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Microplastic abundance and biodiversity richness overlap: Identification of sensitive areas in the Western Ionian Sea

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ABSTRACT

Plastic pollution in the Mediterranean Sea has been widely reported, but its impact on biodiversity has not been fully explored. Simultaneous sampling of microplastics (MP) with a manta net and surveys of large marine vertebrates were conducted along the coastal waters of Sicily (Western Ionian Sea). A total of 17 neustonic samples have been collected and 17 marine species (cetaceans, sea turtles, seabirds, and fish) have been sighted in the target area. Kernel density estimation was evaluated to highlight a possible overlap between the presence of large marine fauna and MP densities to provide a preliminary risk assessment. The highest biodiversity and MP concentration (0.197 ± 0.130 items/m^2) were observed in the southernmost part of the studied area. The overlap between biodiversity hotspots and the occurrence of MP, potential contribute to the identification of sensitive areas of exposure in a poorly studied region.

1. Introduction

Nowadays, marine litter is commonly observed across all oceans and marine ecosystems (Bergmann et al., 2015). Mainly represented by plastic (up to 80%) (GESAMP, 2019), which under environmental conditions may fragment into smaller items called meso- (5 mm–2.5 cm) micro-5 mm–1 μm), and nano-particles (<1 μm), they can be transported over long distances (Lebreton et al., 2018). Microplastic presence has been detected on coastlines where it may accumulate due to current, wave and wind actions, river outflows and direct littering at the coast (GESAMP, 2019). Moreover, it occurs on the ocean surface, along the water column, on the seafloor and in association with biota, due to entanglement or ingestion (Baini et al., 2018; Fossi et al., 2012, 2017; GESAMP, 2019; Suaria et al., 2016). In the last 50 years, since the first record available in the scientific literature published by Kenyon and Kridler in 1969, the number of species affected by plastic litter has increased steadily reaching 914 species (Kühn and van Franeker, 2020). Bearing this in mind, monitoring and assessment programs appear essential to address specific questions about the distribution of marine litter, including microplastics, and its potential impacts on marine biodiversity.

At the European level, the Marine Strategy Framework Directive (MSFD) (2008/56/EC) and at the Mediterranean level the UNEP/MAP (IMAP indicators), have been developed to protect the marine environment as well as to ensure its sustainable use. Based on several descriptors the ultimate goal of these regulations is the achievement of Good Environmental Status (GES) for the marine waters by the EU Member States. In particular, the provisions of the MSFD Descriptor 10 and Ecological Indicator 10, respectively, aim to protect the marine ecosystems against harm caused by the emerging issue of plastic litter. As highlighted by several ocean circulation models (Fossi et al., 2017, 2018; Liubartseva et al., 2018; Mansui et al., 2015; Politikos et al., 2020), the Mediterranean Sea has been considered a sensitive plastic litter accumulation zone with an average concentration comparable to the great oceanic gyres (Cózar et al., 2015; Suaria et al., 2016; UNEP/MAP, 2015). Mainly due to the limited exchange of surface waters with the Atlantic Ocean, and intensive land- and marine-based sources of pollution significant amounts of marine litter enter and accumulate in this basin. Coastal areas and waters, in particular, face significant pressures from heavy population densities to maritime, touristic, and

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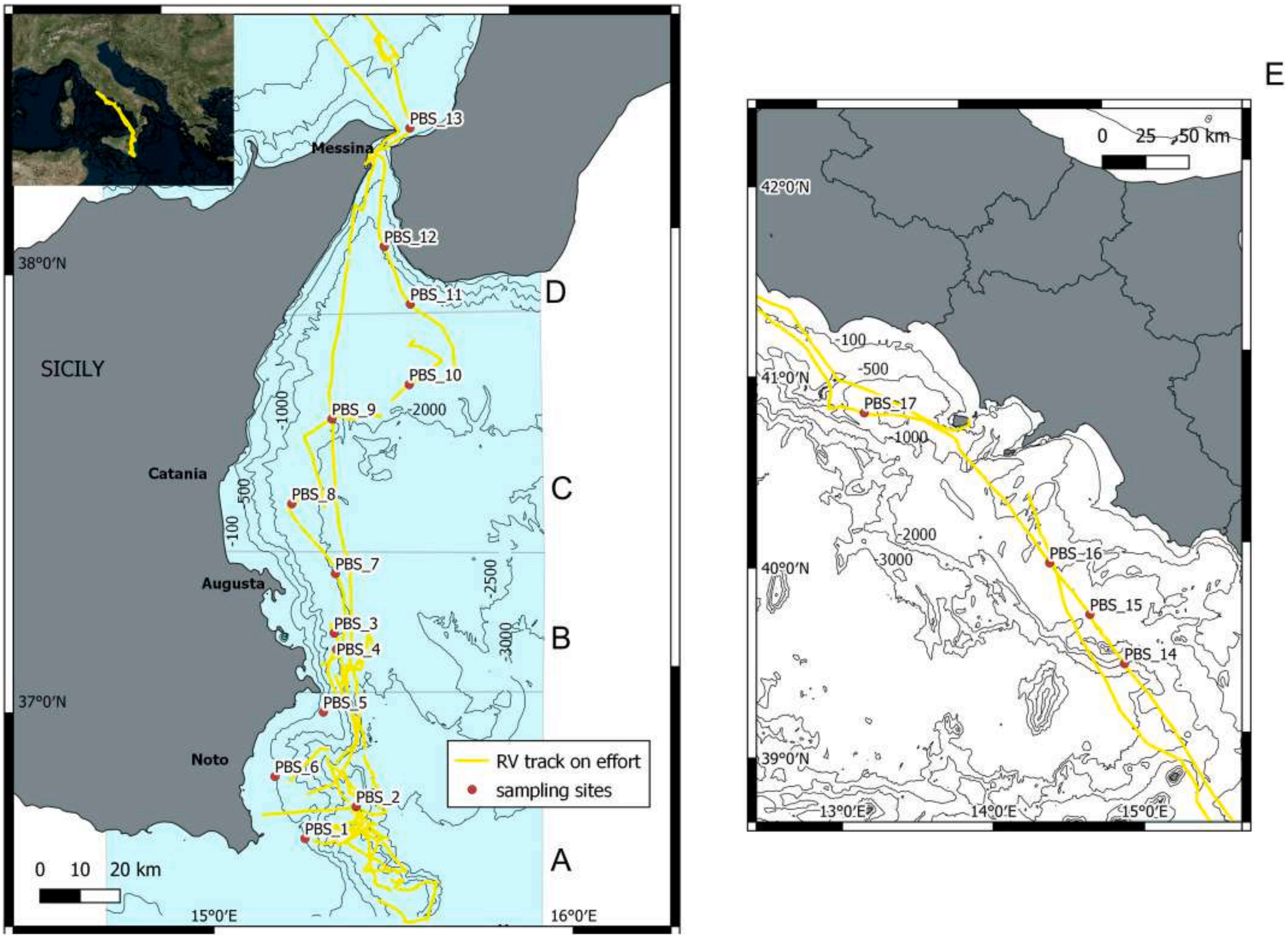

Fig. 1. Survey area, bathymetry, marine species sighting effort track (yellow line) and plastic litter sampling sites (orange dots) among the five subregions (A: Gulf of Noto, B: Gulf of Augusta, C: Gulf of Catania, D: Strait of Messina, and E: Tyrrhenian Sea). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

industrial activities leading to a decrease in the integrity of marine ecosystems (Coll et al., 2012, 2010; UNEP, 2016). While the identification of biodiversity hotspots and sensitive areas is a well-established procedure for these zones, usually resulting in the identification of Marine Protected Areas, the offshore waters are usually less investigated. Marine megafauna, such as cetaceans and sea turtles as an example, are often used as umbrella species. Large vertebrates can be also extremely valuable integrators of environmental quality and be considered as indicators of various anthropogenic pressures on marine environment including plastic pollution (Fossi et al., 2020). The identification of particularly sensitive areas as well as biodiversity hotspots in the pelagic realm can be effectively run by focusing on these valuable species. In addition, subsequently protection actions can be accomplished thanks to their charismatic influence in driving conservation efforts (Germanov et al., 2018).

Studies evaluating the potential risk connected to the spatial distribution of plastic litter and the presence of organisms inhabiting the marine ecosystems were only recently published worldwide (Everaert et al., 2018; Jâms et al., 2020; Mazarrasa et al., 2019; Schuyler et al., 2016; Wilcox et al., 2018, 2015) and in the Mediterranean Sea (Compa et al., 2019; Darmon et al., 2017; Fossi et al., 2017; Soto-Navarro et al., 2021). Although some risk evidence was highlighted for the most studied species, such as sea turtles and birds, there is still a lack of data regarding the simulation-based risk approach and the real threats that may affect the marine fauna (Soto-Navarro et al., 2021). Empirical data collection on the magnitude and typology of plastic litter, the spatial distribution of organisms and the potential impacts on them is needed to assess a more accurate and reliable risk scenario.

