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Relationships between size and abundance in beach plastics: A power-law approach

Fabio Bozzeda [a,b], Francesco Zangaro [a,b], Marina Antonia Colangelo [c], Maurizio Pinna [a,b,*]

[a] Department of Biological and Environmental Sciences and Technologies, University of Salento, DiSTeBA, S.P. Lecce-Monteroni, 73100 Lecce, Italy
[b] Research Centre for Fisheries and Aquaculture of Aquatina di Frigole, DiSTeBA, University of Salento, 73100 Lecce, Italy
[c] Department of Biological, Geological and Environmental Sciences, University of Bologna, via S. Alberto 163-13, 48120 Ravenna, Italy

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ABSTRACT

Sandy beaches are one of the most relevant coastal environments in terms of socio-ecological and economical value. So, the presence and accumulation of plastic litter determines a degradation of these values, and calls for management actions for cleaning are required. In this research, we investigated the features of plastic litter distribution on a Mediterranean beach in relation to size and abundance of the sampled items. Simple allometric models were applied with the aim to provide a parsimonious tool for estimating the amount and sizes of the beach plastic litter. The results show effective relations between size and abundance of plastic items according to the power-law distribution. This relationship could support decision-makers to estimate the total amount of beach plastics through the application of a simple model instead of more complex models requiring the estimation of many parameters and the availability of large datasets.

1. Introduction

During the last decade, the problem of plastic litter spread in the environments has been strongly recognized worldwide. Its extension and the emergency with which it is presented after decades of accumulation (Wang et al., 2019) leads to the need of keeping collecting data and information to define management protocols (Barnes et al., 2009; Rillig, 2012; PlasticsEurope, 2017; Edo et al., 2019).

Plastics are represented by a large variety of polymer types and are produced and designed for many purposes, such as packaging, construction and building, transportation, electronic and electrical devices, agriculture, medical facilities, and sports equipment (Frigione et al., 2021). The massive use of plastic worldwide leads to an increase in its production (PlasticsEurope, 2017).

Moreover, plastic wastes are among the most persistent and pervasive global threats in terrestrial (Zubris and Richards, 2005), subterranean (Panno et al., 2019), freshwater (Gasperi et al., 2014), marine ecosystems (Moore et al., 2001) and beaches (Edo et al., 2019; Fanini et al., 2021). Even the most remote habitats are threatened by plastic wastes, as demonstrated by the finding of the so-called man-made litter in mountain lakes and isolated islands (Free et al., 2014; Lavers and Bond, 2017).

Oceans and seas are widely considered as the main sink for plastic wastes, generated either by terrestrial or marine human activities (Constant et al., 2019). It is estimated that about 8 million tonnes of plastic end into the world's seas and oceans every year and, at this rate, the weight of marine plastics could exceed the weight of marine fish fauna by 2050 (Cózar et al., 2014, 2015; Wang et al., 2019).

The most noticeable impacts of plastics in the coastal-marine environments include the alterations in biodiversity and ecosystem health; entanglement, smothering, and ingestion by coastal-marine vertebrates and invertebrates; and leaching of the plastic additives and chemicals (Frigione et al., 2021).

Among the coastal-marine environments, sandy beaches represent a sink ecosystem for the accumulation of the floating litter which, after becoming stranded, generally gets trapped in and under the sand, or might be blown further inland by the wind (Jayasiri et al., 2013). In opposition to what happens in the open sea, where the accumulation of plastic waste follows known hydrodynamic and circulatory models (Consoli et al., 2020), the rate and intensity of deposition on beaches seems to be independent of exposure, seasonality and intensity of the winds and waves, and tidal range (Fanini and Bozzeda, 2018).

Once on the beaches, the plastic litter is generally subjected to progressive fragmentation under both environmental physical-chemical

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* Corresponding author.
E-mail address: maurizio.pinna@unisalento.it (M. Pinna).

