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Amount, composition, and spatial distribution of floating macro litter along fixed trans-border transects in the Mediterranean basin

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ABSTRACT

Marine litter is a major source of pollution in the Mediterranean basin, but despite legislative requirements, scant information is available for the ongoing assessment of this threat.

Using higher size classes as proxy for litter distribution, this study gave a synoptic estimation of the amount, composition, and distribution of floating macro-litter in the Mediterranean. The average amount of macro-litter was in a range of 2–5 items/km^2, with the highest in the Adriatic basin. Seasonal patterns were present in almost all study areas and were significant in the Ligurian Sea, Sardinian-Balearic basin, and Central Tyrrhenian Sea. Plastic accounted for > 80% of litter in all areas and seasons, with the highest proportion in the Adriatic Sea, Ligurian Sea, and Sicilian-Sardinian Channels; in the Bonifacio Strait, Tyrrhenian Sea, and Sardinian-Balearic basin, litter composition was instead more diverse. Spatial analysis suggested an almost homogeneous distribution of litter without evident regular aggregation zones.

1. Introduction

The term marine litter indicates any solid material which has been manufactured or processed by man and, after its use, has been discarded or disposed and reaches the marine environment (Coe and Rogers, 1997; Galgani et al., 2013a; Veiga et al., 2016). Due to current high plastic consumption patterns, high uses of disposable packaging, consumer behaviour, and illegal dumping into seawater or riversides, the amount of litter in the sea is increasingly becoming an environmental concern.

In the Mediterranean Sea, marine litter is a major threat for living marine organisms. The Mediterranean basin is one of the world's biodiversity hotspots, but it is also one of the most polluted seas worldwide (Barnes et al., 2009; Deudero and Alomar, 2015; Jambeck et al., 2015). Worldwide, over 390 species have been reported ingesting or becoming entangled in debris, such as plastic, monofilament lines, rubber, and aluminium foil (Laist, 1997; Derraik, 2002; Gall and Thompson, 2015). For the marine animals involved, this can lead to the impairment of movements and/or feeding with rebounds on reproductive output, and/or it can cause lacerations, ulcers, and death (Camedda et al., 2014; de Lucia et al., 2014; Derraik, 2002; Laist, 1997). Fishes (Boerger et al., 2010; Davison and Asch, 2011), birds (Ryan, 2008; Van Franeker and Law, 2015), cetaceans (De Stephanis et al., 2013; Gomerčić et al., 2006; Levy et al., 2009; Mazzariol et al., 2011), and marine turtles (Camedda et al., 2014; Campani et al., 2013; Lazar and Gracan, 2011; Matiddi et al., 2017; Schuyler et al., 2014; Tomás et al., 2002) are particularly affected, since it is common to find accidentally-swallowed plastic debris in their digestive tracts. In addition, large floating objects can act as a vector for spreading or introducing pest/alien species in new areas (Barnes, 2002; Aliani and Molcard, 2003; Rech et al., 2016).

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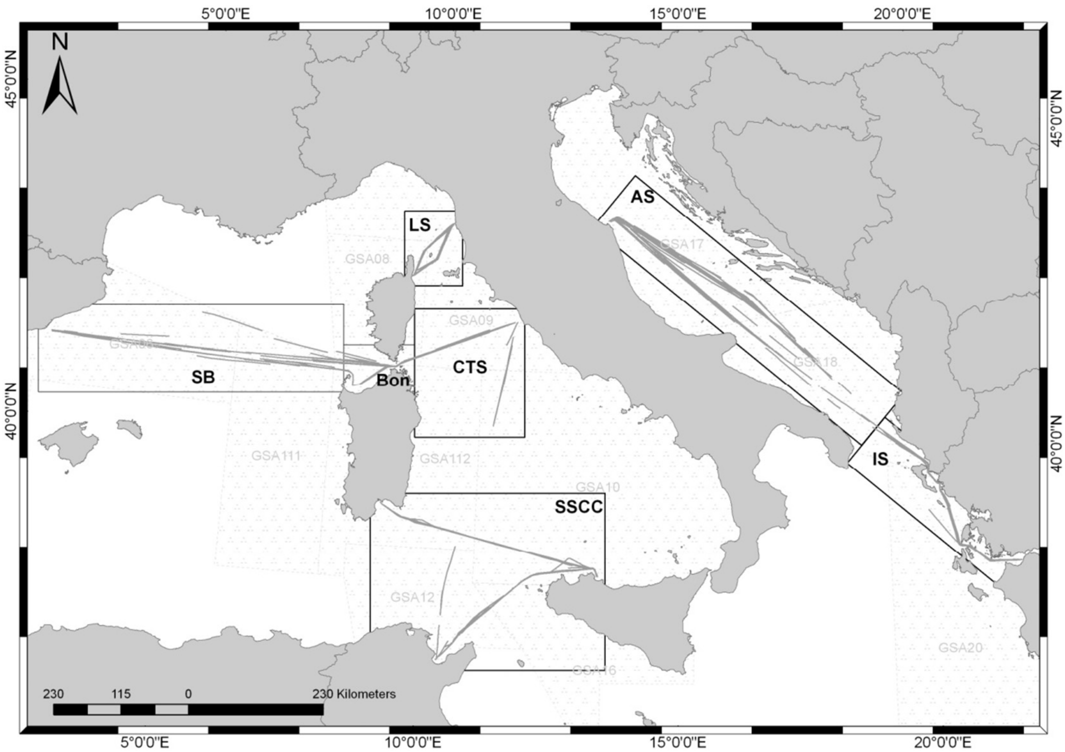

Fig. 1. The Mediterranean Sea basin with the monitored transects (grey lines) included in the seven areas of the study (LS: Ligurian Sea; SB: Sardinian-Balearic basin; Bon: Bonifacio Strait; CTS: Central Tyrrhenian Sea; SSCC: Sicilian-Sardinian Channels; AS: Adriatic Sea; IS: Ionian Sea) within the three MSFD marine subregions: the Western Mediterranean Sea, the Adriatic Sea, the Ionian and Central Mediterranean Sea.

Therefore, marine litter has a significant environmental impact (Galgani et al., 2013a) in spoiling marine ecosystem services, and it can consequently damage all the industries based on the use of marine resources. It also has an important social and economic impact by reducing the aesthetic value of the environment and public use, subsequently creating a reduction in the value of the land, tourism, and the local economy (Barnes et al., 2009; Derraik, 2002; Deudero and Alomar, 2015; Gregory, 2009; Judd et al., 2015).