The coastline waters of the Central-southern Tyrrhenian and the Western Ionian Seas (Mediterranean Sea) were selected as a case study of this pilot project due to their critical anthropic repercussion and huge ecological value in terms of biodiversity richness and coastal geomorphological heterogeneity. Characterized by a narrow continental shelf dropping suddenly, high depths are reached at a very short distance from the coast (ca. 2000 m) (Santoro et al., 2015; Viola et al., 2017). Moreover, the presence of several marine protected areas (e.g. Cyclops Islands and Plemmirio), resting and nesting sites for migratory birds, endemic and threatened species, make these areas a hot spot of biodiversity (Cantasano et al., 2017; Ietto et al., 2018; Lorenti et al., 2011; Salvati et al., 2010; Spanò and Domenico, 2017; Trifuoggi et al., 2017). Nevertheless, urbanization, several industries (such as oil refinery, steelwork, and thermal-power plant), maritime commerce, fishing activities, and coastal tourism leading to increased contamination and discharges into the sea, are the drivers behind the chronic pressures that affect these areas (D'Alessandro et al., 2016; Imperato et al., 2003; Meriç et al., 2005; Ruberti et al., 2018; Tornero and Ribera d'Alcalà, 2014). Plastic presence on the seafloor and the related physical impact on marine organisms inhabiting the above-mentioned areas is well documented (Angiolillo et al., 2015; Battaglia et al., 2019; Consoli et al., 2019; Pierdomenico et al., 2020, 2019). Important ecological and commercial fishes, sea turtles and invertebrate species living in this area are reported to have ingested microplastics (Battaglia et al., 2016; Romeo et al., 2015, 2016; Schirinzi et al., 2020) or been entangled in abandoned plastic items (Bo et al., 2014, 2012; Casale et al., 2010; Ferrigno et al., 2017). On the other hand, plastic floating distribution in the Central-southern Tyrrhenian Sea and the Western Ionian Sea is still poorly investigated. Only a few studies evaluate the occurrence and accumulation of microplastic in these areas, especially in coastline waters (Ruiz-Orejón et al., 2016; Suaria et al., 2016).

Considering the ecological value of the ecosystems and the potential threats that can affect the areas investigated, this study aims: 1. to obtain information about the distribution and abundance of microplastics in the coastal and offshore areas of the Western Ionian Sea and the Central-southern Tyrrhenian Sea; 2. to provide a simultaneous assessment of biodiversity richness of the Western Ionian Sea; 3. to highlight the presence of sensitive areas of microplastic exposure, overlapping their spatial densities and biodiversity abundance.

2. Materials and methods

The sampling campaign was conducted onboard the R/V Headwind (54 ft sailing catamaran property of CIMA Research Foundation) from the 20th of July to the 3rd of August 2017. Overall, 1797 km were surveyed in the area included between the Central-southern Tyrrhenian Sea and the Western Ionian Sea. The simultaneous sampling of microplastic and marine biota surveys was focused over the slope and submarine canyons, limiting the searching effort to favourable conditions (sea state $\leq$3 Douglas scale) and speed (5 knots reduced to 3 knots during microplastic sampling). Date and time, geographical coordinates, and weather conditions (i.e., wave height and speed and direction of the wind) were recorded for each sampling activity accomplished. A total of 17 neustonic samples were collected. Due to the limited effort in marine species monitoring in the Central-southern Tyrrhenian Sea compared to the overall size of the area, the area was excluded from the biodiversity assessment.

2.1. Surveyed area

The survey area expands from the Western Ionian Sea to the Central-southern Tyrrhenian Sea, through the Strait of Messina (Fig. 1). Considering both differences in topographic features and possible anthropogenic pressures, this area was further divided into five subregions: Gulf of Noto (A), Gulf of Augusta (B), Gulf of Catania (C), Strait of Messina (D), and Tyrrhenian Sea (E) (Fig. 1).

The Gulf of Noto (A) represents the southernmost part of the east coast of Sicily. Considered a valuable ecological area due to the high degree of biodiversity with several aquatic birds, and marine species and the inconspicuous anthropogenic impact have allowed it to be selected as a control area in several ecotoxicological studies (e.g., Cappello et al., 2015, 2013; Fasulo et al., 2012).

The Gulf of Augusta (B) has been acknowledged as an elevated environmental risk site by the World Health Organization and classified as a "site of national interest" by the Italian Ministry of Environment (G. U.R.I., L. 426/1998) (Maisano et al., 2017). It hosts Sicilian major oil ports (Augusta, Priolo Melilli, and Santa Panagia) and several oil refineries and petrochemical plants (Signorino, 2012).

The Gulf of Catania (C) covers approximately 250 km^2 (Copat et al., 2018). Characterized by geomorphological and oceanographical heterogeneities, deep waters close to the coast and seasonal increment in primary production it is considered a suitable area for many cetacean species, including dolphins and whales (Sciacca et al., 2015). Despite this, the high population density and the intensive commercial and harbour activities may pose considerable risks to the marine environment (Tigano et al., 2009).

The Strait of Messina (D) is a unique ecosystem in the Mediterranean region. Together with Sicily-Tunisian Ridge, it is one of the two conjunction points between the western and eastern basins of the Mediterranean Sea (Santoro et al., 2015). The strait constitutes a natural submarine barrier to the water flowing through it. The presence of a stable upwelling structure influenced by strong tidal currents between the two basins have significant effects on the abundance and composition of planktonic and nektonic communities (De Santoli et al., 2011; Salvati et al., 2010), concentrate mesopelagic food resources, attract predators of various trophic levels resulting in high species biodiversity (Azzaro et al., 2007; Battaglia et al., 2020).

The Southern Tyrrhenian Sea area (E) focused on the waters facing the coast of the Campania and Calabria Regions. It extends approximately 700 km, including different gulf and protected areas (Cantasano et al., 2017; Ietto et al., 2018; Lorenti et al., 2011; Trifuoggi et al., 2017). The environmental quality of these marine ecosystems is strictly impacted by human activities (420 inhabitants/km^2, 10% of the whole Italian population) (Decembrini et al., 1995; Tornero and Ribera d'Alcalà, 2014; Zingone et al., 2006).

2.2. Neustonic samples collection

Neustonic samples were collected in the selected areas following an experimental design based on the sampling every 5 nautical miles (Fig. 1). A manta net (mouth opening: 60 × 16 cm; mesh size: 330 μm) coupled with a mechanical flowmeter for the estimation of the distance covered were used to perform the sampling activities. The net was towed at a maximum speed of 3 knots for 30 min. At the end of sampling, the net was thoroughly rinsed from the outside to ensure that both plankton and microparticles were washed into the end of the net. Samples were filtered through a 300 μm metal sieve and stored in a 70% ethanol solution for synthetic particle analysis. To avoid contamination throughout the sampling activities, all the materials used for sample collection, including the nets, were carefully cleaned and rinsed before each tow.

2.3. Plastic litter characterization

In the laboratory, neustonic samples were filtered through a sieve (mesh size: 300 μm). A Stereo Zoom NBS Stereo Microscope (mod. NBS-STMDLX-T) equipped with LED light was used to visually inspect the samples and separate the plastics from the organic matter. The particles found were isolated into glass Petri dishes and let dry overnight at room temperature. Each Petri dish was scanned (Scanner, SAMSUNG X328ONR) to allow the evaluation of the particle size using the ImageJ© Software (http://imagej. nih.gov/ij/). Image processing and analysis techniques represent powerful tools to minimize the bias introduced by the operator in sample measurement and obtain accurate, quick, and reproducible results (Igathinathane et al., 2008; Mazzoli and Favoni, 2012).

Following the guidelines proposed by Cadiou et al., 2020, which implement the recommendations of the MSFD TG10, the plastic items were measured and categorized as follows. The Feret's diameter (dF), defined as the longest distance between any two points along the selection boundary (http://imagej. nih.gov/ij/), was considered to classify the particles according to their length in 6 different classes: 0.3–0.5 mm, 0.5–1 mm, 1–2.5 mm, 2.5–5 mm, 5–25 mm and >25 mm. Besides, each particle was characterized by colour (transparent; opaque; white; yellow; orange; red; pink; green; blue; grey; brown; black, and other) and shape according to the following definition: fragments (irregularly shaped hard particles broken down from a larger piece), films (flat and flexible particles with smooth or angular edges), pellets (a hard particle with spherical, smooth or granular shape constituting the building blocks for nearly every product made of plastic), microbead (spheric shaped particles commonly used in cosmetic products), filaments (long fibrous material that has a length substantially longer than its width) and foam (near-spherical particle made of expanded material which easily deforms under pressure). Plastic dry weight was also recorded using an analytical balance OHAUS Explorer (device error ± 0.1 mg). Due to the possible fibers airborne contamination, during the sampling procedures, two Petri dishes containing microfiltered water were placed at the side of the stereomicroscope. Manta trawl results were processed and normalized considering the possible "wind stress effect" as described by Baini et al., 2018.