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and biotic factors, such as mechanical abrasion, UV radiation, and biological degradation due to microorganisms (Barnes et al., 2009; Cole et al., 2011). The continuous breakdown of the plastic debris can generate a wide amount of secondary microplastics ($<$ 5 mm in size), constituting the largest source of microplastics in the aquatic environments (Jiang, 2018). Nevertheless, plastics can even be originally produced in a microscopic size as primary microplastics, which are very common as scrubbers in some personal care products, or as resin pellets for the same plastic production (Cheung and Fok, 2017; Cole et al., 2011). Eventually, primary microplastics may end up in the environment via surface run-off, and domestic and industrial drainage systems (Murphy et al., 2016). Once into the environment, plastics, and microplastics mainly, can widely disperse, resulting in the availability of a large number of plastics for the biota occupying different habitats (e.g., surface water, water column, benthic sediment, beaches, etc.) and trophic levels (Cole et al., 2011; de Sá et al., 2018; Thompson et al., 2009). Other than the adverse effects from ingesting the microplastics themselves, toxic responses could also result from both inherent contaminants leaching from the microplastics, and extraneous pollutants, during time adhered to the microplastics surface, disassociating (Cole et al., 2011). In particular, many Persistent Organic Pollutants (POPs) are toxic substances typically inducing endocrine disruption, mutagenesis and/or carcinogenesis, and, subsequently to accumulation in lower-trophic organisms, may easily biomagnify in higher-trophic organisms (Cole et al., 2011).

The beaches have a well-recognized socio-ecological and economic value (Fanini et al., 2020), so it becomes a priority to improve the monitoring methods to quantify the plastic litter on beaches and to assess a good management of plastic litter. In fact, the plastic litter can impact a range of biological levels, from individuals to communities, related to the beach environment (Costa et al., 2020; Giangrande et al., 2020; Zangaro et al., 2020). It is essential to develop effective protocols for the sampling of plastics and the cleaning of beaches to increase and support awareness campaigns at local, national and transnational level (Fanini et al., 2020).

Several legal and policy frameworks have been developed at a European and Mediterranean scale: the Marine Strategy Framework Directive (MSFD 2008/56/EC), and the Integrated Monitoring and Assessment Programme of the Mediterranean Sea and Coasts and related Assessment Criteria (IMAP). In particular, the descriptor 10 (Marine Litter) of the MSFD, required EU Member States to ensure that, by 2020, “properties and quantities of marine litter do not cause harm to the coastal and marine environment”. According to these, a first step for understanding and for monitoring the problem of plastic litter is to quantify the existing amounts and their distribution (Consoli et al., 2020), and to analyse the most recently developed models to quantify the plastic litter accumulating along the beaches (McLachlan and Defeo, 2018).

Beaches are dynamic transition environments, whose morphology mainly depends on hydrodynamism dominated by currents, waves and wind (McLachlan and Brown, 2006). Morpho-dynamics, beach zoning, transport, and degradation processes can influence the distribution and size of plastic litter on the beach. The concept of beach zoning may be applied for assessing the plastic litter distribution. In particular the beach profile is described by three successive zones: high-tide zone, intermediate dry zone and sub-dune (McLachlan and Brown, 2006). In our beach, the high water mark zone corresponds to the level reached by the sea during the high tide or by the waves and it is characterized by a shallow slope; the intermediate dry zone is the zone corresponding to half transect of the beach not subjected to the pulse disturbance of the tide, characterized by the maximum values of the slope and basically reflective. Finally, the sub-dune corresponds to the zone with low or zero slope, located immediately in front of the dune.

Many models proposed to study accumulation of plastic litter on sandy beaches require the acquisition of many samples and the analysis of a large number of parameters of plastic items, such as, length, width, volume and shape of the plastic items, and all the environmental variables contributing to the dynamism, with the consequent need to build a wide dataset (Schulz et al., 2017; Harris et al., 2021; Kaandorp et al., 2021). Some of these models apply the power-law distribution on plastic litter both in the sea and in the beaches. In general, power-law distributions express the scale-invariance ratio, so that there is a constant relationship between the number of large items and the abundances of the smaller sizes (Dobson et al., 2007; Takeuchi et al., 2011). The scale-invariance ratio indicates that the power-law distributions are fractal distributions (Mandelbrot et al., 1998). However, even though the power-law distributions were sometimes used for validating the models' results, power-law distributions were never applied to directly support the beach management (Cózar et al., 2014, 2015; Enders et al., 2015; Erni-Cassola et al., 2017; Kaandorp et al., 2021). On the other hand, the majority of beaches are poorly managed and/or are under local administrations unable to provide sufficient economic efforts. This causes the impossibility to have a massive application of the most recently developed models aimed to the quantification of the plastic litter accumulating along the beaches in order to correctly manage its waste disposal (Harris et al., 2021).