The role of marine litter in impairing marine life is now widely recognized and regulated by both national and international protocols (e.g. Annex V - MARPOL Convection; Marine Litter Regional Plan - UNEP/MAP Barcelona Convention; Packaging Directive 94/62/EC and successive amending; Plastic carrier bags Directive 2015/720/UE and amending 94/62/EC). In particular in the Habitats Directive, marine litter is considered a main anthropogenic threat (code for pressure/threats H03.03) for many of the marine species listed in the Directive, and the six year report on the conservation status must also include an assessment on pressures (Crosti et al., 2017). The Marine Strategy Framework Directive (MSFD, 2008/56/EC) asks for the good environmental status (GES) of marine waters so that the properties and quantities of marine litter do not cause harm to the coastal and marine environment (descriptor 10); among the others criteria used to assess the achievement of the GES is the evaluation of trends in the amount of floating litter at the surface, including an analysis of its composition, spatial distribution, and where possible, source. All these International agreements, but in particular EU Directives, call on measures for waste reduction, and some of them are, or will soon be, enforced into State legislation (i.e. Italy with specific measures for biodegradable and compostable plastic carrier bags or France with the ban on disposable plastic tableware). As a main consequence, large scale consistent monitoring programs are essential for implementing efficient measures for the ongoing assessment of the environmental status and trends and to support decision-making processes (Cheshire et al., 2009; Galgani et al., 2013a; Ryan et al., 2009). The Monitoring programs are also crucial in increasing our understanding of the multi-level effects of "marine litter" in Mediterranean waters; recently indeed, within the "Integrated Monitoring and Assessment Programme", monitoring programs were shared among the contracting parties of the Barcelona Convection in the context of the Ecosystem Approach (EcAp) and among the EU State members in the context of the MSFD. However, scant information is available from monitoring programs designed to census marine litter and its relationship with the main affected taxa.

Macro litter floating at the surface is considered a pertinent indicator for marine litter monitoring (Di-Méglio and Campana, 2017; Thiel et al., 2003). Floating macro litter is completely included in the marine compartment, and the "timeliness" of this indicator (JRC, 2008) is the shortest since litter only successively submerges and sinks to the sea bottom, is washed ashore, or is fragmented in micro particles. Consequently, even if the mean residence times of litter on the sea surface is still poorly known, floating macro litter at the surface can give indications about what has been more recently discarded from land or sea, the main sources and sinks, and the effects of waste prevention measures (Thiel et al., 2013; Veiga et al., 2016). Since it is responsible for direct harm to marine species, monitoring macro litter can also help identify risky areas and seasons to design appropriate mitigation measures (e.g. Arcangeli et al., 2015; Di-Méglio and Campana, 2017).

Nevertheless, monitoring floating litter is challenging, since the main fraction of litter is often widespread in off-shore areas that are difficult to reach and are presumably subjected to seasonal distributional patterns due to ocean dynamics. The occurrence of floating macro litter has already been investigated around the world using boats or large observation platforms (e.g. Aliani et al., 2003; Day and Shaw, 1987; Di-Méglio and Campana, 2017; Hinojosa and Thiel, 2009; Matsumura and Nasu, 1997; Pyle et al., 2008; Shiomoto and Kameda, 2005; Suaria and Aliani, 2014; Thiel et al., 2003; UNEP-MAP, 2011; Vlachogianni et al., 2016). However, monitoring programs in off shore areas are generally expensive and difficult to run, especially further from summertime. The different approaches adopted to sample the information generates inconsistent results, reducing the ability to geographically compare the outcome and to correctly investigate temporal patterns, ultimately preventing the design of reliable cross-country mitigation measures (Cheshire et al., 2009; Galgani et al., 2013b; Ryan, 2013). Here we investigated the amount of floating macro litter through a large year-round monitoring program within different Mediterranean sub-regions. In doing so, we designed a study with five trans-boundary fixed transects distributed in seven study areas (three MSFD subregions; Fig. 1) where we regularly carried out surveys during all seasons with the same research protocol (ISPRA, 2013). Offshore areas focusing on the main shipping lanes and crossing the major currents and fishery areas were regularly surveyed (Cheshire et al., 2009; Zampoukas et al., 2014). Passenger ferries were used as platform of research for systematic monitoring with a cost-effective regular collection of a large amount of data. The length of the routes and the large number of replicated surveys allowed us to obtain an extensive amount of samples adequate to average out the inherently patchy distribution of floating litter (Ryan, 2013; Ryan et al., 2009; Zampoukas et al., 2014), take into account regional differences and increase the accuracy of the estimates (Cheshire et al., 2009; Galgani et al., 2013b). Thus, the main aim of the present study was to monitor the larger size classes of floating macro litter -above 20 cm- (or mega litter according to Barnes et al., 2009) as a proxy of the macro litter distribution and investigating: i) seasonal trends of macro-litter amount, ii) the qualitative composition, and finally iii) the spatial distribution. Moreover, to assess whether the accumulation of litter items was due to oceanographic factors or to the proximity of sources (such as rivers or discharge areas), a comparison between litter and natural marine debris (natural objects, such as terrestrial and seaweed/marine plants) was investigated to highlight seasonal/spatial differences between the two.

2. Materials and methods

2.1. Study area

Floating macro-litter monitoring was undertaken along five fixed transects connecting Italy to France, Spain, Greece, and Tunisia: Livorno-Bastia; Civitavecchia-Barcelona; Cagliari-Trapani; Ancona-Patras; Palermo-Tunis-Civitavecchia (Fig. 1). The surveyed transects were aggregated into 7 study areas that were almost homogeneous for the oceanographic factors within them, roughly coinciding with the partial overlap of the FAO Mediterranean geographical subareas (Resolution GFCM/31/2007/2), and corresponding to: the south east part of Ligurian Sea (LS), Sardinian Balearic basin (SB), Bonifacio Strait (Bon), Central Tyrrhenian Sea (CTS), Sicilian Sardinian Channels (SSCC), Adriatic Sea (AS), and Ionian Sea (IS). The surveyed area encompasses a large portion of the Mediterranean Sea and falls within three MSFD marine subregions: the Western Mediterranean Sea, the Adriatic Sea, the Ionian and Central Mediterranean Sea.

