blanes, ii) center zone, including the ports of Arenys de Mar, Barcelona, Vilanova i la Geltrú, and iii) south zone, including the ports of Tarragona, l’Ametlla de Mar and La Ràpita, which includes the shallowest zone of them all (Fig. 1). These divisions correspond to 3 different provinces, which, at a certain level, act as different administrative units.

2.2. Sampling

Data were collected from January 2019 to December 2021 onboard registered fishing trawlers from the Catalan trawl fleet following the methods described in Blanco et al. (2023). Briefly, samples were extracted in three depth strata, covering the whole area where the trawl fleet operates regularly, i.e. continental shelf (20–200 m depth), upper slope (200–400 m depth) and lower slope (400–700 m depth). Data were collected monthly from each zone, with a total of 305 hauls (99, 102, and 104 hauls in the north, center, and south zones respectively; Fig. 1; Supplementary Material Table S1). Each haul was geolocated with a GPS device to calculate distance trawled which, together with the horizontal opening of the net’s mouth, were used to calculate the swept area (km^2) for each haul. Then, these values were used to standardize density of ML (kg km^{-2}) to allow comparison between hauls. Depth was estimated calculating an average point between the start and end points of each haul. Mesh size was stablished by law, i.e. 40-mm square-mesh everywhere but in Palamós lower slope, which was 50-mm squared-mesh for the blue and red shrimp fishery. Therefore, the mesh width limits the marine litter size and smaller waste is not removed by bottom trawlers. After each haul, all or a representative fraction of the marine litter ($\geq$25%) was collected and brought to the laboratory to analyze it in detail.

2.3. Marine litter characterization

Following the application of Directive EU 2019/883 of the European Parliament and of the Council as regards to monitoring data methodologies and the format for reporting passively fished waste (EU 2022/92), the characterization of marine litter is described in Table 1. In summary, six categories are defined: metal, plastic, rubber, textile, wood, and other waste. Wood includes all processed wood items, such as boxes, and other waste includes all items that cannot be classified in the previous defined categories. The categories match those reported by the regulation but two subcategories have been added in the plastic main category to detect marine litter that may be a specific issue in the area of the study, i.e. fishing gear and wet wipes. Clinker, a residue of burning coal from the steam ships that navigated the Mediterranean in the XVIII and XIX centuries was excluded from the analyses. This waste has not been generated for the last hundred years, approximately, and it is not included in the official lists of marine litter items.

In the laboratory, all items were classified, grouped by categories, and weight to the nearest $\pm$ 0.1 g. Wet wipes and other adsorbent items were manually drained before weighing.