In this research, we have investigated if the size-abundance distribution of the plastic litter collected along a not-urbanized beach of the Southeast Apulia Region coastline (Adriatic Sea, Italy) follows an allometric model. Since a significant allometric model was calculated (power-law distribution), our proposal is to demonstrate the possibility to directly estimate the quantity of plastic litter that is accumulated on a beach, by applying the power-law distribution, through a simple and cheap sampling design. Consequently, we aim to exploit the easiness of parametrisation of the power-law distribution to evaluate whether or not this method could allow a good management of beaches even by administrations unable to apply more complex, and expensive models.

In particular, our hypothesis assumes that a parsimonious sampling along a delimited beach zonation and a simple data acquisition and processing (number of items/abundance, size/weight per item) allow to calculate the power-law distribution of the beach plastic litter. In particular, we verified if the plastic litter present on the beach follow a power-law distribution both at the transect and beach (transects sum) level. The power-law distributions assume a constant relationship between the number of large items and the abundances of the smaller sizes that is expressed by the scale-invariance ratio (Dobson et al., 2007; Takeuchi et al., 2011). The scale-invariance ratio indicates that the power-law distributions are fractal distributions (Mandelbrot et al., 1998). If the fractal distribution is verified, it is possible to estimate the actual quantity of plastic litter and the size distribution in the beach starting from relatively few observations. Furthermore, it would be used for management of plastic litter because is easy to calibrate and to adapt for every beach.

2. Materials and methods

2.1. Study area

The sandy beach of Aquatina is located within the NATURA 2000 Site named “Aquatina di Frigole” (NATURA 2000 Site Code: IT9150003; Fig. 1). The site is narrowed on one side by the homonymous lagoon hosting a high biodiversity (Specchia et al., 2020; Tzafesta et al., 2021) and on the other side by a marine area characterized by an expanse of *Posidonia oceanica* (Delile, 1813) meadow hosting some important and endangered species such as *Pinna nobilis* (Linnaeus, 1758) (Marrocco et al., 2018, 2019). The beach is divided from the lagoon by a system of natural dunes, is about 3 km long, and is interrupted by two groins perpendicular to the coast. The beach is not exploited by bathing establishments and a low tourist flow is registered. For these reasons, the beach is characterized by a low anthropic use and a high nature value, occasionally hosting *Monachus monachus* (Hermann, 1779) specimens (Zangaro et al., 2020). These features allow it to be considered totally

Fig. 1. Aquatina di Frigole Beach. In the figure, the 3 transects sampled (Transect 1, Transect 2, and Transect 3) and the three sampling stations (A, B, C) per transect are showed. Sampling station A corresponds to the high water mark zone, sampling station B correspond to the medium beach zone, and sampling station C correspond to the base of the dune zone.

natural and to study the zoning dynamics of the plastics accumulated without incurring anthropogenic interferences, like the direct littering and/or programmed clean-up, that are often difficult to consider in this type of study. The beach sampling was realized in April 2019 before the starting of programmed and unexpected clean-up activities by volunteers and local administration. For the whole stretch, the width of the beach is between 20 and 40 m with sediment accumulation points in correspondence with the north sides of the two groins. The tidal range during the year is about 1 m from −50 cm for the lowest tide to +50 cm for the highest tide, so that the accumulation of plastic litter on the beach seems to be dominated by waves and winds. The prevailing winds are those from the north/north-eastern quadrants which determine an important component of horizontal marine litter transport to the coast, to the back dune, and to the lagoon. The beach is considered to have a medium-low risk of erosion due to the presence of a sand reservoir (dune) and the *Posidonia oceanica* meadow in front of the beach which acts as a natural breakwater.

2.2. Sampling design and samples analysis

Within the defined sampling area, three transects were randomly chosen (Fig. 1). The sampling was carried out on three sampling stations along each transect and located from the shoreline to the base of the dune; specifically: the high water mark zone (A), the medium beach zone comprised between the high water mark zone and the base of the dune zone (B), and the base of the dune zone (C) as shown in Fig. 1. The beach profile has been defined using the open-source software QGIS© and then graphically described using Microsoft Excel©. It is characterized by a marked slope from the high water mark line up to about half the beach; from half the beach towards the dune, the slope is less marked until it disappears in the last stretch up to the dune (Fig. 2). At each sampling station, three replicates of a surface of 30 cm × 30 cm and a depth of 10 cm were taken using a box corer. The sampled material included plastic litter, sand, and organic material. To isolate the plastic items, each sample was preliminarily sieved in the field by using a 2 mm mesh size sieve with the aim to remove fine sand and organic material and was then singularly stored and labelled in a plastic bag. Each label reported the indications of the sampling date, the transect, the sampling station, and the replicate. In the laboratory, each sample was washed using tap water, air-dried, and then exsiccated in a stove at 30 °C for 24 h. Once the sample was dried, each plastic item was manually separated by the remaining sand and other materials and was stored apart, obtaining a collection of clean plastic items for each sample.