2.2. Data collection

An initial protocol was set up based on the guidelines completed by the technical subgroup of MSFD (Galgani et al., 2013b; Zampoukas et al., 2014) and a large literature search (e.g. Matsumura and Nasu, 1997; Pyle et al., 2008; Hinojosa et al., 2011; Hinojosa and Thiel, 2009; Shiomoto and Kameda, 2005; Thiel et al., 2003) in order for it to be simple and effectively used by any large research vessels and, for the purpose of this study, applied from ferries. After a testing phase of six months during 2013 (Luperini et al., 2013), a detailed protocol was applied along the 5 fixed trans-border transects. The sampled transects were chosen in order to cover large high sea areas in the Mediterranean basin and cross areas with expected different densities of litter. The use of ferries as research platforms allowed cost-effective repeated sampling from the same transect during all seasons (Zampoukas et al., 2014) (winter: January–March; spring: April–June; summer: July–September; autumn: October–December).

In this study, we show results from a 3-year survey's program (from October 2013 to September 2016) performed by dedicated and trained observers in standard effort conditions. Surveys were performed by the side of the navigation bridge (17–25 m high) with best visibility and in the vicinity of the bow in order to avoid the turbulence generated by the bow itself. The equipment consisted of: binoculars, GPS, range finder, digital camera, and recording data sheet. A dedicated handheld GPS was used for automatically recording the survey tracks at the finest resolution, marking the beginning/ending points and locations of floating objects. The observation was made by naked eye, and the binocular was used to confirm, when in doubt, the types of items. Only items bigger than 20 cm (longest dimension) were recorded. This size limit was chosen after the initial calibration during the testing phase. It comprises several common litter items (i.e. plastic drink bottles, gloves, shopping bags, tableware) and, most importantly, was the size that undoubtedly could be seen from the mean height of a ferry within the detection strip. Monitoring was carried out only in optimum weather conditions (≤ 2 of the Beaufort scale), in a range of speed 19–25 knots, and with a mean duration of 1.5 h to avoid fatigue of the observer. A fixed strip width (Thiel et al., 2003; Pyle et al., 2008; Topcu et al., 2010) was defined at the beginning of the effort, from 25 m up to a maximum of 100 m (Shiomoto and Kameda, 2005) depending on sea state, glare, and speed, requiring that all items > 20 cm were surely sighted. The strip was estimated using a range finder and was regularly checked during the effort. The identification of a predetermined strip width and size classes was chosen as a best method given the spatial scale of the study, to simplify the data collection in order to reduce the risk of missing items and to concentrate on object characterization; density data were normalized taking into account the strip width (see Data analysis section).

Identification and categorization of items was organized by material (Artificial polymer material, Glass, Processed wood, Metal, Textile, Paper, Rubber, Natural debris) and general names, according to the MSFD master list (Galgani et al., 2013b). While not used in this present study for each item, source (land, sea, undefined) and buoyancy (positive, negative, neutral) were also recorded; details about the production sector, color, and object state (entire, fragment) were recorded when possible.

2.3. Data analysis

2.3.1. Amount

Litter data were entered into the Geographic Information System (ArcGIS 2.1) and the surveyed transects were aggregated in the 7 study areas (Fig. 1). Within each area, the length and width of the surveyed transects, and the number of items of litter and natural fractions recorded were associated with each portion of the surveyed transects that fell into the corresponding area. Each survey transect within each area was used as a statistic unit. The amount of marine litter and natural debris were measured as density (Matsumura and Nasu, 1997; Shiomoto and Kameda, 2005; Thiel et al., 2003) and calculated as: $D = n / (w \times L)$ with n = number of items observed, w = width of the strip, and L = length of the surveyed transect (km). Density was calculated by pooling data from the three years together *per* each area and *per* season. Statistical differences were studied using the non-parametric Kruskall-Wallis test (KW) with the Bonferroni correction and the post-hoc pair-wise comparison of Mann-Whitney *U* test (MW) to test the hypothesis of equal medians among samples. A preliminary analysis on yearly trends, even if only for the 3 years of the study, was carried out for each area. Statistical analyses were performed with the software Past 2.17 (Hammer et al., 2001).

2.3.2. Composition

Composition, expressed as a percentage contribution of each category, was first analyzed to explore the relationship between litter and natural debris portions within areas and seasons, and then as a proportion of the seven litter materials (artificial polymer materials, glass, processed wood, metal, textile, paper, rubber) to the whole composition of litter. The densities of the seven litter materials were assessed for each area and for the entire region *per* season. Additionally, the five most common items were identified for each area.

2.3.3. Distribution

To analyze the spatial distribution of litter and natural debris densities, the study area was divided into a 5 × 5 km grid cell (enclosing the ship route variability) and exclusively the cells crossed by at least one trackline of effort were selected from the entire grid. Using the spatial tools in ArcGIS, a buffer was built around each surveyed track corresponding to the value of the transect width. The buffered tracks were associated within the intersected cell and pooled (using the *Dissolve* tool) together. The total surveyed area, the number of litter and natural items recorded, and the density values of litter and natural debris were then calculated *per* each cell.

The records of litter and natural items were initially tested separately to highlight whether data showed random patterns or clusters of accumulation using the *Average Nearest Neighbour* and the *Morans I* index with the spatial analysis tools in ArcGIS 10.1. The kernel density estimation was then performed based on the density value per cell: the isopleths corresponding to 90% of the total values of the entire region were obtained to highlight areas of litter and natural items accumulation. Then, the density values *per* cell were used to investigate locations of statistically significant hot spots of accumulation (or cold spots) using the Getis-Ord Gi* analysis (Getis and Ord, 1992). The Gi* analysis produces Z scores and *P*-values: a high Z score and small p-value indicate a significant hot spot, while a low negative Z score and small P-value indicate a significant cold spot. Accumulation areas were thus considered as areas where cells with high density values were spatially clustered. For this study, only the highest (or lowest) Z score values (> 2.58 or < -2.58 Std. Dev.) were used for displaying the more intense clusters.