The relative concentrations were expressed in terms of the number of particles (items/m^2) and weight (mg/m^2). A polymer analysis was performed on 20% of the total number of microplastics isolated. The particles were selected among all the microplastics isolated taking into account the different percentages of the abundance of each category (size, colour and shape). The chemical structure of plastic particles was identified by applying the Fourier Transform Infrared (FT-IR) Spectroscopy Technique using an Agilent Cary 630 FTIR spectrophotometer (Agilent Technologies). Agilent MicroLab FTIR Software was adopted for the identification and elaboration of spectra following the method proposed by Fossi et al., 2017. Data from the most frequently sighted marine species and plastic concentrations were imported and processed using Quantum GIS platform (Version 3.10.1 A Coruña) and R (R Core Team, 2017). The statistical Shapiro-Wilk test was applied to check the non-normal distribution of the data. Significant differences in plastic densities for all studied subregions were tested using the non-parametric Kruskal–Wallis test. The level of statistical significance was set at $p < 0.05$. All analysis was performed using RStudio (R Core Team, 2017).

2.4. *Marine species visual survey*

Visual census of marine species presence was carried out by at least 3 trained Marine Mammal Observers (MMOs), covering 360° all around the R/V, following line transect method (Evans and Hammond, 2004). MMOs shifted position every 30 min to avoid fatigue, alternating 90′ effort to 30′ resting. The searching effort was performed naked eye and with 7*50 binoculars. Monitored species included marine mammals, sea birds, sea turtles and all marine fauna sighted at the sea surface. For cetaceans the active mode was applied and the main course of the vessel was interrupted in order to focal follow the cetacean group and perform photo-id of individuals. For other marine megafauna, a passive mode was applied so no change in the vessel course occurred.

2.5. *Biodiversity assessment*

A 5 km grid was superimposed on the study area and used to assess species diversity. Species Richness, Shannon index, and evenness were calculated to explain the relationship between the overall abundance of each species classification and to examine how evenly distributed individual taxa were within each cell that contained sightings (Matear et al., 2019; Simpson, 1949). The Species Richness (S) is defined as the number of species encountered in a cell. The Shannon or Shannon–Weaver (or Shannon–Wiener) Index (H) (Eq. (1)) was calculated as:

$$H = -\sum_{i=1}^{S} p_i \, lnp_i \tag{1}$$

where p$_i$ is the proportional abundance of species i, and S is the number of species. Values of H, obtained from empirical data, fall between 0 and 5, usually ranging from 1.5 to 3.5 and rarely surpassing 4 (Magurran, 2004). Species Evenness (J) (Eq. (2)), defined as a measurement of the relative abundances of species contributing to the richness of an area, was also calculated applying Pielou's evenness formula:

$$j = \frac{H}{1n\, S} \tag{2}$$

where H is the Shannon index and S is the number of species. Kruskal–Wallis test was used to test differences in Shannon Index, Evenness and Richness among the 4 different sub-areas. Wilcoxon Rank Sum post hoc test was used to inspect pairwise differences. All analysis has been performed using R software. Biodiversity indexes were computed using the vegan package.

2.6. *Spatial risk assessment*

The spatial risk assessment process foresaw two separate steps. First, sensitive areas have been mapped, based on the distribution of species of particular interest. Kernel density estimation was used to determine the general and core area of distribution of main megafauna species. General distribution is defined by the 95% density and the Core Distribution by the 50% Density. For striped dolphin (*Stenella coeruleoalba*) and loggerhead turtle (*Caretta caretta*), Kernel density was weighted considering the number of sighted individuals. The spatial distribution and densities of microplastics within and/or close to highlighted areas have then been added to the sensitive maps and considered for the spatial risk assessment. A Hazard Score (HS) was assigned to each region, based on the microplastic densities (values range: 1–3, considering if mean ± SD value of the considered region were under (1), within (2) or over (3) mean ± SD values for the overall area). An Exposure score, based on the number of species for which the General distribution (Sensitive Score 1 SS$_1$, values range: 1–6, considering the maximum number of species for which the kernel density analysis has been performed) and the Core Distribution (Sensitive Score 2 SS$_1$, values range:1–6) were recorded in the area. Overall risk assessment (R) (Eq. (3)) was evaluated following the general formula:

$$R = HS{*}E \tag{3}$$

where HS is the Hazard Score and E was given by the sum of SS$_1$ and SS$_2$. Relative Riske index (RI) (eq. 4) was then computed as

$$RI = \frac{HS\,(SS_1 + SS_2)}{36} \tag{4}$$

considering 36 as the maximum possible RI value.

RI can vary between 0 and 1. We defined as low -risk areas where RI was below 0.3, medium risk areas those characterized by a RI between 0.3 and 0.7 and high -risk areas those characterized by a RI > 0.7.

3. Results and discussion

3.1. *Plastic litter: Presence and distribution*

Plastic particles (n = 2509 items) were found in all samples with a mean abundance of 0.154 ± 0.094 items/m^2 and a total weight of 1641.63 mg (mean: 0.040 ± 0.040 mg/m^2). The overall size class distribution revealed a prevalence of microplastic (87%) followed by mesoplastic (12%) and macroplastic (1%). The concentrations show a similar pattern of distribution both for the number of items and weight. In the Tyrrhenian Sea (E), the highest values were found along the coast of Campania, near the Gulf of Salerno (PBS16: 0.329 items/m^2 and 0.475 mg/m^2). The presence of macroplastic in this area was registered in one out of four samples collected. In the Ionian Sea, the highest values were found in the Gulf of Augusta (B) (PBS3: 0.353 items/m^2 and 0.251 mg/m^2) and the Gulf of Catania (C) (PBS10: 0.214 items/m^2 and 0.087 mg/m^2). Weight abundances were strongly influenced by the presence of macroplastic (more than 58% in weight). In the following sections only data referred to microplastic concentrations in terms of the number of items (items/m^2) and mass unit (mg/m^2) will be presented, being this dimensional class (0.3 mm–5 mm) the target size range of the manta net used during the sampling campaign and being available for ingestion from a wide range of marine organisms.

3.1.1. *Microplastic: presence and distribution*

A total of 2177 microplastics were isolated with an average concentration of 0.134 ± 0.084 items/m^2 (Table SI_1). Highly variable

Table 1
Literature data on floating microplastic densities (items/m^2 ± standard deviation) for the Mediterranean waters (<50 km far away from the coast).

Mediterranean basin	Region	Net mesh (μm)	Items/m^2 ± SD	Source
Ionian basin	Italian coastlines	330	0.10 ± 0.06	Present study
Balearic basin	Balearic islands coastlines	335	0.86 ± 4.08	(Compa et al., 2020)
Algerian and Balearic basin	Spanish coastlines	335	0.10 ± 0.09	(de Haan et al., 2019)
Algerian and Balearic basin	Spain, Mallorca and Menorca channel	333	0.22	(Ruiz-Orejón et al., 2019)
Tyrrhenian basin	Italian coastlines	330	0.69 ± 0.83	(Baini et al., 2018)
Adriatic basin	Italian, Slovenian, Croatian and Greek coastlines	330	0.32 ± 0.57	(Zeri et al., 2018)
Balearic basin	Balearic islands coastlines	333	0.90 ± 1.12	(Ruiz-Orejón et al., 2018)
Corso-Ligurian basin	France, Bay of Marseille	780	0.10 ± 0.27	(Schmidt et al., 2018)
Adriatic basin	Croatian coastlines	308	0.13 ± 0.29	(Palatinus et al., 2019)
Corso-Ligurian basin	France, Gulf of Lion	333	0.18	(Constant et al., 2019)
Levantine basin	Israeli coastlines	333	1.52	(van der Hal et al., 2017)
Corso-Ligurian basin	Franch and Italian coastlines	333	0.16 ± 0.16 * 0.08 ± 0.04 **	(Pedrotti et al., 2016)
Adriatic basin	Slovenia, Gulf of Trieste	300	0.41	(Gajšt et al., 2016)
Mediterranean basin	Balearic Islands, Italian and Greek coastlines	333	0.19 ± 0.23	(Ruiz-Orejón et al., 2016)
Corso-Ligurian basin	Italian coastline and Gulf of Asinara	200	0.31 ± 1.17 $^{\alpha}$	(Fossi et al., 2016)
Corso-Ligurian basin	Italy, Gulf of Asinara	330	0.10 ± 0.12	(Panti et al., 2015)
Corso-Ligurian basin	Corse, Bay of Calvi	333	0.12	(Collignon et al., 2014)
Corso-Ligurian basin	Italian coastline and Gulf of Asinara	200	0.62 ± 2.00	(Fossi et al., 2012)

*Values refer to the concentrations found within the 1 km and ** from 1 to 10 km water strips, respectively. $^{\alpha}$ Sampling activities were carried out with a WP2 plankton net and expressed as items/m^3.

concentrations of microplastics in coastline waters have been previously observed in other Mediterranean basins. The most relevant findings available in the literature are reported in Table 1.