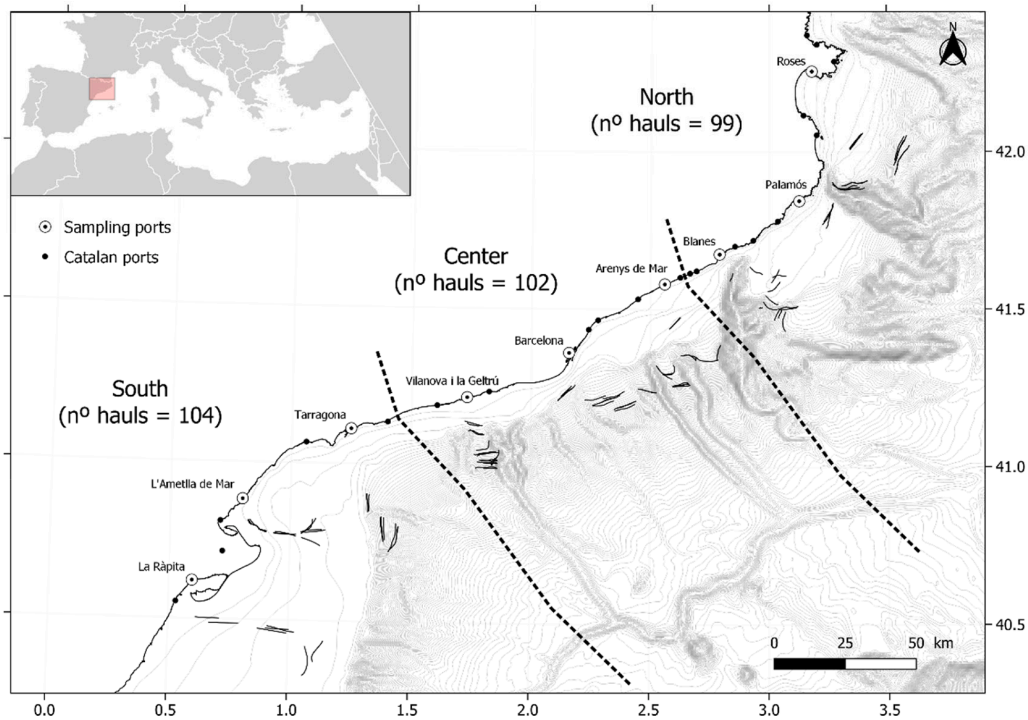

Fig. 1. Map plotting the studied area (Catalan coast) with dotted lines indicating zones (North, Center and South) and dots indicating fishing ports along the coast. Black short lines are the sampled hauls, with the number of sampling hauls shown for each zone in parenthesis.

Table 1
Classification of the marine litter categories in the laboratory.

Category	Description
Metal	Items or pieces made with ferrous and non-ferrous metals, i.e. cans, lids
Plastic	Items or pieces made with plastic, i.e. bags, containers
Fishing gear	Plastic fishing related items, i.e. buoys, nets, line, bait
Wet wipes	Hygienic single use moistened pieces of non-woven fabric
Rubber	Items or pieces made with rubber, i.e. balloons, boots, tyres
Textiles	Clothes and pieces of fabric
Wood	Items and pieces made with wood, i.e. corks, boxes or poles
Other waste	All other marine litter which does not fit in the specific categories

2.4. Marine litter analysis

To have a better understanding of the marine litter fished unintentionally by the trawling fleet of the Catalan coast, the data for the 3 years of the study were analyzed together. Four different analyses were performed:

- The total mass (kg) of marine litter removed from all samplings, including all hauls, was calculated to analyze differences between categories.
- Differences in marine litter density (kg km^{-2}) were analyzed by zone and categories.
- Within the plastic fraction, plastic density was analyzed between ports.
- Lastly, marine litter density was analyzed across depth and categories.

All four analyses were done using Generalized Linear Models (GLM). The selected family error distribution was “quasi-poisson” because the data set contains many zero values (i.e. litter categories that did not appear in a haul). When over-dispersion of data was detected, the selected family structure was “negative-binomial” for highly left-skewed data (applied for plastic density analyses). The choice for the most appropriate link function and error distribution was made based on residual analyses. The goodness of the fitted model was tested with a Chi-Squared test based on residual deviance and degrees of freedom. The GLM analysis was done with R v4.2.2 package mgcv and pairwise comparison with the package emmeans (R, 2013).

2.5. Potential removal of marine litter

To evaluate the effect of fishing for litter strategies for the bottom trawl fleet in the area of the study, the amount of marine litter accidentally caught by the fleet per year was estimated and described as the potential marine litter removal (t y^{-1}). To do so, first, the total fishing time (in hours) of the Catalan bottom trawl fleet per port and year was obtained from Vessel Monitoring System (VMS) data. The VMS is a satellite-based monitoring system that provides data from fishing vessels (position, speed and course) to the fisheries authorities in order to control fishing activities allowing the calculation, after database treatment, of the fishing time (h) of each vessel (Sala-Coromina et al., 2021). Second, the rate of marine litter removal (kg h^{-1}) per year was obtained from our sampling data, as an average of all hauls performed per year, assuming neither seasonal nor spatial variability. Finally, the potential marine litter removal per year (t y^{-1}) was calculated by multiplying the total number of fishing hours each year by each removal rate. The result was expressed as an average of the three years of sampling (2019–2021).

3. Results and discussion

3.1. Marine litter overview

Only 8 hauls out of the 305 performed in the 3 years of the study had no marine litter, which accounts for the presence of waste in 97 % of the hauls. This value matches with the study from Garofalo et al. (2020) although they only found it for one depth strata (501–800 m) whereas other depths reported lower percentages (i.e. 63 % in 51–100 m depth). Other studies also reported lower values in the Mediterranean, i.e. 75 %

(Alvito et al., 2018) or 88 % (Alomar et al., 2020).