3. Results

3.1. Amount

In nearly 30.000 km surveyed, covering an area of 2725 km^2, a total of 7746 items were recorded with 88% composed by anthropogenic litter and 12% by natural objects. Table 1 reports the effort *per* each study area and the total amount of recorded litter and natural debris items. The highest density of litter, averaged *per* each study area, was recorded in the Adriatic Sea (Table 1) with nearly 5 items recorded per km^2 and was statistically different from all the other areas (MW, $p < 0.01$ paired compared), except the Sicilian-Sardinian Channels. The differences among and between litter densities in the other areas were not significant ($p > 0.05$), whereas means between 1.8 and 2.8 per km^2 were recorded. The natural debris fraction was in general lower than litter with maximum densities recorded in the Ionian Sea (23% of the total recorded items) and minimums in the Sicilian-Sardinian Channels (3%).

Looking at seasonal data (Fig. 2), in the Adriatic Sea the highest values of litter density were recorded in all seasons compared to the other areas, with a maximum in winter. No seasonal significant differences were documented in the Ionian Sea and the Bonifacio Strait.

Differences were instead significant in the: Ligurian Sea (KW, $p < 0.01$) with higher densities recorded in spring and summer, with spring significantly higher than winter and autumn (MW, $p < 0.01$); Sardinian-Balearic basin (KW, $p < 0.01$) with maximums in spring and summer with summer significantly higher than winter (MW, $p < 0.05$); Central Tyrrhenian Sea (KW, $p < 0.05$), with maximum density values in spring significantly different from winter (MW, $p < 0.05$).

The natural debris fraction (Fig. 3) ranged from the minimum of 0.02 items/km^2 during summer in the Sicilian-Sardinian Channels up to a maximum of 1.11 items/km^2 during winter in the Ligurian Sea.

The density of litter and natural debris fraction displayed opposite trends in the Ligurian Sea and Sicilian-Sardinian Channels, while similar patterns were observed, even with some differences, in the other areas with maximums generally recorded during spring and summer (Figs. 2 and 3). No significant evidence of yearly trends was found in the investigated areas.

3.2. Composition

The artificial polymer materials were the most abundant litter fraction recorded (90% for the entire region), ranging from 82% in the Bonifacio Strait up to 97% in the Ligurian Sea. The other relevant components of the litter were paper (6%) and processed wood (2%), while metal, textile, glass, and rubber accounted for a smaller portion of records in all areas ($< 1\%$) (Fig. 4).

In almost all the areas, plastic bags, plastic sheets, plastic bottles, and polystyrene objects were listed in the five most common items, representing 50–70% of all records. Only in the Sicilian-Sardinian Channels, the category “tableware” was found within the five most common items, while “paper bag” was in the top five in the Bonifacio Strait and Sardinian-Balearic areas.

Seasonally for the entire study area, artificial polymer materials were again the dominant litter category and always represented approximately 90% of all items with a maximum contribution in summer (Fig. 5). Conversely, the highest percentage in total composition reached by paper ($> 6\%$) and processed wood ($> 2.5\%$) occurred in autumn and winter. The other categories accounted, even seasonally, only for a smaller portion of records ($< 1\%$).

3.3. Distribution

Litter items were detected along all the surveyed transects (Fig. 6). Higher densities of litter were recorded in the Adriatic Sea than in other

Table 1
Survey effort data: transect lengths and area surveyed within each area of the study, total number, and density values of anthropogenic and natural items recorded.

	Total survey length km	Total surveyed area km^2	Average transect length km	Litter items N	Density of litter N/km^2	Natural items N	Density of natural debris N/km^2
Adriatic Sea (AS)	6733	661	570	2679	4.7 ± 0.5	225	0.35 ± 0.06
Ionian Sea (IS)	4565	400	170	686	1.9 ± 0.2	205	0.48 ± 0.13
Ligurian Sea (LS)	3724	346	357	701	1.8 ± 0.2	150	0.60 ± 0.1
Sardinian-Balearic basin (SB)	5098	473	498	1162	2.5 ± 0.3	153	0.33 ± 0.06
Bonifacio Strait (Bon)	2303	216	219	441	2.4 ± 0.4	74	0.55 ± 0.17
Central Tyrrhenian Sea (CTS)	2488	233	760	428	2.1 ± 0.4	83	0.46 ± 0.14
Sicilian-Sardinian Ch. (SSCC)	4500	396	150	735	2.8 ± 0.5	24	0.12 ± 0.06

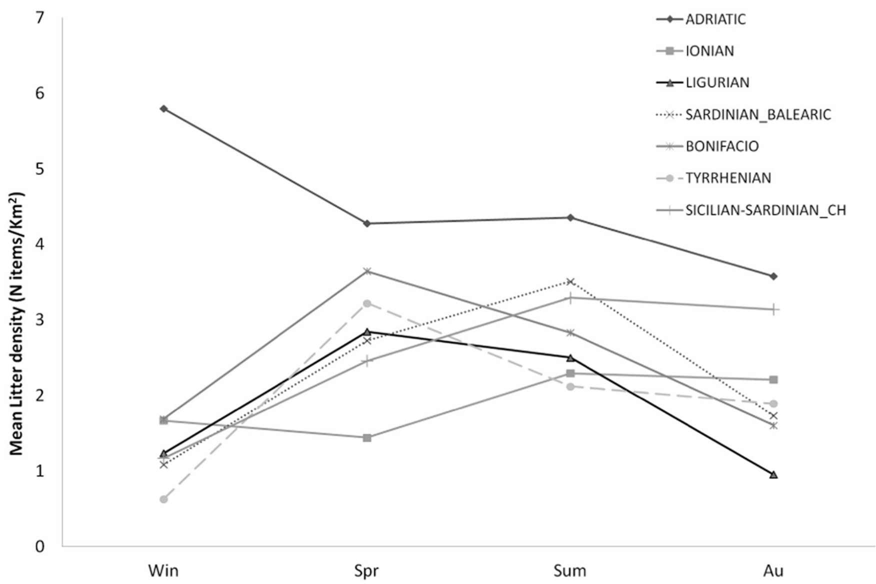

Fig. 2. Seasonal trends in litter density (number of items observed on the surveyed area) recorded in the seven areas of the study.