For each transect, sampling station, and replicate, the collected items were then counted and weighed singularly with a microbalance ±0.0001 g (BELL ENGINEERING – Ultra Mark 205A). The smallest linear dimension of each item was defined by the mesh size used for sieving (2 mm). The weight of the plastic items was used as a measure of size instead of linear dimensions because the weight of the plastic fragments is more conservative than the shape: plastic items with different shapes can have the same weight because it was observed that the weight density of the collected plastic polymers is constant (Frigione et al., 2021).

The identification of the polymers composing each plastic item was achieved using a differential scanning calorimeter (DSC). The differential scanning calorimetry belongs to the thermal analyses (TA), a set of analytical techniques that allow to measure the properties or property changes of any material as a function of temperature or time (Frigione et al., 2021). In the present study, a Mettler Toledo DSC 822 was employed for the thermal analysis. For each plastic item, a small sample (from 6 mg to 15 mg) was cut, weighted, and inserted in a standard aluminium crucible. The crucible was covered with an aluminium lid. On the lid, a small hole was made to allow the drainage of the gas released during the heating of the material under analysis. The crucible containing the material was then introduced in the DSC oven. The experiments were performed in dynamic mode, employing a constant heating rate of 10 °C/min from 15 °C to 250 °C. The experiments were carried out under nitrogen atmosphere (flow rate: 80 mL/min) in order to avoid the occurrence of thermo-oxidative processes, able to prevent the melting of the polymer. From the DSC tests, employing the

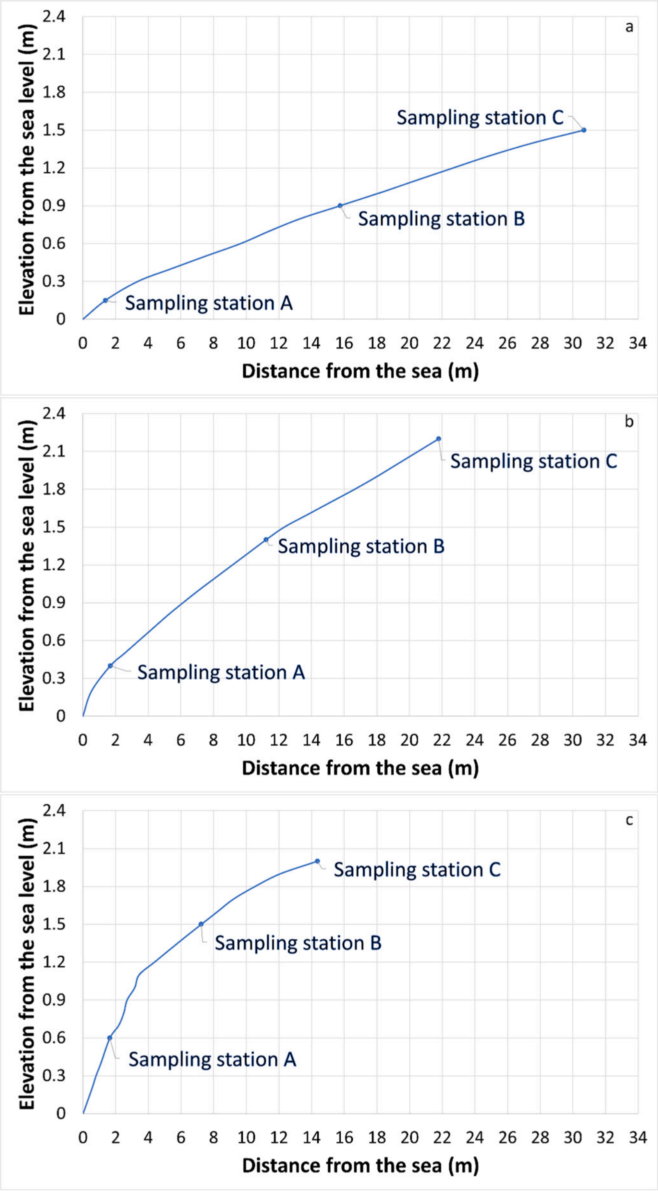

Fig. 2. Cross-sectional diagrams of the Aquatina di Frigole beach in correspondence of transect 1 (a), transect 2 (b), and transect 3 (c).

acquisition data system connected with a dedicated software (STARe©) it was possible to determine the glass transition temperature (Tg) and/or melting peak temperature (Tp) and enthalpy (ΔH) of the polymers composing the plastic items under analysis and, consequently, to identify the kind of polymers by comparing these characteristics with those present in the literature for different polymers. Furthermore, the weight density of the polymers collected on the beach resulted to be constant (Frigione et al., 2021). This allows us to consider the weight of each plastic item as a measure of size.