The amount of marine litter removed with the sampling hauls during the three years of the study was 349.4 kg for all 305 hauls. From all the marine litter collected, the categories had significantly different masses (ANOVA; $F_{5,1824} = 60.85$, $p < 0.001$) (Fig. 2; Supplementary Material Table S2). In detail, plastic was caught in greater quantities than all other categories ($z(inf)_{Metal - Plastic} = -6.52$, $p < 0.001$; $z(inf)_{Other\ waste - Plastic} = -7.91$, $p < 0.001$; $z(inf)_{Plastic - Rubber} = 4.55$, $p < 0.001$; $z(inf)_{Plastic - Textiles} = 7.95$, $p < 0.001$; $z(inf)_{Plastic - Wood} = 6.27$, $p < 0.001$), with a mean weight per haul of 0.74 ± 0.11 kg accounting for the 64.2 % of the total marine litter caught in the fishing nets (Fig. 2; Supplementary Material Table S3). Accordingly, other studies also report plastic as the waste with the highest percentages, ranging between 60 % and 80 % but it can account for the 90 % of the marine litter (Derraik, 2002; Galgani et al., 2015; Saladié and Bustamante, 2021). Wood was the second most common category found in this study, with a mean weight per haul of 0.25 ± 0.03 kg haul^{-1} accounting for the 21.5 % of the total marine litter caught ($z(inf)_{Metal - Wood} = -4.51$, $p < 0.001$; $z(inf)_{Other\ waste - Wood} = -4.01$, $p < 0.001$; $z(inf)_{Rubber - Wood} = -3.55$, $p = 0.005$; $z(inf)_{Textiles - Wood} = -3.75$, $p = 0.002$) (Fig. 2; Supplementary Material Table S3). Processed wood includes items such as boxes, lumber or poles, which tend to be both big items but also heavy. These two features are probably the reason why weight-wise, wood is the second category because when analyzed by number of wood items, this category usually represents a much smaller fraction (Garofalo et al., 2020; Spedicato et al., 2019). Finally, there were no significant differences between textile and other waste ($z(inf)_{Textiles - Other\ waste} = -0.40$, $p > 0.05$) or between metal and rubber ($z(inf)_{Metal - Rubber} = 1.08$, $p > 0.05$) (Supplementary Material Table S3), which accounted for the lowest proportion of items, coinciding with findings reported in previous studies (Galimany et al., 2019; Pham et al., 2014).

3.2. Zone

The density of marine litter was significantly different by zone (ANOVA; $F_{2,1827} = 22.17$, $p < 0.001$) (Supplementary Material Table S4). The densities were 5.35 ± 0.89 kg km^{-2}, 13.75 ± 3.25 kg km^{-2}, 5.86 ± 1.04 kg km^{-2} for the north, center and south zones respectively (Fig. 3a), with the center having the highest density of all. Densities of marine litter in the Mediterranean have been reported to vary from 1.39 kg km^{-2} in the Balearic Islands to values as high as 1536.6 kg km^{-2} in the Catalan coast (Alomar et al., 2020; Ramirez-Llodra et al., 2013). Different factors can influence the amount of litter found in the oceans, i.e. distance to urban areas, coastal uses, winds, current, or navigation routes (Bergmann, 2015). It is well stablish that most marine litter has a land-based origin, estimating that 80 % of the waste found in the oceans was dumped on land (UNEP, 2009). The center zone of this study includes the great metropolitan area of Barcelona, which is one the largest from Europe, with 4.9 millions inhabitants in 2017 (EU, 2019). Moreover, it holds one the busiest airports and ports, with a great amount of tourism in the area (EU, 2019, 2022). These results, then, are in accordance with other studies, that associate marine litter with industrialization and urbanization along with waste mismanagement (Bergmann, 2015; Galimany et al., 2019).

The types of marine litter found in each zone are reported in Fig. 3b. Plastic and wood were found to be present in first and second place, respectively, for all zones, but their densities varied. The center had significantly higher values of plastic (10.23 ± 2.57 kg km^{-2}) than the north and south zones ($z(inf)_{Plastic\ Center - North} = 5.95$, $p < 0.001$; $z(inf)_{Plastic\ Center - South} = 5.41$, $p < 0.001$) (Supplementary Material Table S5), but no differences were observed between the plastic density in the north and the south, with values of 2.43 ± 0.42 kg km^{-2} and 3.27 ± 0.97 kg km^{-2}, respectively ($z(inf)_{Plastic\ North - South} = -1.04$, $p > 0.05$) (Supplementary Material Table S5). Apart from plastic density, no other significant differences were observed in the other marine litter categories between zones ($p > 0.05$; Supplementary Material Table S5). The types of litter may also be influenced by the proximity to highly populated areas, among other factors. Plastic seems to be an indicator of urban areas and touristic sites, as the center zone of this study (Barnes et al., 2009). Thus, understanding quantity and type of plastic marine litter may be a good indicator of waste mismanagement to place proper management actions to prevent marine litter.