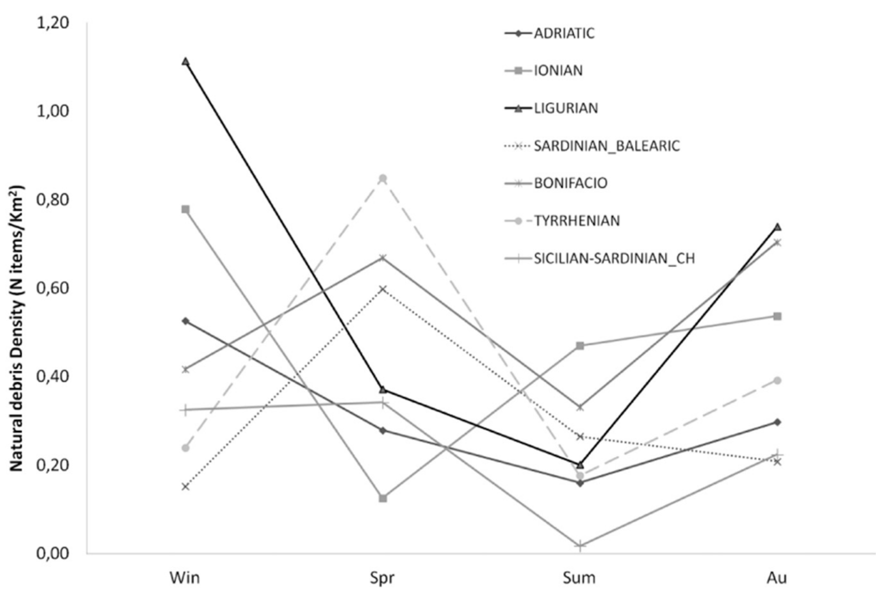

Fig. 3. Seasonal trends in natural debris density (number of items observed in the surveyed area) recorded in the seven areas of the study.

basins where the kernel analysis identified main concentration areas of litter (Fig. 8), most of which coincided with significant clusters of litter aggregation identified by the Getis-Ord G* analysis (> 2.58 SD., grey cells in Fig. 7). Other areas of aggregation were found again coinciding with significant G* hot spots in: the Central Tyrrhenian Sea close to the coast of Latium (nearby the Tiber river mouth), in proximity to the Bonifacio Strait, in the Sardinian-Balearic basin west of the Bonifacio Strait, and east of the Spanish continental shelf. A significant cluster was also found close to the Tunisian coast in the Sicilian-Sardinian Channels (Fig. 7).

Natural items accumulated almost in the same spots of litter in the Adriatic Sea but not in the other areas (Fig. 7). The large concentration

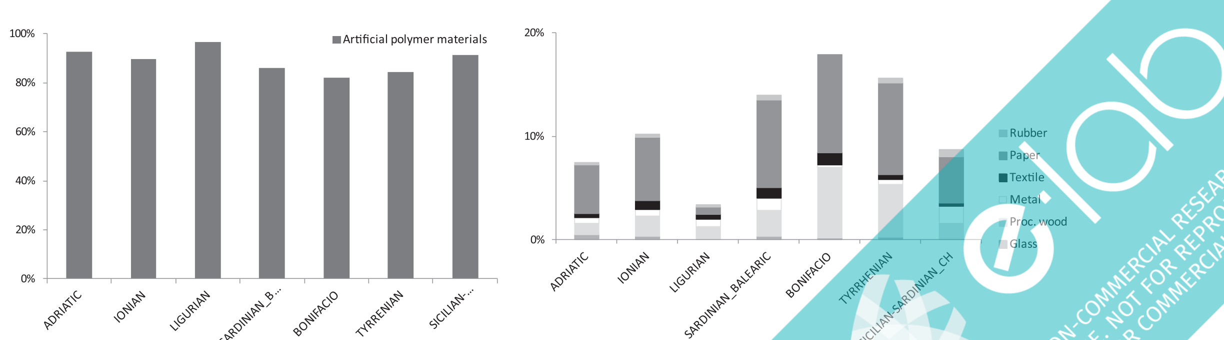

Fig. 4. Composition of litter in the seven areas of the study. Left: percentage of the artificial polymer materials. Right: percentages of the other litter materials.

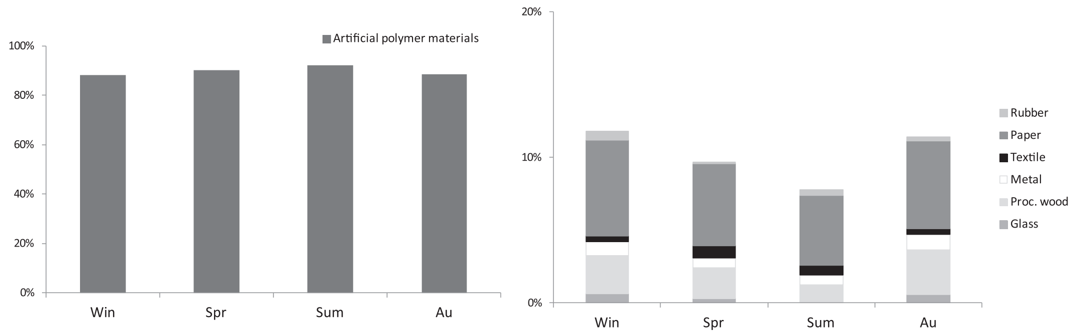

Fig. 5. Seasonal composition of litter for the entire study area. Left: percentages of the artificial polymer materials. Right: percentages of the other litter materials.

of natural debris materials was indeed found mainly in the southernmost part of the Adriatic Sea, the Ionian Sea, the western part of the Bonifacio Strait, and in the Asinara Gulf.

4. Discussion

Using floating macro-litter as a proxy of litter distribution, this study gave a synoptic estimation of the amount, composition, and distribution of floating macro-litter in different areas of the Mediterranean basin, providing interesting insights about seasonal and regional distributional variability. The combination of multiple source inputs and the variable transportation of floating objects by winds and currents results in a large spatial and temporal variability in litter amounts and, to date, differences in sampling areas and techniques made comparisons among studies very challenging (Cheshire et al., 2009; Ryan, 2013). The large effort and the well-defined sampling of this study was able to intercept these changes, so it can be considered a first attempt for a large-scale monitoring program through the application of a robust shared protocol.