Also, in each sampling station (A, B, and C) of each transect (T1, T2, and T3), three samples (replicates) of beach sediment (sand) have been collected. In particular, one litre of sand has been collected per replicate. Then, the collected replicates have been dried in a stove at 60 °C for 36 h. Finally, the dry weight has been registered using a balance ±0.01 g (Alessandrini Italy - Exacta P5). The resulting dry weight of each replicate corresponded to the specific weight of the beach sediment in each replicate (g/L).

2.3. Data processing

For each sample, the number of plastic items per sample was considered as an index of abundance, and the weight of each plastic item in each sample was considered as a measure of size (Kaandorp et al., 2021). The specific weight of the beach sediment in each sampling station per each replicate, and the beach sampling stations (A, B, C) have been included in the data analysis as descriptive factors of the abundance arrangement of plastic items from the sea to the dune.

The data relating to abundance and composition by size of the plastics were also analysed through the application of a multivariate analysis carried out on weight and abundance of the plastic items, and then displayed through a non-metric multidimensional scaling (nMDS; Kruskal, 1964) based on an Euclidean distance similarity matrix. To investigate how the abundance of plastic items distributes along each transect with respect to their size, the fittings of the data we obtained were tested with different allometric curves, to verify the best-fitting allometric relation between size (weight) and abundance of plastic items collected in the different sampling stations along each transect. The non-parametric index of Levene Monte-Carlo was applied to the three transects for the analysis of the variances (Mara et al., 2015) in case of acceptance of the null hypothesis, in order to join the three transects and perform the allometric analysis on the total of the three transects.

In order to assess whether the size-frequency distribution of plastic items could be fit by a power-law equation, we related the weight of each sampled plastic item and the abundance of the items with the same weight. Then, we tested the power-law distribution according to the following equation:

$$y = \beta x^{\alpha}$$

in which y represents the abundance, x is the size of each plastic item (weight), α is the scaling exponent, and β is the intercept (Clauset et al., 2009).

Therefore, we fitted the power-law to the data using the methods implemented by Clauset et al. (2009), through which we estimated α and the lower limit of observed power-law behaviour, x_{min}, using the maximum likelihood method. The power-law equation was then tested through the Kolmogorov-Smirnov (KS) statistic for the goodness of fit between empirical data and a large number of synthetic data sets. This generates a p value that quantifies the plausibility of the hypothesis: if it is greater than 0.1, the hypothesis of the power-law can be accepted for the data since the actual KS statistic is better than the 10% of those generated for the synthetic distributions. As a last step, the power-law was compared with alternative hypotheses (log-normal and exponential distributions) using a likelihood-ratio test to evaluate the statistical support for the power-law hypothesis (Table 1).

Differences among sampling stations (A, B, C) and among transects (T1, T2, T3) were tested through the non-parametric test with PERMANOVA permutations (Anderson, 2001); differences were considered as significant when the test provided values of p lower than 0.05.

The plastic samples found in the 3 transects were subjected to the Levene Monte-Carlo test (LMC; 100,000 simulations), resulting in a value of 0.74, which allows us to consider the three transects as belonging to the same population. The applied LMC test is used to make

Table 1
Likelihood-ratio test: the values are referred to the 3 tested distributions of abundance and weight of the retrieved beach plastic items (power-law, exponential and Log-Normal distributions), calculated for each transect (T1, T2, T3) and for the 3 transects altogether ($T_{1, 2, 3}$).

Distribution tested	T1	T2	T3	$T_{(1, 2, 3)}$
Power-law	0.643	0.745	0.611	0.730
Exponential	0.200	0.110	0.260	0.236
Log-Normal	0.350	0.240	0.372	0.228

a comparison between means of two or more groups, not necessarily showing the same number of records. The LMC test can assume values between 0 and 1; the closer the calculated value is to 1, the more the averages are similar to each other (Miller, 1968). Generally, if the value of the LMC test is higher than 0.5, the means are considered as identical. Therefore, it was possible to estimate the power-law distribution for the entire set of items recorded (Fig. 7).