3.3. Plastic per port

This section analyses the specific fraction of plastic within all the

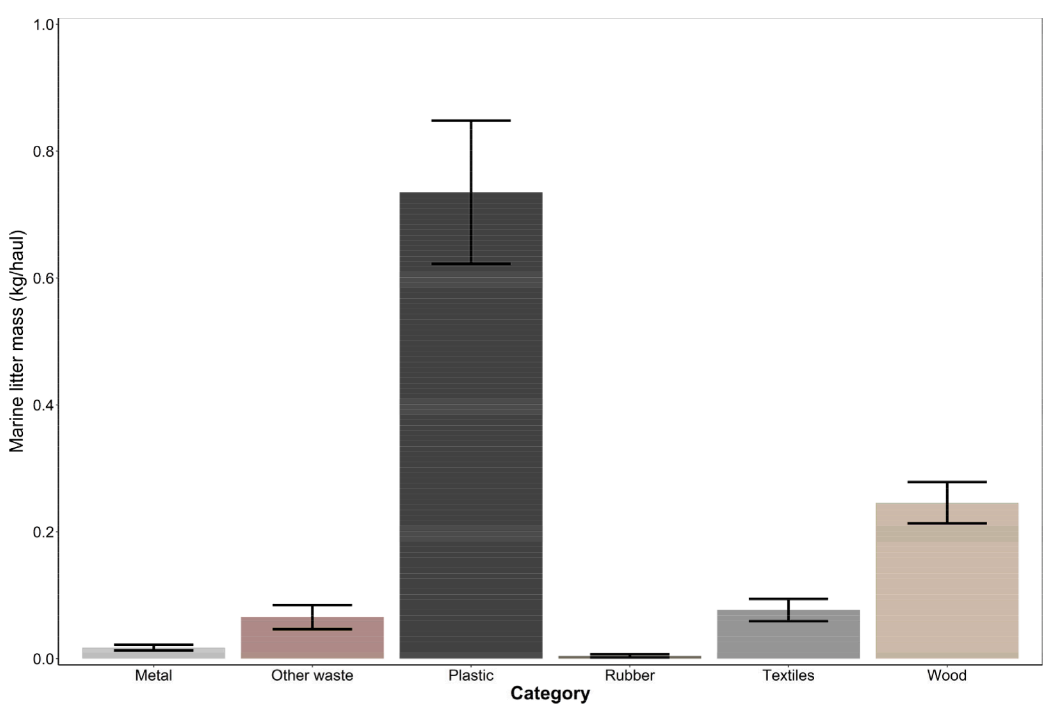

Fig. 2. Marine litter caught with the bottom trawler nets throughout the study (2019–2021). Bar plot (±SD) of marine litter mass per haul of each category.