The average amount of macro-litter (measured as density: number of items per km^2) found in the different areas of our study was in a range of 2–5 items/km^2. Several studies have investigated the amount of marine litter in the Mediterranean Region using ships as platforms of observation; in many cases, the short time in the survey effort was the main obstacle in intercepting the high variability in litter loads, while discrepancies of the density values obtained was often due to differences in survey methodologies (Ryan, 2013). For example in his early study, Morris (1980) found a density of 2000 objects/km^2 in the Southern Mediterranean Sea, while later McCoy (1988) reported a density of 0.12 objects of "megalitter" (> 50 cm) per km^2 in offshore waters of the Eastern basin. Aliani et al. (2003) found an estimated density of "large debris" in the range of 15–25 objects/km^2 in the Ligurian Sea in 1997, but in the successive surveys in 2000 a lower density was estimated (1.5–3 objects/km^2). Differences between the two survey periods were attributed to different sampling protocols, oceanographic conditions, and litter inputs. In 2008, a maritime campaign of HELMEPA members spread along several routes in the Mediterranean Sea found a density of 2.1 of "selected litter" items/km^2, with higher concentrations close to coastal areas (UNEP-MAP, 2011). Recently, Suaria and Aliani (2014) found a mean total density of 24.9 items/km^2 ranging from 0 to 194.6 items/km^2 from their large scale survey in the Mediterranean basin. Our results are in line with the lower density values of macro litter reported in these studies (e.g. Aliani et al., 2003; Topcu et al., 2010; UNEP-MAP, 2011).

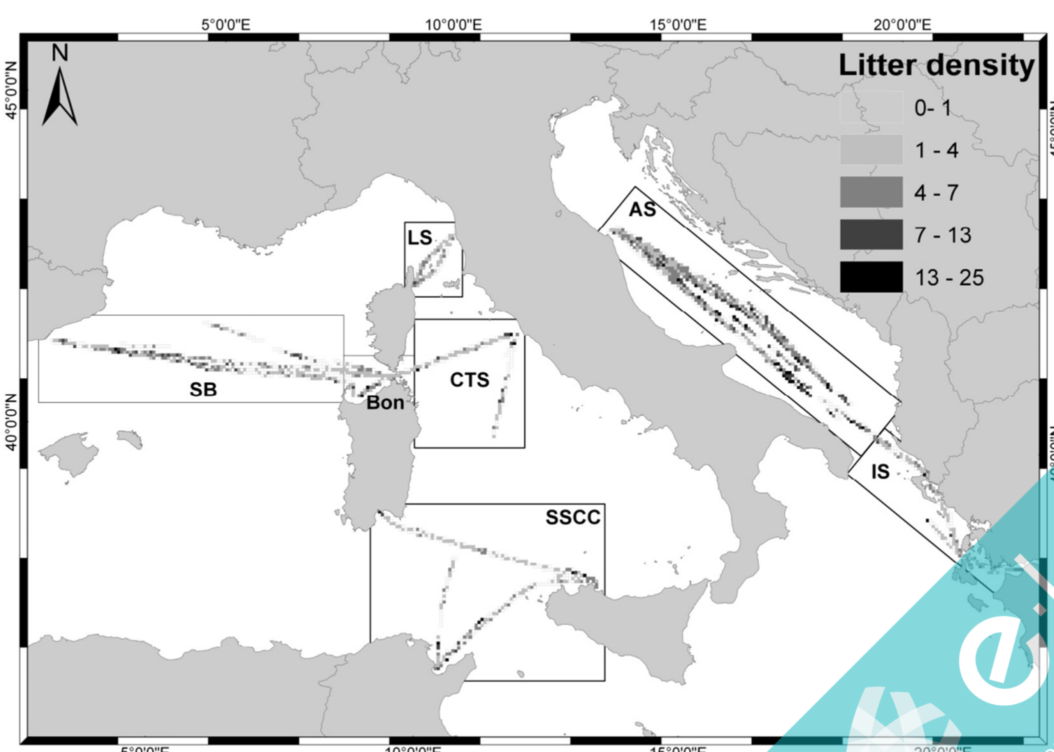

Fig. 6. Density of litter calculated per cell of 5 × 5 km in the seven areas of the study.

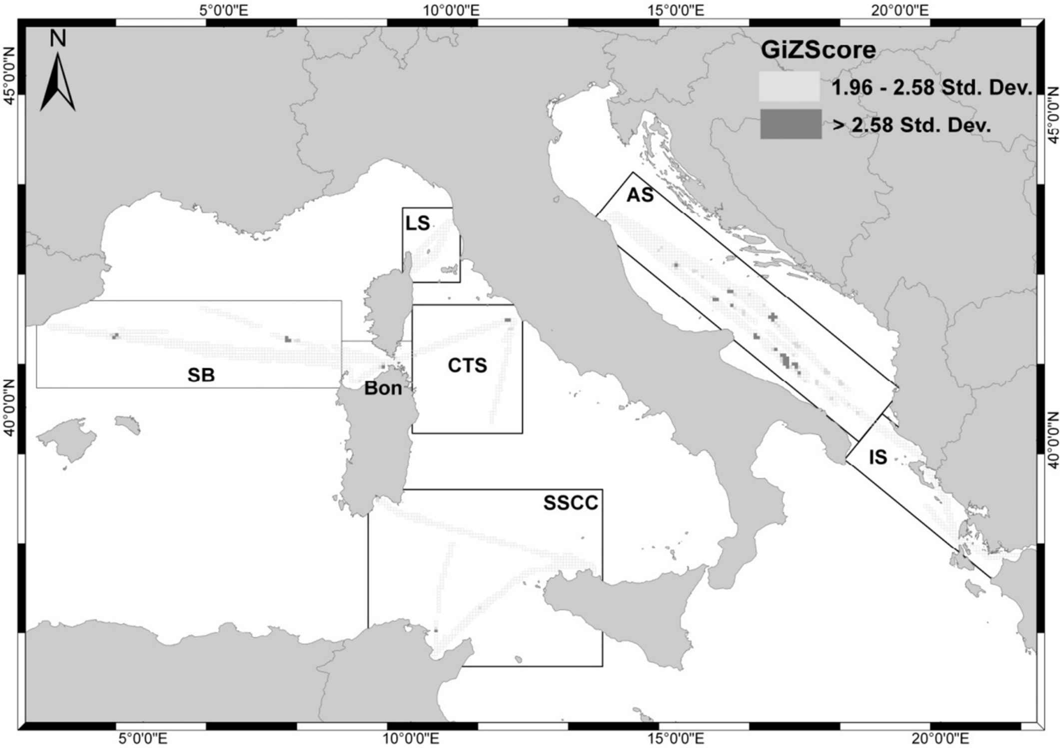

Fig. 7. Cells of litter density significantly clustered individuated by the Hot Spot Getis-Ord G* analysis (grey cells) of total values of the entire region.