To validate our application proposal, we estimated the amount of plastic litter in the transect 2 by using the optimal, minimum, and maximum power-laws obtained combining the transects 1 and 3. The calculation was made on the size classes found on the two known transects (T1 and T3).

3. Results

Transect 2 shows higher abundance of plastic items with respect to the other transects (Fig. 3) due to the natural variability existing among different transects, despite the ANOVA test showed the transects to belong to the same statistical population. On the contrary, in all the three transects the same upward trend for the abundance of plastic items from the high water mark zone (sampling station A) to the area close to the base of the dune zone (sampling station C) were shown in Fig. 3. Concerning the size (weight) of the plastic items, these follow the same upward trend observed for the abundances (Fig. 4). The retrieved weight density of the beach sand showed a maximum value of 1814.75 g/L, a minimum value of 1506.83 g/L, and a mean value of 1682.83 g/L. The one-way ANOVA on the retrieved densities did not show significant differences between the transects (p-value = 0.592). The nMDS obtained from the similarity matrix calculated on the abundance samples organized for size, shows a deposition gradient with a discrete regrouping level between the sampling stations (A, B, and C) rather than between the three transects (Fig. 5). Moreover, since the retrieved density of the beach sediment in each of the replicates did not show any significant difference (p-value = 0.592), the factor was excluded from the analysis.

PERMANOVA results show significant differences for the "sampling stations" (A, B, C; p-value = 0.017; 9999 permutations), while the transect factor did not result significant (p-value = 0.074; 9999 permutations). The nMDS shows a gradient, albeit less clear than that relating to abundances, that seems to be influenced by the position of the transects with respect to the breakwave perpendicular to the beach, however also the distribution of sizes per replica seems to respect the gradient identified for the abundances (Fig. 5).

At the transect level, the size-abundance relationships of the retrieved beach plastic litter follow a power-law distribution, which demonstrates an invariance of scale among the lighter pieces (Fig. 6a, b, c). However, all the three distributions show a widening in the tail corresponding to the presence of heavier plastic items with low values of abundance.

The equations describing the power-law distributions of plastic items in the three transects are the following:

Transect 1. $y = 1.0559\ x^{-0.5047}$; $R^2 = 0.635$; $n = 586$ plastic items (Fig. 6a);

Transect 2. $y = 0.6665\ x^{-0.7400}$; $R^2 = 0.721$; $n = 1006$ plastic items (Fig. 6b);

Transect 3. $y = 0.3212\ x^{-0.8366}$; $R^2 = 0.633$; $n = 707$ plastic items (Fig. 6c).

The power-law equation fitted on the merging of the three transects is the following:

Transect$_{(1,2,3)}$: $y = 1.4053\ x^{-0.7049}$; $R^2 = 0.711$; $n = 2299$ plastic items (Fig. 7).

This expresses the invariance of scale with respect to the entire set of data collected.

It is noted that, in any case, the tails widen in correspondence with the plastic items with a mass greater than 3 g, corresponding to the last five quantiles of the distribution. In each of the three transects, a widening of the tails was observed, a phenomenon that is typical of the