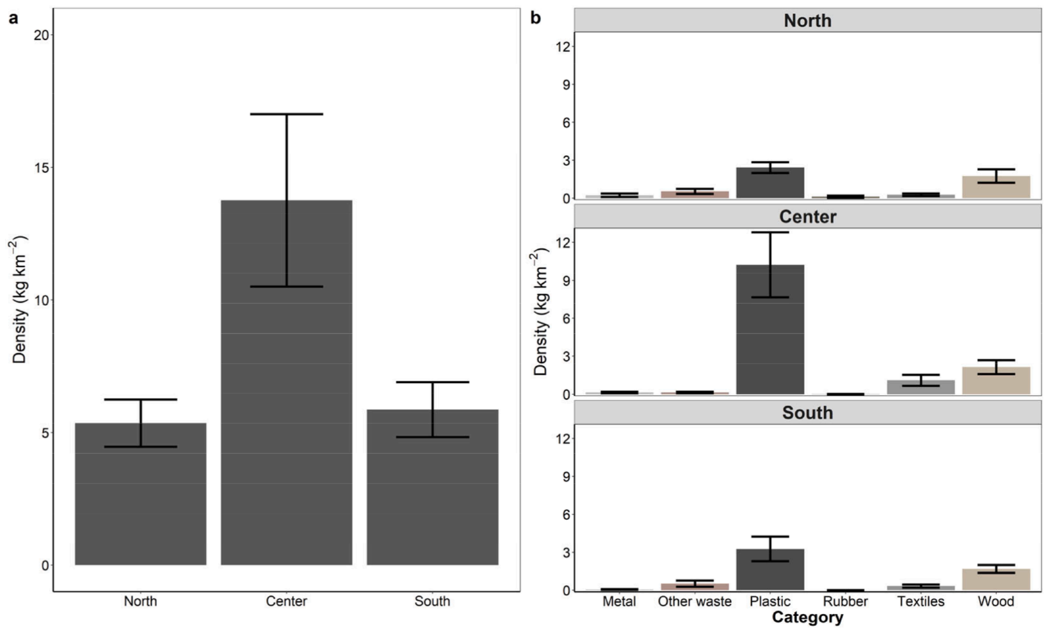

Fig. 3. Marine litter by zones. a) Bar plot with average density (±SD); b), Bar plot with average density (±SD) of each type of marine litter.

marine litter categorized. The plastic density was statistically different among ports (ANOVA; $F_{8,296} = 24.15$, $p < 0.001$) (Fig. 4; Supplementary Material Table S6). Supplementary Material Table S7 details the specific differences among all ports, but here we highlight the global differences found, which are the ports with the lowest and the highest presence of marine litter in the fishing catch. The port with the least amount of plastic was Arenys de Mar, with 0.17 ± 0.07 kg km^{-2}, which did not differ statistically from Roses (z(inf) = -3.09, p = 0.05) but differed from all other ports (z(inf) $_{\text{Arenys de Mar – Barcelona}}$ = -9.37, p < 0.01; z(inf) $_{\text{Arenys de Mar – Blanes}}$ = -5.83, p < 0.01; z(inf) $_{\text{Arenys de Mar – L'Ametlla de Mar}}$ = -5.39, p < 0.01; z(inf) $_{\text{Arenys de Mar – La Ràpita}}$ = -5.17, p < 0.01; z(inf) $_{\text{Arenys de Mar – Palamós}}$ = -4.84, p < 0.01; z(inf) $_{\text{Arenys de Mar – Tarragona}}$ = -5.98, p < 0.01; z(inf) $_{\text{Arenys de Mar – Vilanova i la Geltrú}}$ = −6.57, p < 0.01). Barcelona had the greatest density of plastic, with 23.62 ± 6.49 kg km^{-2}, and differed significantly when comparing with all the other ports (z(inf) $_{\text{Barcelona – Arenys de Mar}}$ = -9.37, p < 0.01; z(inf) $_{\text{Barcelona – Blanes}}$ = 5.68, p < 0.01; z (inf) $_{\text{Barcelona – L'Ametlla de Mar}}$ = 6.53, p < 0.01; z(inf) $_{\text{Barcelona – La Ràpita}}$ = 6.70, p < 0.01; z(inf) $_{\text{Barcelona – Palamós}}$ = 6.92, p < 0.01; z(inf) $_{\text{Barcelona – Roses}}$ = 8.69, p < 0.01; z(inf) $_{\text{Barcelona – Tarragona}}$ = 5.09, p < 0.01; z(inf) $_{\text{Barcelona – Vilanova i la Geltrú}}$ = 4.42, p < 0.01) (Supplementary Material Table S7). Barcelona is the city that concentrates most of the population from the metropolitan area and, despite it has sewage treatment plants and waste management initiatives, highly populated coastal cities discharge great quantities of waste, which end up accumulating in the oceans (UNEP, 2015). This marine litter from Barcelona is then washed to Vilanova i la Geltrú, a port that is just south of Barcelona, as a results of the downward currents occurring off the Catalan coast (Font, 1990).