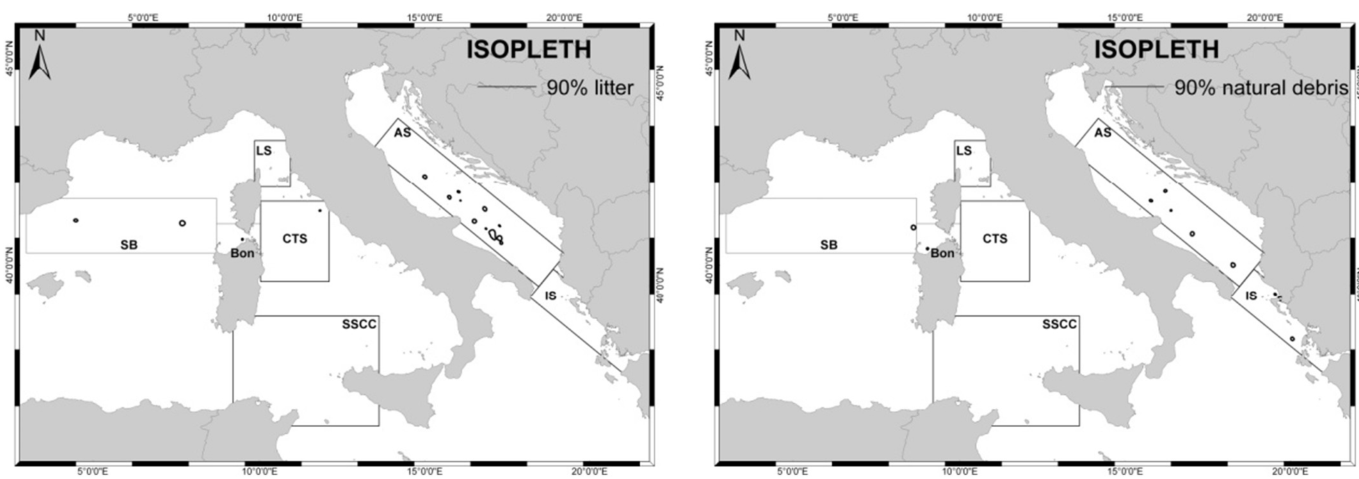

Fig. 8. Kernel density estimate: 90% volume contour of the isopleths of litter (left) and natural debris (right) of total values of the entire study area.

Looking at regional variability from our data, the mean density of floating litter was greatest in the Adriatic Sea followed by the Sicilian-Sardinian Channels and was least in the Ionian and Ligurian Seas. The density of the natural debris fraction was instead higher in more coastal areas (Ligurian Sea, Bonifacio Strait, Ionian Sea, and Tyrrhenian Sea), while lower occurrences were recorded in the Sicilian-Sardinian Channels. This generally suggests different patterns of distribution of the floating materials, and different origins of the anthropogenic and natural fractions. Results in the Adriatic Sea are in line with the higher values of marine litter predicted by several models of plastic inputs from land into the sea, based on population density, waste management, and runoff (Lebreton et al., 2017; Liubartseva et al., 2016). In agreement with our results, Suaria and Aliani (2014) also described the highest amounts of anthropogenic litter in the Adriatic Sea and high values of natural debris in the Ligurian Sea (Corsica Channel), while other discrepancies could probably be due to differences in the location or season of surveys.

Seasonal patterns were generally shown in almost all our study areas, and were significant in the Ligurian Sea, Sardinian-Balearic basin, and Central Tyrrhenian Sea. This variability likely depends on local scale features which represent important elements in defining litter production, transport, and concentration (Deudero and Alomar, 2015). Accordingly, based on the Lagrangian modelling distribution of near-surface drifters in Mediterranean, Zambianchi et al. (2017) found transient accumulation in locations varying by season. Less seasonal variability was instead detected in the Adriatic Sea, as was reported in a few studies conducted in other parts of the world (Hinojosa et al., 2011; Hinojosa and Thiel, 2009; Thiel et al., 2013). This is probably due to the semi-enclosed characteristics of the basin, with a less evident seasonal variability (Zambianchi et al., 2017) which creates conditions for a higher concentration of materials (Carlson et al., 2017). However, even if less pronounced compared to other areas, we recorded the maximum values of both litter and natural debris fractions during winter in the Adriatic Sea, likely linked to land contribution (Carlson et al., 2017;

Jambeck et al., 2015; Sadri and Thompson, 2014). Vianello et al. (2015) showed an increase in concentrations of discharged litter especially from the Po River in the Adriatic Sea from spring to winter; still in the Adriatic Sea differences among seasons, explained by basin scale circulation, were also found by Liubartseva et al. (2016) through a model simulation. However, while our data showed a decreasing trend from winter to spring/summer for the natural debris, the litter amount remained almost stable throughout the year, supporting the hypothesis of an increased input related to human pressure on the coasts in these latter seasons. In other studies, the minor abundance of litter in summer/spring compared to winter/autumn was linked to dominant offshore accumulation induced by winds in the latter seasons (Diaz-Lopes et al., 2016; Lecke-Mitchell and Mullin, 1997).

Opposite trends in the seasonal densities of litter and natural debris were also described by our data in the Ligurian Sea and Sicilian-Sardinian Channels where the highest litter densities were again recorded during seasons with strong anthropogenic pressure on the coast (spring and summer). In our study, however, we observed a decrease in litter density from spring to summer in the Ligurian Sea, Tyrrhenian Sea, and Bonifacio Strait. Di-Méglio and Campana (2017) also found a general reduction of litter amounts in the central summer months along the French coast, as a possible result of sensibilization actions and beach maintenance.