As shown in Table 1, the microplastic concentration reported by this study is consistent with the results of other studies conducted in Mediterranean waters by Collignon et al., 2014; de Haan et al., 2019; Palatinus et al., 2019; Panti et al., 2015; Pedrotti et al., 2016; Schmidt et al., 2018. Considering the other studies, the heterogeneity of the data could be attributed to different inputs from the coasts or to retention, vertical distribution, sedimentation and processes due to coastal currents (Zeri et al., 2018). As confirmed by several plastic distribution models, the Mediterranean Sea is not uniformly affected by human impacts, which, in combination with the seasonal formation of fronts, eddies and accumulation areas, can influence the presence and distribution of microplastics (Fossi et al., 2017; Liubartseva et al., 2018; Mansui et al., 2015; Ourmieres et al., 2018; Zambianchi et al., 2017). In this respect, the highest concentrations presented in Table 1 seem to correspond to the most critical and affected areas highlighted by these models. Indeed, the Balearic Basin, the Tyrrhenian Basin and the Levantine Basin have been identified as particularly vulnerable areas susceptible to plastic particle accumulation (Baini et al., 2018; Compa et al., 2020; Fossi et al., 2016, 2017; Ruiz-Orejón et al., 2019; van der Hal et al., 2017).

The results of this study show the same trend observed considering all plastic size classes, with the highest concentration found in the central-southern Tyrrhenian Sea (Fig. 2A). Considering the four samples collected in the coastal waters of this area, the average abundance of microplastics increases to 0.193 ± 0.061 items/m^2 (Table SI _1). Despite the lack of information on the presence and distribution of plastics along the coasts of Campania and Calabria, these areas seem to be affected by a moderate accumulation of floating particles, as suggested by the 2018 study by Liubartseva and collaborators. Characterized by local patterns of plastic distribution and limited sea circulation, this coastal stretch seems to be affected by the temporary formation of hot-spot accumulation areas (i.e. Gulf of Naples) and moderate fluxes of stranding beaching particles of 8.2 and 2.6 kg (km day^{-1}), respectively (Liubartseva et al., 2018).

In terms of weight (Fig. 2B), the whole microplastic dataset accounts for a total of 694.87 mg and an average concentration of 0.134 ± 0.084 mg/m^2 (Table SI_1). This value was one to two orders of magnitude lower than the results reported by Collignon et al. (2012) (0.20 mg/m^2), Cózar et al. (2015) (0.42 mg/m^2), Suaria et al. (2016) (0.46 mg/m^2), and Ruiz-Orejón et al. (2016) (0.57 mg/m^2). This difference could be explained considering the extension of the surveys performed. Being large sampling campaigns carried out across the Mediterranean Sea, these studies show an elevated number of items isolated that may reflect in higher weight concentrations of plastic particles. Comparing the data with more focused research, in terms of the area investigated, our results are in line with those found by de Haan et al. (2019) (0.03 ± 0.02 mg/m^2) and Schmidt et al. (2018) (0.06 ± 0.18 mg/m^2) along the Spanish coast and in the Bay of Marseille (France), respectively. Along the Sicilian coast, the average abundance found for microplastic particles was 0.116 ± 0.084 items/m^2 (Table 1). As confirmed by the results obtained for the weight of the particles ranging from 0.010 to 0.164 mg/m^2 (Table 1), the highest concentrations of microplastic were found in the waters of the Gulf of Catania (C) and Gulf of Augusta (B) facing the most densely populated, industrialized and touristic cities such as Syracuse, Catania, and Taormina (PBS4, PSB3, PBS9, and PBS10) (Fig. 2A and B). On the contrary, the lowest values were found in the Gulf of Noto with an average abundance of 0.064 ± 0.025 items/m^2 (PBS1, PBS2, PBS5, and PBS6). This subregion is characterized by the presence of two natural reserves (Cavagrande del Cassibile and Vendicari Natural Reserve) (Table SI_1). Nevertheless, no statistical differences in microplastic concentrations among the four subregions considered were found (Fig. SI_4).

The variability of the data here presented may suggest once again a potential relationship between the presence of plastic particles and the human pressures insisting on this area. Terrestrial inputs as the high touristic activities especially in the summer months and possible gaps in the proper management of waste could have influenced their presence and accumulation. This seems to be confirmed also by the only study carried out in the north of Sicily by Ruiz-Orejón et al. (2016). Showing a decreased average concentration of microplastics moving away from the mainland (0.25 ± 0.27 items/m^2 to 0.05 ± 0.03 items/m^2), it states how high densely cities such as Palermo, can contribute to the release of particles in seaside ecosystems and influence their abundance (Ruiz-Orejón et al., 2016). Moreover, the seasonal variability of the hydrodynamic features of this area, especially near the Strait of Messina, may significantly affect the dispersion of microplastic. During the summer period, this area is interested in superficial currents moving from the Adriatic to the Ionian Sea, penetrating the Gulf of Taranto, and reaching the Strait of Messina and the Southern-Tyrrhenian Sea (Brancato et al., 2001; Iacono et al., 2013; Liubartseva et al., 2018; Pierdomenico et al., 2019). These currents associated with tide variations and the local wind forcing are considered the main factors driving the plastic dispersion within this area and fluxes of beached particles estimated to be 9.6 kg

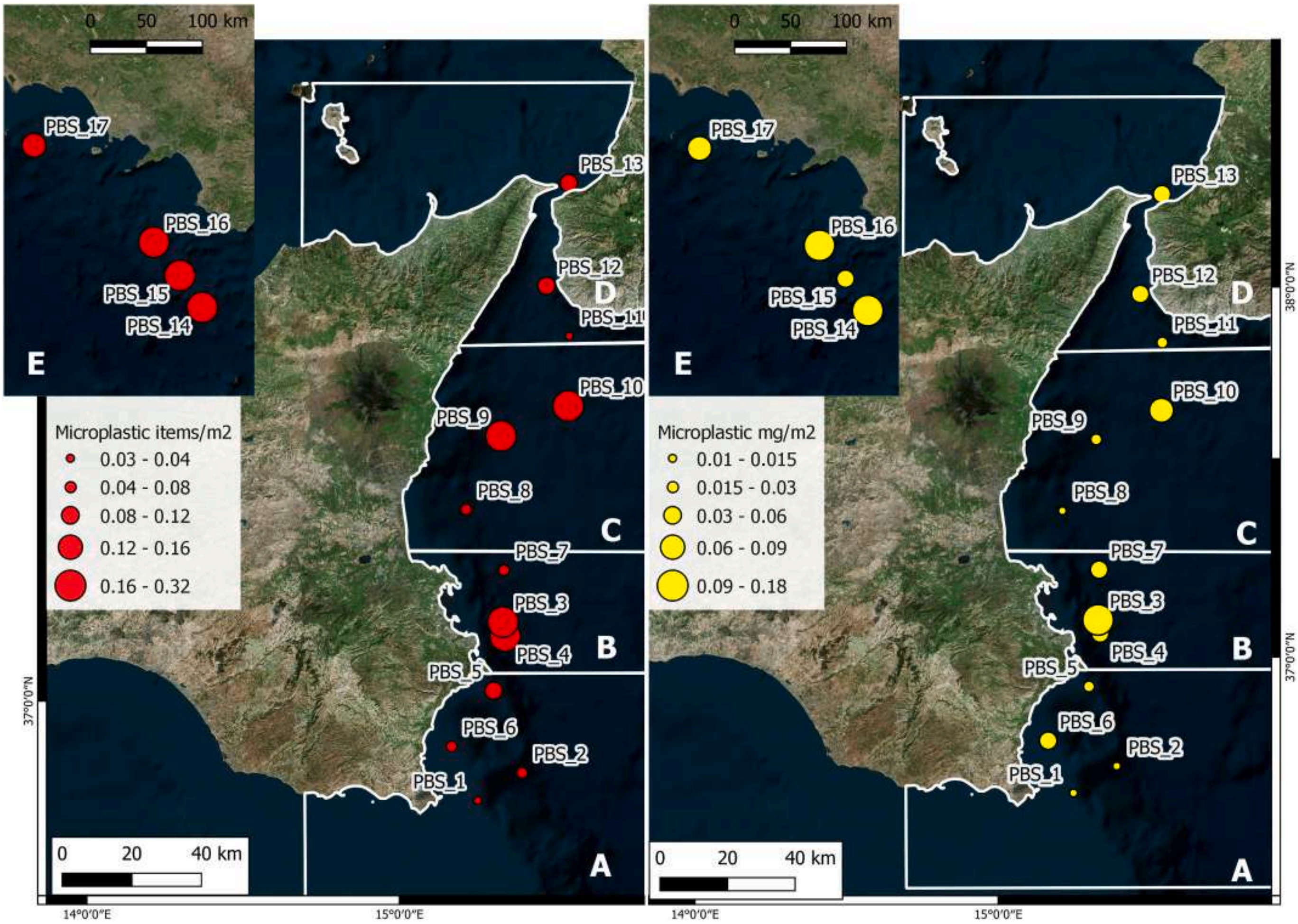

Fig. 2. Microplastic concentrations found in the study area expressed in terms of items/m^2 (A) and weight/m^2 (B).