The marine litter transport from Barcelona towards the south of the coast is also evidenced by the type of litter recorded in each port (Fig. 4). Wet wipes had very high density in Barcelona and Vilanova i la Geltrú, with 15.64 ± 5.34 kg km^{-2} and 2.77 ± 1.46 kg km^{-2} respectively, and the density decreased towards the south. Wet wipes are manufactured with PET (polyethylene terephthalate) fibers, including products labelled as flushable (Pantoja-Munoz et al., 2018). As a result, wet wipes

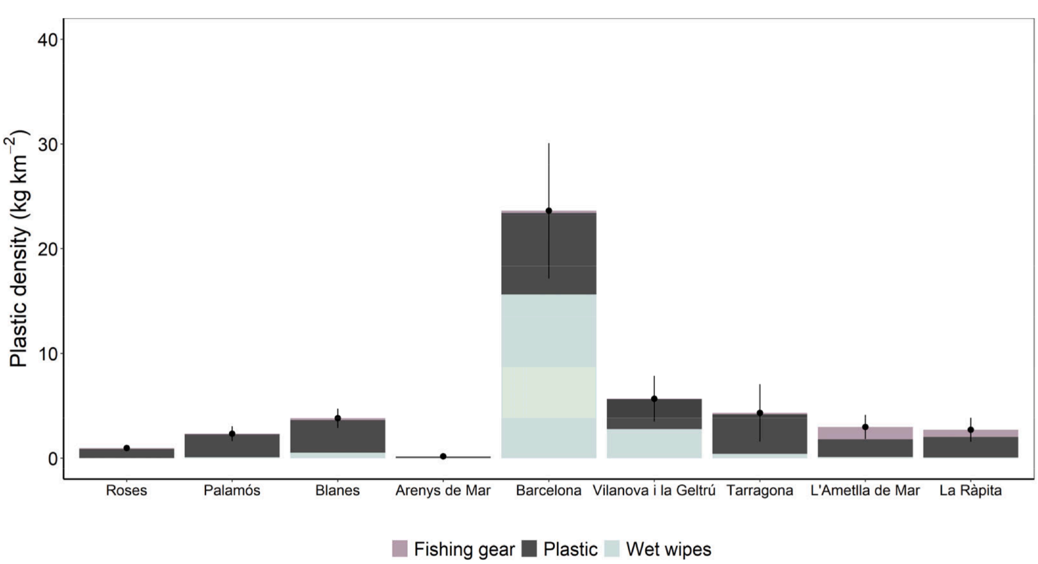

Fig. 4. Bar plot with average density (±SD) of plastic by port. Black dots are the mean plastic density, bar color represents the density of different types of plastic. Ports are plotted from the northern (Roses) to the southern (La Ràpita), along the Catalan coast.

are a main component of sewage and waste water treatment plants blockages (Mitchell et al., 2017) and, as a consequence, water may be released without any filtration or depuration process to the environment (Morritt et al., 2014). Then, all locations with waste water treatment plants may still release wet wipes in the sea.

The results from the types of plastic items analyses highlight the scarce fishing gear found on the seabed of the Catalan coast (Fig. 4). The port where most fishing gear is found is L'Ametlla de Mar, with 1.17 ± 1.10 kg km^{-2} (39.3%). However, this is a very low density compared to other studies. For example, in an area of the Tyrrhenian Sea (Mediterranean Sea), derelict fishing gear accounted for 77.9 % of the total marine litter (Consoli et al., 2019). Abandoned, lost or discarded fishing gear is variable according to context and region specific with a rough estimate of accounting for the 10 % of the marine litter by volume (Löhr et al., 2017; Macfadyen et al., 2009).

3.4. Depths

The density of marine litter varied significantly according to depth (ANOVA; $F_{2,1827}$ = 20.43, $p < 0.001$) (Supplementary Material Table S8), with waste on the continental shelf (12.15 ± 2.40 kg km^{-2}) being higher than that from the upper slope (5.58 ± 0.76 kg km^{-2}) and from the lower slope (4.24 ± 1.05 kg km^{-2}) (Fig. 5a). Some studies reported that the highest densities of marine litter were found in submarine canyons, whereas continental shelves had the lowest litter concentration, and related it to hydrodynamic processes that occurred in the investigated canyons such as strong water flow transporting litter down to deeper waters (Pham et al., 2014; Tubau et al., 2015). In contrast, as found in this study, some authors documented major marine litter abundances in near-shore sites and continental shelves, especially in front of coastal cities, where there was an additional input of waste coming from inland sources (Galgani et al., 2000; Koutsodendris et al., 2008). Similarly, a study from the Adriatic Sea (Mediterranean Sea) analyzing marine litter from the surface to 100 m depth reported that the highest densities were obtained between 0 m and 30 m, with values as high as 116 ± 58 kg km^{-2}, suggesting that the large volume of marine litter coming from inland and coastal sources mainly concentrates in shallow waters (Pasquini et al., 2016).