Looking at the composition of litter, artificial polymer materials were, as expected, the most common category found, confirming that as a permanent part of the marine environment (Moore, 2015), they accounted for > 80% of litter in all areas and seasons, in accordance with many studies (Cózar et al., 2015; Derraik, 2002; Dufault and Whitehead, 1994; Morris, 1980; Suaria and Aliani, 2014; Thiel et al., 2003, 2013). The predominance of plastic at the sea surface has been explained with its floating capacity and durability so that it can be transported over long distances; moreover, the widespread use of cheap plastic products makes them the majority of waste (Derraik, 2002; Galgani et al., 2013a; Gregory, 2009; Laist, 1997).

The highest proportion of plastic material was found in the Adriatic Sea, Ligurian Sea, and Sicilian-Sardinian Channels, while in the Bonifacio Strait, Tyrrhenian Sea, and Sardinian-Balearic basin, litter composition appeared more diverse by the presence of other categories. Because some objects can be attributed, with a high level of confidence, to a certain industry, the most common items gave some indication about the sector of activity. The top five items mostly derived from packaging (plastic bags, wrappings, sheets), food consumption (paper bags, bottles, tableware), and fisheries (polystyrene boxes). Polystyrene items are in fact considered directly linked to aquaculture or fishing activities and represented about 8–20% of the total floating litter composition in all areas, which is in line with values reported by other researchers (Di-Méglio and Campana, 2017; Sá et al., 2016; Shiomoto and Kameda, 2005; Suaria and Aliani, 2014; Thiel et al., 2013). All this information suggests a determinant contribution of litter related to the increased human pressure during spring/summer when there is a higher presence and use of coastal and sea resources. Plastic objects were observed more frequently in summer, according to the general highest amounts of litter in all the areas.

Paper and processed wood were other relevant components of marine litter, particularly in autumn and winter. Despite their easy degradation, their conspicuous presence in the records indicates regular inputs in the waters for these materials. Their biggest proportions were reported in the Bonifacio Strait, Tyrrhenian Sea, and Sardinian-Balearic Seas, according to the more diversified composition of litter observed in these areas. As with plastics, most paper items were food-related (packaging or tissues), while wood objects were harder to identify (boat parts, crates, pallets), indicating a great variability of possible sources.

Heavier materials, such as glass, metal, textile and rubber, were regularly observed in all areas, but as these materials are expected to sink fast due to their scarce buoyancy, their presence far from the coasts suggests a possible sea-based origin for these kinds of items, representing a low but constant contribution to marine litter.

A deeper investigation on litter categories and objects in all the areas would surely provide useful details to point to specific sources and consequently plan effective mitigation measures.

Floating litter was distributed everywhere in our surveys. As a semi-enclosed basin surrounded by developed countries, the Mediterranean Sea is clearly exposed to particularly high concentrations of marine pollution (Barnes et al., 2009; Deudero and Alomar, 2015; Jambeck et al., 2015). In addition, the seasonal variability in the climatic and circulation regime do not allow the convergence of litter in stable accumulation areas (Cózar et al., 2015; Mansui et al., 2015; Zambianchi et al., 2017). Indeed from our records, the distribution of litter showed some spatial heterogeneity and artificial and natural debris items appeared separated in all study areas except for the Adriatic Sea. Densities of litter and natural debris showed different seasonal patterns too. For the Adriatic Sea, the coincidence of many high density areas of both litter and natural material indicated a possible common origin of the materials (land) and distribution mostly guided by surface currents (Carlson et al., 2017). Moreover, the location of some accumulation areas in high seas (i.e. far from land sources) suggests the presence of sea-based sources in this basin, originated likely from shipping and fishing (Carić and Mackelworth, 2014; Sá et al., 2016; Vlachogianni et al., 2016). This is not the case for other areas of our study, where the accumulation of floating material was identified closer to land but in separate hotspots, indicating the importance of local inputs to the global distribution of litter and natural debris. Significant litter hotspots were found in proximity to land, such as next to the Tiber river mouth in the Tyrrhenian Sea, in the Bonifacio Strait, and close to the port of Tunis, where the accumulation is likely dependent on local coastal inputs. Concentration areas in high seas were observed only in the Sardinian-Balearic basin, where the material is probably driven by currents and retained in this low-energy area (Mansui et al., 2015). For the natural fraction, hotspots always occurred in proximity of the coast in the Ionic islands and in the Asinara Gulf, where the predominant mistral wind from north-west leads the accumulation of natural material, as well as litter (e.g. Lecke-Mitchell and Mullin, 1997).

It is noteworthy that spatial analysis did not reveal any hotspots of natural debris in the Ligurian Sea, where the highest densities were recorded, suggesting a homogeneous distribution of these objects along this transect.

In summary, litter occurred everywhere in the Mediterranean Sea, but without evident aggregation zones, which could explain the relatively low density values obtained in relation to the expected input (Cózar et al., 2015). Moreover, circulation in the basin is variable at seasonal and regional scales, with highly dynamic areas, such as the Sicilian-Sardinian Channels and the Ligurian Sea, which prevent the formation of regular oceanographic features (Mansui et al., 2015).

Surely, a finer spatial and seasonal resolution is needed to better understand the relationships between floating litter and circulation dynamics in the different areas.

5. Conclusions

The Mediterranean Sea represents an extremely sensitive ecosystem for the coexistence of high anthropogenic pressures and biodiversity richness (e.g. Coll et al., 2012; Deudero and Alomar, 2015). The basin is considered one of the places with the highest concentration of floating litter in the world (Cózar et al., 2015), and apart from the aesthetic issues, the effects of marine pollution in physical and biological processes is undeniable (e.g. Deudero and Alomar, 2015; Gall and Thompson, 2015). Given the transboundary nature of the problem, concerted regional responses throughout the whole Mediterranean region are urgently required.

Our results confirm how a regular, multi-year, synoptic monitoring over the whole Mediterranean Sea is appropriate to intercept the great variability in the average levels and trends of pollution in space and time (Cheshire et al., 2009; Galgani et al., 2013b; Zambianchi et al., 2017), and can help identify the main sources. This monitoring program can thus represent a valuable response to recent policy drivers (e.g. Habitat Directive, MSFD, Waste Directive) which focus on trends in pressures and impacts and assessing the effectiveness of legislative measures (Galgani et al., 2013b; Zampoukas et al., 2014).

Further investigation at a finer scale could help with the analysis of meso-scale processes, the identification of local sources of litter, and the evaluation of its potential impact on biota. This study once more highlighted the need for fine tune methodological approaches in order to facilitate comparison among different monitoring campaigns.

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