(km day^{-1}) (Liubartseva et al., 2018).

Focusing on the samples collected near the Strait of Messina (PBS11, PBS12, and PBS13), an average microplastic abundance of 0.076 ± 0.038 items/m^2 was found. This data contributes to enlarging the knowledge about the plastic presence in this unique ecosystem for biodiversity, biocoenosis, and the number of species (Spanò and Domenico, 2017). Large concentrations of plastic debris on the seafloor have been reported in the Sicilian and Calabrian canyons (Consoli et al., 2019; Pierdomenico et al., 2020), showing an average concentration of 5.19 ± 4.63 items/10 m and approximately 4000 litter items observed (Pierdomenico et al., 2019). Fish species collected in this area such as the *Trachinotus ovatus*, *Coryphaena Hippurus*, *Xiphias gladius*, *Thunnus thynnus*, and *Thunnus alalonga* have been affected by the ingestion of microplastic, showing a frequency of occurrence ranging from 12% to 32% (Battaglia et al., 2016; Romeo et al., 2015; Schirinzi et al., 2020).

3.1.2. *Microplastic: size-class, shape, and colour analysis*

The physical properties of microplastics could influence their behaviour and fate in the marine environment (Chubarenko et al., 2016). Accordingly, microplastics isolated were characterized by size classes, shape, and colour following the MSFD TG10 protocol.

The size distribution into the classes considered revealed a high abundance of particles between 1 and 2.5 mm (57%; n = 1252) (Fig. 3a), which is confirmed by the mean length of the pieces: 2.21–1.03 mm. This result is consistent with other studies conducted at the Mediterranean Sea (Baini et al., 2018; Compa et al., 2020; Suaria et al., 2016) and elsewhere (Cózar et al., 2015; Eriksen et al., 2013; Lusher et al., 2014). Only 8% (n = 191) of the total plastic dataset has a dimension smaller than 1 mm in length (Fig. 3.a). The spatial distribution and impacts of this size fraction of plastic particles on marine organisms still represent a challenging issue to be addressed by the scientific community. The hypothesis of their potential loss from the water surface has been widely accepted in the literature for both the Mediterranean Sea (Cózar et al., 2015; Pedrotti et al., 2016; Ruiz-Orejón et al., 2018; Zeri et al., 2018) and ocean basins (Cózar et al., 2015; Eriksen et al., 2013; Hidalgo-Ruz et al., 2012), as well as their presence in a wide range of marine organisms, was reported (Corazzola et al., 2021; Giani et al., 2019; Schirinzi et al., 2020). According to that, since small microplastics occupy the same size fraction of several planktonic organisms, they are potentially bioavailable to a wide range of species through direct ingestion during the feeding activities or indirectly through contaminated prey. Moreover, increasing toxicity to organisms related to size decrease of microplastic has been recently reported by Beiras and Schönemann (2020), highlighting the urgency needed to assess the risk posed by these synthetic particles.

Six shape categories of microplastics have been identified. The majority of particles (79%) were fragments, followed by films (17%) and filaments (2%) (Fig. 3b). The other form classes considered (pellets, microbeads, and foam) have a concentration of less than 2%. The three main categories found here have been reported as the most abundant worldwide (Baini et al., 2018; Cózar et al., 2015; Suaria et al., 2016). No variations in shape distribution patterns were highlighted within the studied areas (Fig. 3b).

Light-coloured plastics, dominated mainly by white, opaque, and transparent items (83%), predominated over dark and cool colour classes, which has been confirmed by previous studies (Palatinus et al.,

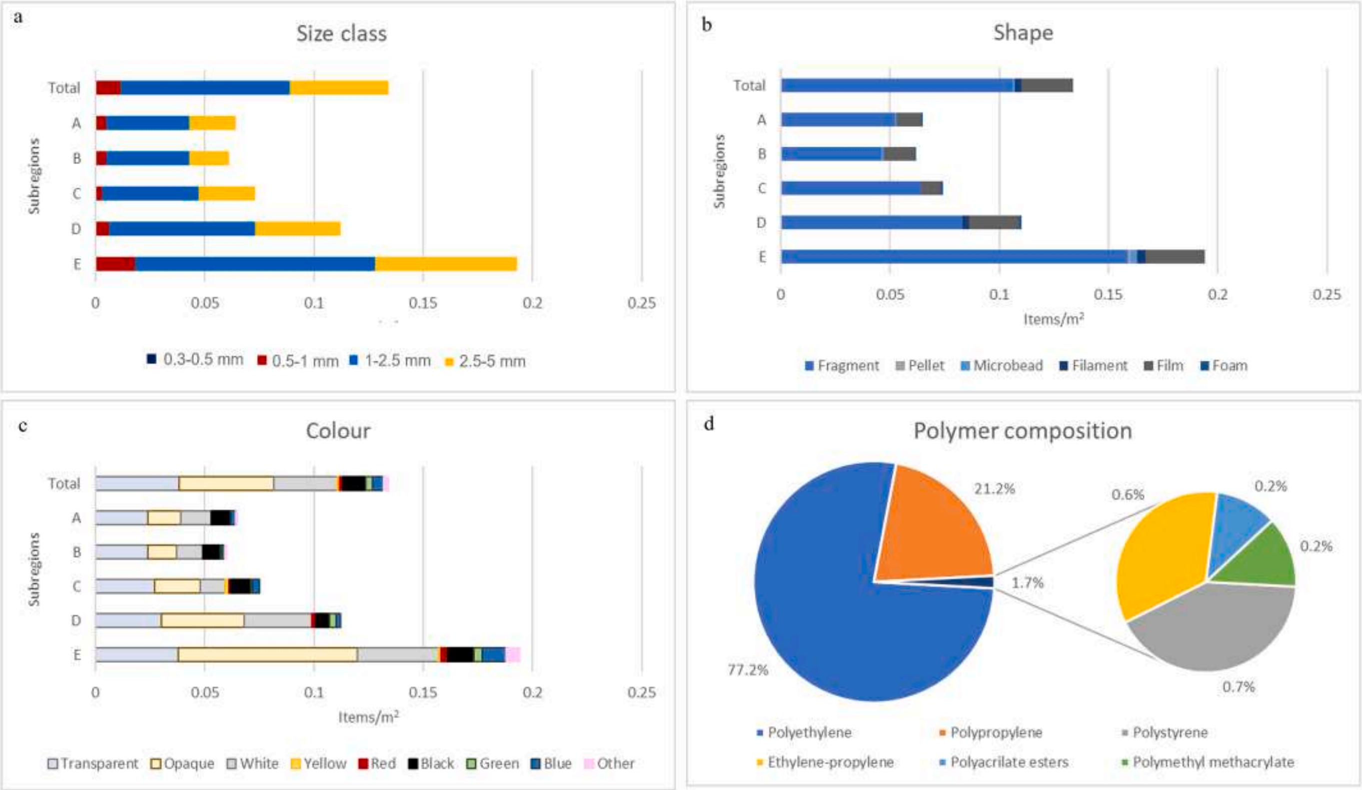

Fig. 3. Microplastic average concentrations according to size-classes (a), shape (b) and colour (c), obtained in each subregion (A: Gulf of Noto, B: Gulf of Augusta, C: Gulf of Catania, D: Strait of Messina, and E: Tyrrhenian Sea) and the whole study area (Total). Polymer composition (d) refers to 20% of all plastic particles isolated in the whole study area.

2019). Studying the shape and colour of plastic particles could help to provide information on the different factors affecting their spatial distribution and possible interaction with marine organisms. Fragments and films have been shown to have greater buoyancy than filaments, resulting in a longer residence time on the sea surface and a higher probability of being sampled (Kooi et al., 2016). Their presence in coastal waters could be due to the possible degradation of meso- and macroplastics, as predicted by the plastic distribution model published by Isobe et al. (2014).

White, transparent, and blue-coloured microplastics, which accounted for 55%, 28%, and 4%, respectively, in this study (Fig. 3c), are reported to be most commonly ingested by marine species (Ory et al., 2017; Schirinzi et al., 2020; Shaw and Day, 1994; Wright et al., 2013). Because they resemble their natural prey, these particles may be mistaken as potential threats. However, to demonstrate a clear impact of microplastic colour patterns on food selection by organisms, further field studies are needed.