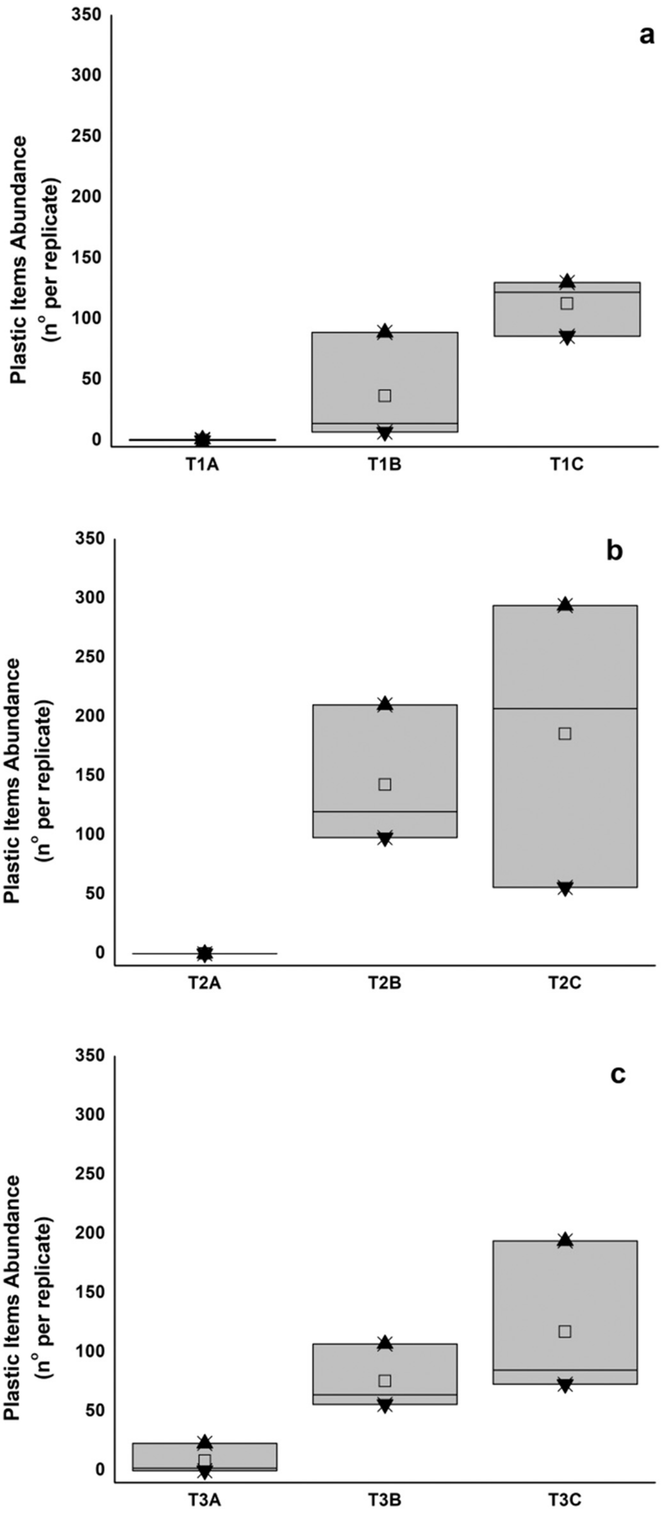

Fig. 3. Box-plots of the abundance of plastic items sampled within the Aquatina di Frigole beach. In the Transects 1 (a), 2 (b) and 3 (c), respectively. A, B, C are the sampling stations located in different beach zones and respectively at high water mark zone, medium beach zone and base of the dune zone. Legend: ▲ and ▼ respectively represent the maximum and the minimum; × represents the confidence intervals; - represents the median; and □ represents the mean value.