The area of study has a high amount of waste water treatment plans (>500) (Mas-Ponce et al., 2021), which may block and release unfiltered water (Mitchell et al., 2017). In fact, studies from the European Commission indicated that their conditions are not optimal imposing fines for the lack of compliance with the 1991 Directive on wastewater treatment for 2 main reasons, i.e. deficiencies in collecting and treating urban waste water, and the absence of tertiary treatments to municipalities with populations > 10,000 people (Rodríguez-Villanueva and Sauri, 2021). Despite this might be an important source of marine litter, other sources such as rivers or wind (Bergmann, 2015; Chassignet et al., 2021) may also be considered to explain the highest amount of marine litter in the shallowest depth studied.

The composition of the marine litter was very similar among depths with plastic values ranging from 2.55 ± 0.63 to 7.95 ± 1.95 kg km^{-2} or wood ranging from 1.01 ± 0.43 to 2.81 ± 0.47 kg km^{-2} (Fig. 5b). Significant differences were only observed between plastic density in the continental shelf and the lower and upper slope (z(inf) $_{\text{Plastic Continental Shelf – Lower slope}}$ = 4.28, $p < 0.01$; z(inf) $_{\text{Plastic Continental Shelf – Upper slope}}$ = 3.48, $p < 0.05$) (Supplementary Material Table S9). No differences were observed either between both slopes in terms of plastic density (z(inf) $_{\text{Plastic Lower slope – Upper slope}}$ = -0.94, $p > 0.05$) or between depths for all the other marine litter categories (Supplementary Material Table S9). The values obtained for plastics have also been reported in other studies in the Mediterranean Sea at different depths (Ioakeimidis et al., 2017). Thus, in the Catalan coast, zones seem to have a greater influence on the composition of marine litter than depth.

3.5. Potential removal rates and future developments

With all the marine litter data analyzed in this study, and considering the fishing hours of the bottom trawlers in Catalonia, the fleet can potentially remove 237 ± 36 t of marine litter yearly, with a maximum value of 308 t in 2020 and a minimum of 187 t in 2019. Knowing that 64.2 % of the marine litter is plastic, bottom trawlers may remove about 152 t of plastic each year. A big scale pioneer project on FFL strategies in Scotland quantified that 200 fishing vessels removed 200 t of marine litter during 3 years (KIMO, 2015). Strategies to remove marine litter are important to prevent entanglement or ingestion of waste by fauna, which deleterious effects are increasingly being recorded in all studied zoological groups (Kühn et al., 2015). These initiatives not only clean up the seafloors from waste but also have other benefits, including social aspects. For example, FFL strategies can create constructive

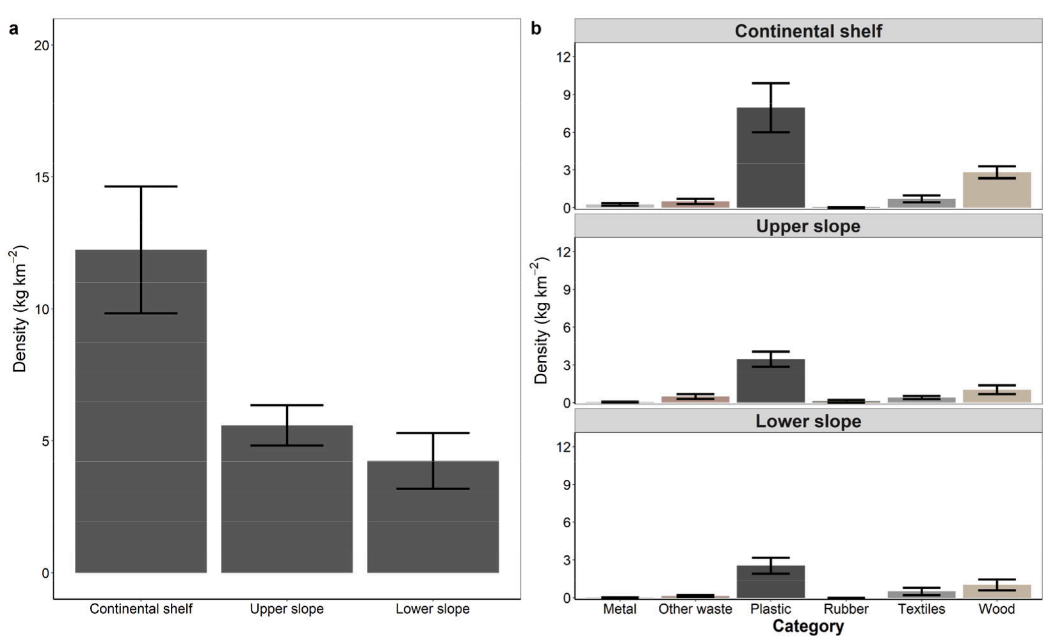

Fig. 5. Marine litter by depths. a) Bar plot with average density (±SD); b), Bar plot with average density (±SD) of each type of marine litter.