3.1.3. Microplastic: polymer analysis

Chemical characterization of plastic particles can be a useful tool to gain a better understanding of their potential sources and input pathways to the marine environment. In this regard, a total of 440 microplastics (20% of the total number isolated) were analysed (Fig. 3d). Polyethylene (PE) and polypropylene (PP) were the most abundant polymers, accounting for 78% and 20% of the total, respectively (Fig. 3d). Despite the low percentage (1%), the polymer polymethyl methacrylate (PMMA) was detected for the first time in Mediterranean waters. It is a clear, colourless hard plastic available in the form of pellets and sheets and is used as a shatterproof substitute for glass (Ali et al., 2015).

Accounting for 37% of global plastic demand (Plastic Europe, 2019), the occurrence of polyolefin thermoplastics in the Mediterranean Sea (Baini et al., 2018; Compa et al., 2020; Suaria et al., 2016; Zeri et al., 2018) and other ocean basins (Cózar et al., 2014; Enders et al., 2015) is well known. Their widespread use in packaging and disposable products, their susceptibility to being easily degraded in the marine environment, and their long residence time in surface waters (density: 0.85 to 0.97 g/mL) as heavy polymers may explain their ubiquitous distribution and higher concentration in the collected samples.

3.2. Biodiversity assessment

3.2.1. Recorded species

In the coastal waters of Eastern Sicily, 380 sightings were recorded during the sampling cruise, distributed among 17 different species: 5 species belong to the order Cetacea and the suborder Odontoceti: *Physeter macrocephalus, Steno bredanensis, Stenella coeruleoalba, Tursiops truncatus, Ziphius cavirostris* and the remaining 12 species belong to different taxa: sea turtles, birds, fish and rays (Table 3).

The presence and distribution of marine megafauna in the nearshore waters of this area are poorly studied and reported. Based on occasional visual and acoustic boat-based surveys (Caruso et al., 2019, 2015; Sciacca et al., 2015), few data are available on the presence and ecology of cetaceans in this area. The striped dolphin was the most frequently sighted species, followed by Cuvier's beaked whales, while there was only one sighting for the other species. Of particular note was the presence of a rough-toothed dolphin, a species considered rare in the Mediterranean (see Caruso et al., 2019 for more details on this sighting). The presence of Cuvier's beaked whales in the area has only been confirmed by strandings (Carlucci et al., 2020; Podestà et al., 2016), while these are the first records of this species in the sea. Sperm whales are known to occur regularly in the area (Caruso and Cosentino, 2014; Caruso et al., 2015; Pavan, 2006; Santoro et al., 2015). The low presence of bottlenose dolphin is due to the limited survey effort in shallower

Table 3
Marine species recorded in the study area.

Common name	Scientific name	N° sightings	N° individuals
Cetacean species			
Striped dolphin	*Stenella coeruleoalba*	56	995 best estimation
Cuvier's beaked whale	*Ziphius cavirostris*	5	19
Sperm whale	*Physeter macrocephalus*	1	1
Rough-toothed dolphin	*Steno bredanensis*	1	1
Bottlenose dolphin	*Tursiops truncatus*	1	1
Sea turtle species			
Loggerhead sea turtle	*Caretta caretta*	38	40
Seabird species			
Scopoli's shearwater	*Calonectris diomedea*	170	369
Yelkouan shearwater	*Puffinus yelkouan*	17	75
European storm petrel	*Hydrobates pelagicus*	12	18
Black tern	*Chlidonias niger*	5	26
Northern gannet	*Morus bassanus*	1	1
Fish and ray species			
Tuna	*Thunnus* sp.	29	schools
Flyingfish	*Exocoetidae fam.*	26	212
Devilfish	*Mobula mobula*	2	2
Stingray	*Dasyatis violacea*	3	3
Swordfish	*Xiphias gladius*	1	1

waters. The presence of these species has already been recorded in the Ionian Sea, but mainly in relation to local studies (Carlucci et al., 2020; Crosti et al., 2017; Pulcini et al., 2014), Ionian Sea region (Bearzi et al., 2005; Lacey and Moscrop, 2007) or acoustic surveys (Sciacca et al., 2015).

As for the other species sighted, both the high ecological value and the intensive primary production have a great influence on their presence and distribution in the study area. Sea turtles, pelagic fish such as tuna. and swordfish are reported to migrate through the Strait of Messina (Bentivegna, 2002; Parenti, 2019). Seabird colonies are particularly present in the southernmost sector of the study area. Characterized by a complex system of lagoons and coastal dunes, it can represent a nesting and feeding site (Ientile et al., 2016).

3.2.2. *Biodiversity indexes*

Species Richness was higher in the southern part of the study area (Fig. 4). More precisely, the southernmost subregions showed the highest value with a total of 15 different species. The gulfs of Augusta and Catania accounted for 11 and 8 different species, respectively, while only 5 different species were recorded in the Strait of Messina. As shown in the maps, species richness varied greatly within sub-regions and generally followed a latitudinal gradient, with southern areas hosting biodiversity hotspots, and a depth gradient, with deeper areas showing the highest values. In particular, nearshore waters at depths greater than 2000 m in the Gulf of Noto and Gulf of Augusta regions showed the highest richness values of the entire study area. The Kruskal–Wallis test confirmed differences between regions (Kruskal–Wallis chi-squared = 47.425, df = 3, p-value = 2.822e−10). The Wilcox test confirmed that all regions were statistically different from each other, except for the Gulf of Noto and the Gulf of August, for which no statistical difference was confirmed (Table SI _2).

The Shannon index takes into account the degree of evenness in species abundances. The maximum diversity that could occur would be found in a situation where all species have equal abundances (Magurran, 2004). Similar to the richness, a general latitudinal and depth gradient can be demonstrated and the highest values are found in the areas mentioned above. Some remote cells with high values are also present in the northern part of the study area (Gulf of Catania and Strait of Messina), coinciding with depths of 1500 m (Fig. 4). As expected, the KW test also confirmed the differences between regions (Kruskal–Wallis chi-squared = 23.973, df = 3, p-value = 2.53e−05), further confirmed by the post hoc analysis (Table SI _3). In this case, the north-south gradient is even more evident, with the Strait of Messina region being different from all other regions, while no difference is highlighted between the border regions (Gulf of Catania is not different from the Gulf of Augusta, but with the southernmost region, while again no difference is seen between Augusta and Noto).

Species Evenness had a maximum value of 1, where individuals were evenly distributed among the observed species. In this case, the cells are scattered throughout the study area. For the cells that consisted of only one species, the result according to Pielou's Evenness formula was not a number, and they are shown hatched, without colour (Fig. 4). Differences between regions were statistically significant (Kruskal–Wallis chi-squared = 29.681, df = 3, p-value = 1.611e−06), showing the same pattern for the Shannon index in pairwise comparisons (Table SI _4).

In summary, the two southernmost regions, the Gulf of Augusta (B) and Gulf of Noto (A), showed no significant difference for all three biodiversity variables tested (Richness, Shannon Index, Evenness). Both areas showed higher values than the northern regions, with the Strait of Messina showing the lowest values. However, it must be stressed that in this region, known to be an important hotspot area, sampling was scarce, so these results should be considered carefully. Cetaceans, such as fin whales, are known to be in this area in spring to feed, while in autumn they regularly cross the strait to migrate across the Mediterranean Sea (Aïssi et al., 2008). For tuna and swordfish, it is a crucial site for spawning and migration, as well as for bird species crossing the Central Mediterranean Sea (Battaglia et al., 2013; Panuccio et al., 2019).

3.2.3. *Sensitive areas*

Only species with a consistent number of sightings (>15), were considered for the creation of sensitivity maps. The general and core distribution areas of Striped dolphin (*Stenella coeruleoalba*), Loggerhead sea turtle (*Caretta caretta*), sea birds (*Calonectris diomedea* and *Puffinus yelkouan*) and pelagic fishes (*Thunnus* spp. and *Exocoetidae* spp.) are shown below (Fig. 5.1–.6).

The general distribution of the striped dolphin is spread in subregions A and B, but the species also occurs in region C and has also been sighted in region D (Fig. 5.1). Two core areas are identified, one at the border of the A and B regions and one in the southernmost part of the A region, in steep slope areas (Fig. 5.1). Although the striped dolphin is the most abundant cetacean in the Mediterranean Sea, it is classified as 'Vulnerable' by the IUCN Red List (Braulik, 2019). This species, typically found in productive open waters beyond the continental shelf, faces potential anthropogenic threats due to increasing human use of coastal and offshore areas within the Mediterranean Sea (Azzolin et al., 2020). Along the Sicilian coast, its presence has been detected mainly between Messina and Catania, in association with the high trophic availability of the area, as a consequence of local upwelling currents (Monaco et al., 2016; Santoro et al., 2015). In particular, the Gulf of Catania (C), characterized by the large fishing fleet, has been found to be the most affected area for stranded striped dolphins, together with the east coast of Sicily, due to the direct interaction with fishing activities (Crosti et al., 2017). Moreover, a strong toxicological burden has been pointed out for this species sampled in the study area (Fossi et al., 2013; Panti et al., 2011). MP Ingestion by the striped dolphin has been recently confirmed by two studies conducted on stranded organisms in Western Mediterranean Sea (Corazzola et al., 2021; Novillo et al., 2020). Like other marine organisms, they can ingest microplastics directly from the water column or via trophic transfer (Fossi et al., 2018; Nelms et al., 2018). Since they feed mainly on cephalopods and mesopelagic fish species such as myctophids (Aznar et al., 2017; Novillo et al., 2020), which have

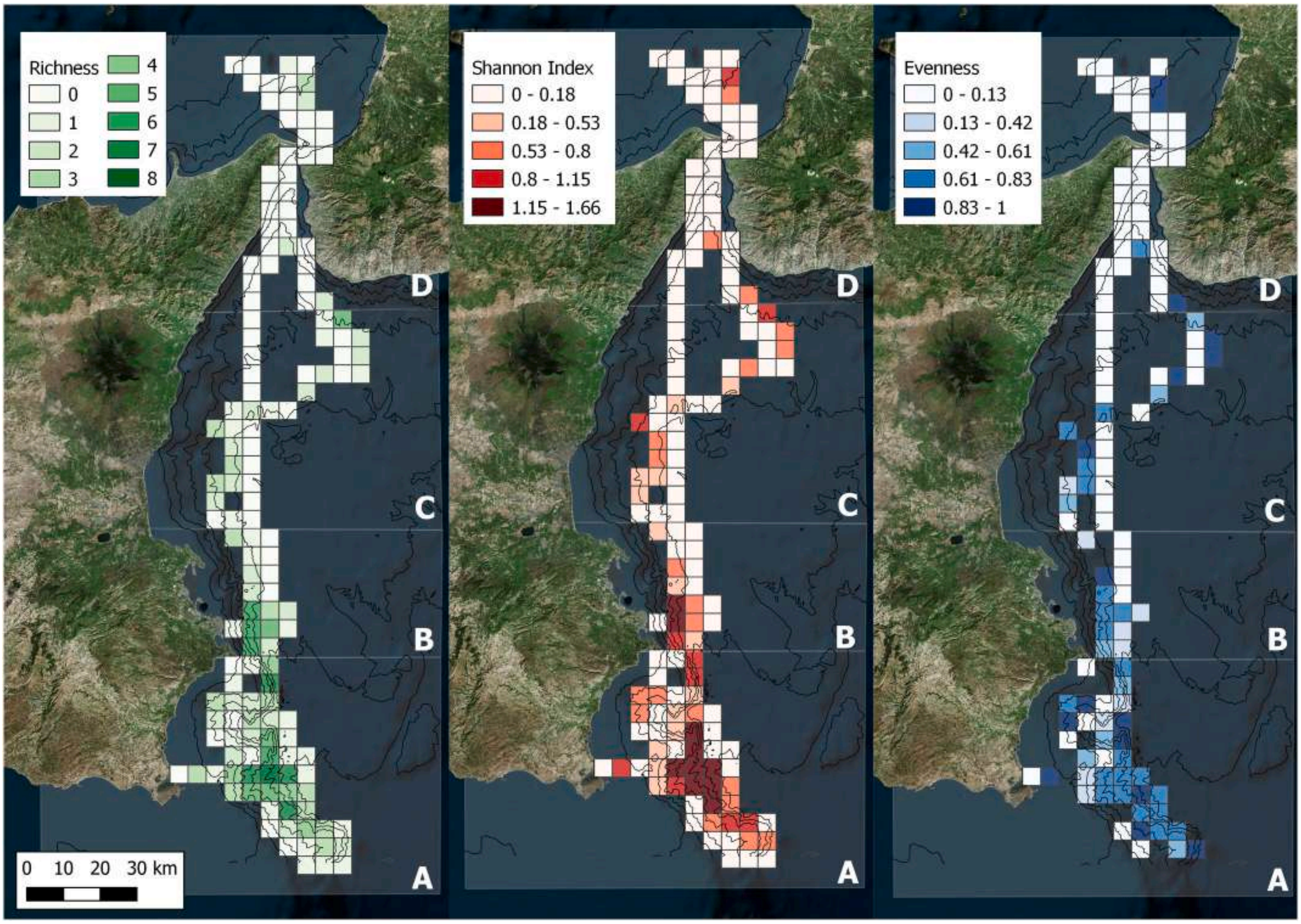

Fig. 4. Spatial distribution of Species Richness, Shannon Index and Species Evenness in the study area using a 5 km grid in the different subregions (A: Gulf of Noto, B: Gulf of Augusta, C: Gulf of Catania, D: Strait of Messina, and E: Tyrrhenian Sea).

been reported to ingest plastic (Pietro Battaglia et al., 2016: Romeo et al., 2016), the striped dolphin and other apex marine predators could help us understand the extent to which microplastics are present in marine organisms and assess whether they pose a threat to the marine food chain (Nelms et al., 2018).

A very similar distribution is observed for the loggerhead sea turtle, where both the general and core distribution almost overlap with that of the striped dolphin (Fig. 5.2). This species, currently classified as “Least concern” by IUCN experts (Mediterranean Sea) (Casale and Tucker, 2017), comes to the eastern sector of this basin and migrates through the Strait of Messina mainly in spring and autumn (Bentivegna, 2002). Due to the intensive fishing and heavy shipping traffic in this area (Pernice, 2013), incidental catch by fishing gear has been widely confirmed in Sicilian waters, especially along the northern and eastern coasts (Arizza et al., 2019; Caracappa et al., 2018; Russo et al., 2003). Regarding shearwaters, the Scopoli’s shearwater is more dispersed throughout the study area, while the Yelkouan shearwater occurs only in regions A and B (Fig. 5.3 and .4). Core areas for the Scopoli’s overlap with those above, while only one core area was identified for the Yelkouan (Fig. 5.3). Very few data is available on the distribution and migration routes of these species along the Sicilian coasts. The Linosa and Malta Islands in the Sicily Channel, host two of the largest colonies of Scopoli’s and Yelkouan Shearwater in the Mediterranean (Baccetti et al., 2009; Cecere et al., 2012; Gatt et al., 2019; Raine et al., 2011, 2009). Because of this, it is reasonable to assume that sighted individuals fledged from breeding colonies to feed in the study area.

Finally, the analysis revealed the presence of tuna and flyingfish in the study area, confirming previous studies that documented pelagic fish spawning and feeding in the eastern Ionian Sea (Battaglia et al., 2013; La Mesa et al., 2005; Parenti, 2019; Zava and Fiorentino, 2010). Although their occurrence was more dispersed than that of other species studied, their general and core distributions nevertheless overlapped with those described above (Fig. 5.5 and .6). The toxicological data available in the literature on Atlantic bluefin tuna in the Strait of Messina also raise concerns about the possible ingestion of plastics through direct and secondary ingestion as a result of predation on mesopelagic fish, as reported by Romeo et al. (2016) and Romeo et al. (2015), as well as about the chemical hazard that may exist in this area (Di Bella et al., 2006; Fossi et al., 2006, 2004, 2002; Licata et al., 2005; Maisano et al., 2016), highlighting once again the potential impact that plastics could have on the marine food chain.

3.3. Spatial risk assessment

The spatial risk assessment was evaluated for each subarea, considering the microplastic density values and the sensitive scores related to the general and core distribution of the most frequently sighted species (Table 4).