relationships among fishers, port authorities, coastal municipalities and government as well as cooperation between fishers and scientists (Ronchi et al., 2019).

Economically, the recycling of marine litter is currently expensive because the plastic items are mixed with many other materials difficult to sort and clean (Madricardo et al., 2020). However, it is creating an opportunity for recycling and research innovation companies to improve the capability of marine plastic recycling enhancing blue growth economy (Ronchi et al., 2019). For example, different projects worldwide have recycled marine litter and converted it into thread and yarn to make clothes and carpets, whereas other projects have converted the recycled marine litter in packaging and piping products, or even skate boards (OSPAR, 2020; Ronchi et al., 2019). The development of this new market encourages the fishing sector to be actively involved in FFL initiatives promoting efficiency and sustainability in their sector (Nguyen and Brouwer, 2022).

Another economic aspect is that the fishery sector may have costs associated to cleaning nets or repairing clogged pipes or entangled propellers, disadvantaging a sector that is directly negatively affected by litter that was mainly dumped on land (Nguyen and Brouwer, 2022). Therefore, as suggested by Ronchi et al. (2019), "a producer responsibility program integrating the environmental cost of products throughout their life cycles into the market price may be implemented at the European level to create a fund that can ultimately be used by the Member States for waste management, including the implementation of the FFL scheme".

4. Conclusions

In the Catalan coast, bottom trawling activities collect marine litter in 97% of the hauls, although its density varies according to zone and depth. Geographically, the determined marine litter densities were 5.35 $\pm$ 0.89 kg km^{-2}, 13.75 $\pm$ 3.25 kg km^{-2}, 5.86 $\pm$ 1.04 kg km^{-2} for the north, center and south zones respectively, with plastic being particularly abundant in sea bottoms, next to highly urbanized environments. In detail, the density of plastic from the center was 10.23 $\pm$ 2.57 kg km^{-2}, whereas the north and south had 2.43 $\pm$ 0.42 kg km^{-2} and 3.27 $\pm$ 0.97 kg km^{-2}, respectively. Barcelona was the most polluted port, with 23.62 $\pm$ 6.49 kg km^{-2} of plastic being wet wipes the majority of the items. When relating marine litter and depth, the continental shelf had higher densities (12.15 $\pm$ 2.40 kg km^{-2}) than the upper slope (5.58 $\pm$ 0.76 kg km^{-2}) and the lower slope (4.24 $\pm$ 1.05 kg km^{-2}), with a similar composition of the marine litter among depths. Fishing for Litter (FFL), a strategy consisting in using the fishing fleet to remove the accidentally caught marine litter with their nets, could help tackle the marine litter issue in the Catalan coast, where bottom trawlers could remove 237 $\pm$ 36 t of waste yearly. Finding the origin of marine litter is key to develop policies to sustainably manage coastal and marine environments. Therefore, further research characterizing types of plastic, for example, may be key to track the origin of the marine litter to promote best waste management practices on land.

CRediT authorship contribution statement

Marc Balcells: Data curation, Writing – original draft. **Marta Blanco:** Formal analysis, Writing – original draft. **Ana I. Colmenero:** Methodology, Writing – review & editing. **Claudio Barría:** Methodology, Writing – review & editing. **Ricardo Santos-Bethencourt:** Writing – review & editing. **David Nos:** Writing – review & editing. **Cristina López-Pérez:** Writing – review & editing. **Jordi Ribera-Altimir:** Software, Writing – review & editing. **Joan Sala-Coromina:** Writing – review & editing. **Mariona Garriga-Panisello:** Writing – review & editing. **Alba Rojas:** Writing – review & editing. **Eve Galimany:** Conceptualization, Supervision, Writing – original draft.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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Appendix A. Supplementary material

Supplementary data to this article can be found online at https://doi.org/10.1016/j.wasman.2023.05.021.

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