The Gulf of Noto (A) hosts the highest biodiversity values and a sensitive map for this area is characterized by the general distribution of 6 species and the core distribution of 6 species. The density of microplastics here is low, but still within the overall values highlighted for the area, both for coastal and nearshore areas. The risk index for this region is 0.7, which can be classified as Medium given the high biodiversity

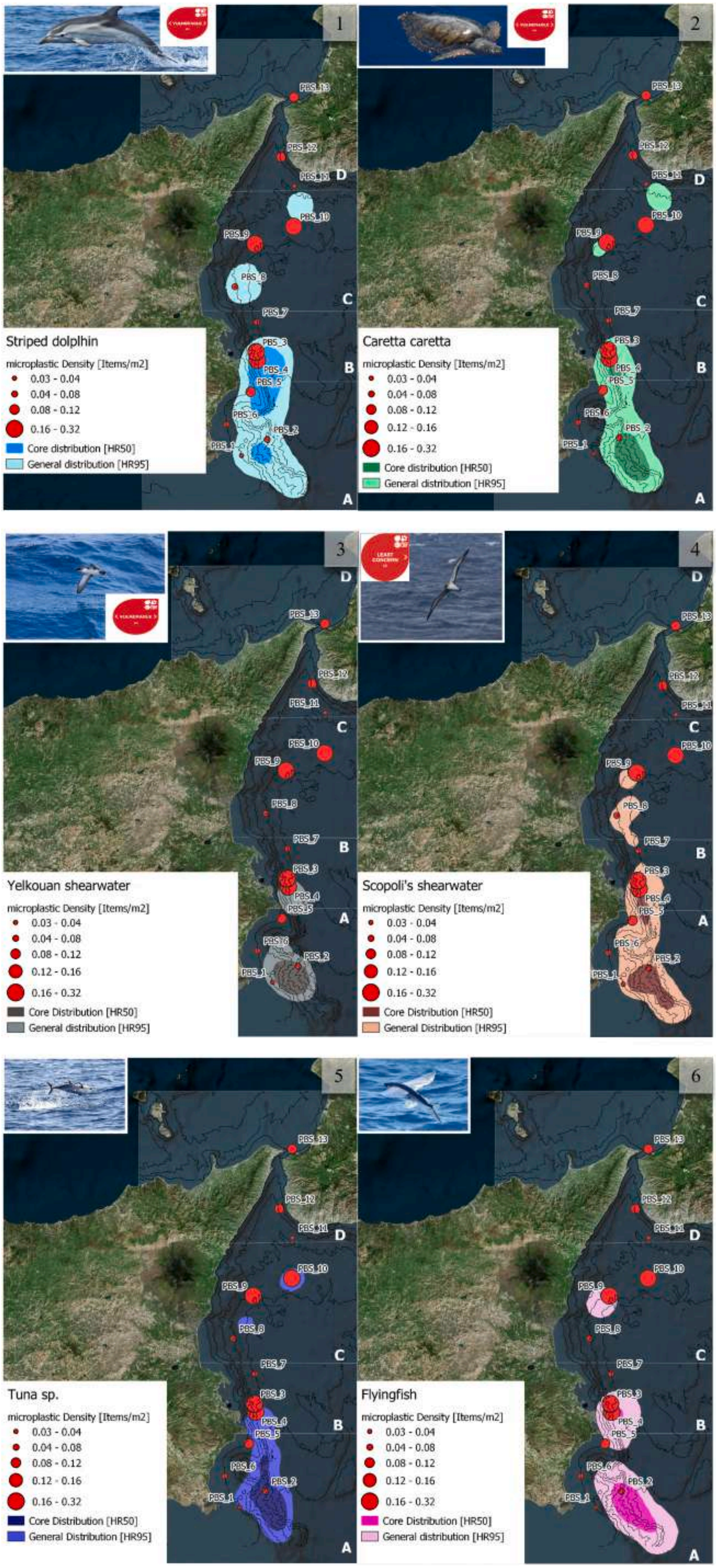

Fig. 5. Sensitivity maps for *Stenella coeruleoalba* (5.1), *Caretta caretta* (5.2), *Puffinus yelkouan* (5.3), *Calonectris diomedea* (5.4), *Thunnus spp* (5.5) and *Exocoetidae* spp. (5.6). General and core distribution areas of the sighted species that overlapped with the density of the sea surface MP in the different sub-regions (A: Gulf of Noto, B: Gulf of Augusta, C: Gulf of Catania, D: Strait of Messina, and E: Tyrrhenian Sea). IUCN conservation status was provided when available (BirdLife International, 2018; Braulik, 2019; Casale and Tucker, 2017).

Table 4

Spatial risk assessment elaboration. Values attributed (ranging from 1 to 3) refer to plastic concentrations (items/m^2), sensitive score 1 and 2 (species general and core distribution, respectively) variables among different subregions (A: Gulf of Noto, B: Gulf of Augusta, C: Gulf of Catania, D: Strait of Messina, and E: Tyrrhenian Sea).

Subregion	Items/ $m^2 \pm$ sd	HS (1–3)	Sensitive score 1	Sensitive score 2	RI
A	0.064 ± 0.025	2	6/6	6/6	0.7 – medium
B	0.197 ± 0.130	3	4/6	6/6	0.8 – high
C	0.143 ± 0.064	2	0/6	5/6	0.3 – medium
D	0.076 ± 0.038	2	0/6	1/6	0.1 – low

value of the area.

Sub-region B shows the highest values for density concentrations of microplastics, especially at the southernmost sampling stations. While low values were recorded at 2000 m depth, the steep slope area facing the Gulf shows high values. As a result, the H-score for this region is high (3). In addition, the sensitivity score 1 was the highest because the general distribution areas of all species considered are present in this region (Table 4). Sensitivity score 2 is also high because core distribution areas of 4 out of the 6 species considered are located here (Table 4). As a result, the risk index is 0.8, which can be defined as high.

Medium values for microplastic density and rather high values for species richness and diversity were found in the Gulf of Catania (C). The presence of cetaceans in this area is well documented and our analysis confirmed that the area is part of the general distribution of cetaceans, sea turtles and pelagic fishes. Sensitive Score 1 was quite high (5), but there is no core area in this region (Sensitive Score 2 = 0) (Table 4). The risk index in this area is 0.3, which can be classified as medium.

The Strait of Messina (D) was characterized by medium-low values of microplastic density. The biodiversity values seem to indicate a low richness of species present. The sensitivity values assessed by our data were low, but this must be weighted with the reduced effort in this area (Table 4). Overall, then, the risk in this area can be considered low.

At the Mediterranean level, few studies have attempted to calculate a risk assessment of plastic pollution on marine biodiversity (Compa et al., 2019; Darmon et al., 2017; Fossi et al., 2017; Soto-Navarro et al., 2021). While the first focused on the likelihood of plastic ingestion by cetaceans and sea turtles living in the North-Western sector of the Mediterranean Sea, the study by Compa et al. (2019) assesses a global risk to multiple species within the entire basin. In this work, the spatial risk assessment is addressed towards specific sub-areas, where an overlap of plastic abundance with core and general areas of umbrella species is highlighted. This method allows for the preliminary risk assessment of areas where little knowledge on the presence and distribution of marine species is described, thus helping in better addressing future research efforts. This is furthermore important when considering the offshore and pelagic habitat, where data on species presence and distribution are usually more difficult to achieve and where usually less conservation effort is dedicated, compared to coastal areas.

4. Conclusions

This paper strengthens knowledge of the threats that plastic debris, and microplastics, can pose to marine ecosystems by assessing, for the first time, their presence, abundance, and potential overlap with biodiversity hot-spots in the Western Ionian Sea and south-central Tyrrhenian Sea.

Unlike recent studies that assess the risk associated with plastic ingestion by marine species using provisional and numerical models, the methodology proposed here represents a first attempt to bring together field and observational data to monitor and define the levels of plastic that could harm organisms, populations, and, ultimately, species exposed to plastic pollution and alter their ecological function and community structure. In particular, top predators such as dolphins, seabirds and large pelagic fishes that are exposed to multiple stressors, including plastic pollution, can serve as reliable wide scale indicators of environmental quality.

The study areas appeared to be a highly sensitive zone, not only because of the uniqueness of their habitats and ecosystems, but also because of the intense anthropogenic pressures and hydrographic and oceanographic features that may contribute to marine and coastal pollution. The preliminary small-scale risk assessment conducted here allowed us to highlight potential areas of concern by quantifying the overlap between marine species biodiversity indices and floating plastic densities. In addition, these preliminary results may serve to inform greater data collection efforts in the identified critical areas to better understand the extent of plastic pollution impacts and to drive the development of effective protection/mitigation measures. However, further research efforts are needed to calculate a comprehensive risk assessment that integrates the spatial assessment conducted here with the other potentially harmful interactions such as chemical contamination and the results of the ecotoxicological analysis due to plastic pollution.

CRediT authorship contribution statement

Matteo Galli performed the microplastic analysis, analysed the data and coordinated the writing, review and editing of the manuscript; Paola Tepsich performed and coordinated the biodiversity and spatial risk assessment, wrote, reviewed and edited the manuscript; Matteo Baini performed the sampling activities, coordinated microplastic analysis, wrote, reviewed and edited the manuscript; Cristina Panti performed the sampling activities, contributed to the analysis of the data, wrote, reviewed and edited the manuscript; Massimiliano Rosso designed the survey, performed the marine species visual survey, obtained funding for the sampling activity, reviewed the manuscript; Ariadni Vafeiadou and Martha Pantelidou performed the biodiversity and spatial risk assessment; Aurélie Moulins contributed to design the survey and reviewed the manuscript; Maria Cristina Fossi conceived the study, participated to the sampling activities, obtained funding and coordinated laboratory analysis, wrote, reviewed and edited the manuscript.

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.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.marpolbul.2022.113550.

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