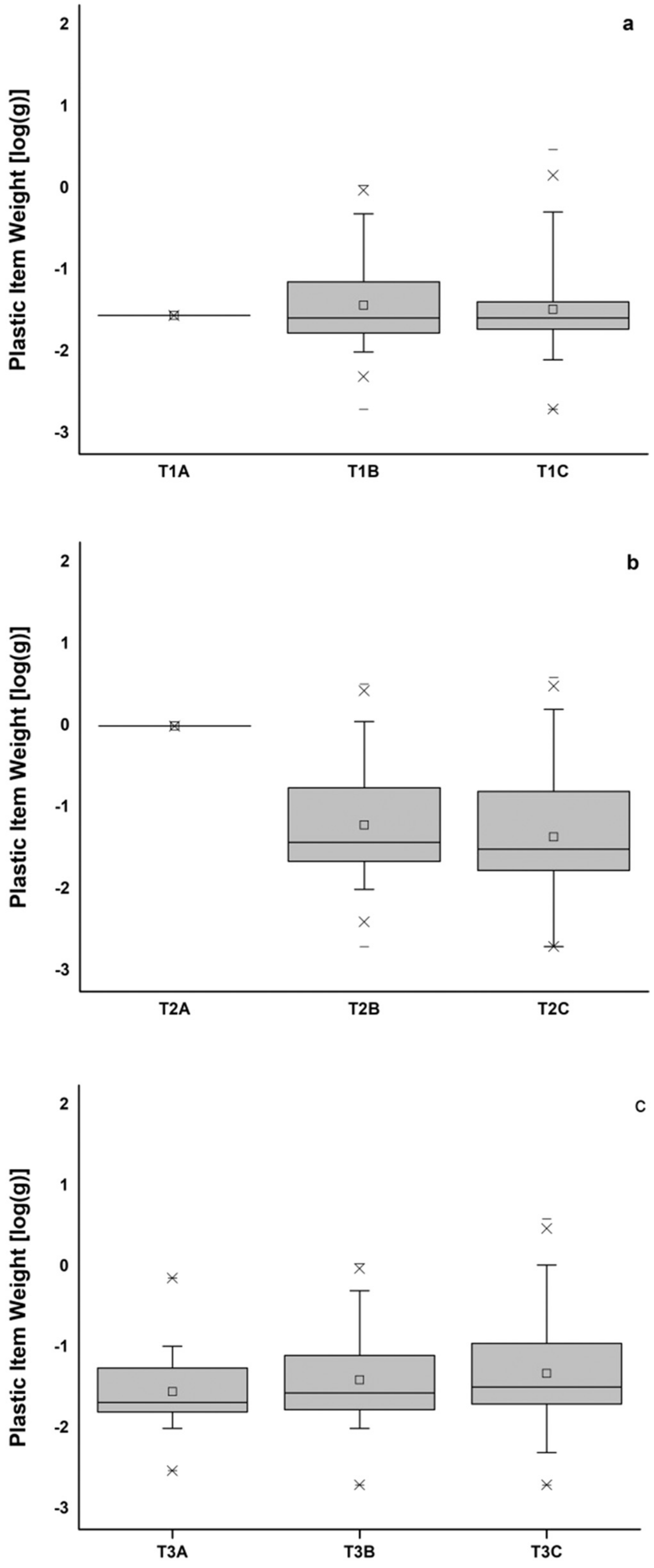

Fig. 4. Box-plots referring to the size (weight) of plastic items in the Aquatina di Frigole beach. The graphs a, b and c are referred to the Transects 1, 2 and 3, respectively. A, B, C indicate the sampling stations located in different beach zones and respectively at high water mark zone, medium beach zone and base of the dune zone. Legend: × represents the confidence intervals; - represents the median; and □ represents the mean value.

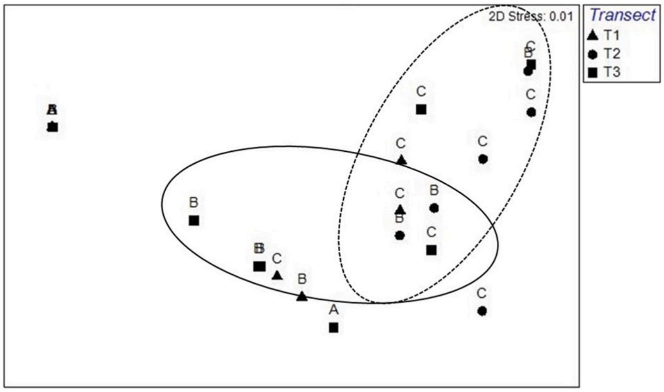

Fig. 5. nMDS showing the differences among transects and sampling stations (A, B, and C) considering the abundance and the weight of the beach plastic items. A, B, C indicate the sampling stations located in different beach zones and respectively at high water mark zone, medium beach zone and base of the dune zone. The continuous-line ellipsoid indicates the grouping of the sapling station B. The dashed-line ellipsoid indicates the grouping of the sampling station B. However, the two groupings are partially overlapped.

empirical distributions (Goldstein et al., 2004). The cumulative curves show that the enlargement is observed in correspondence with the heaviest plastic items, which represent the 3% of the total observed data, meaning that their abundance is strongly lower with respect to the lighter items (Fig. 8). To better consider the magnitude of the oscillation induced by the heavier items, we calculated the values of the parameters corresponding to the lower and upper limits (*xmin* and *xmax*) of the observed distributions. The results show that, in any case, the distributions retain the characteristics of a power law. In the transect 1, we observed a variation from 0.713 to 1.399 for the first parameter (β) and from -0.564 to -0.445 for the scaling exponent (α) (Fig. 6a). In the transect 2, we observed a variation from 0.546 to 0.787 for β and from -0.776 to -0.704 for α (Fig. 6b). In the transect 3, there is a variation from 0.232 to 0.411 for β and from -0.898 to -0.775 for α (Fig. 6c). Concerning the total of items observed on the beach, β varies between 1.210 and 1.793 and the α exponent between -0.717 and -0.650 (Fig. 7). For all fitted distributions, the value of *xmin* calculated by the algorithm (Clauset et al., 2009) corresponds to the minimum recorded value (0.001 g).

The validation of the proposed approach showed good fitting results. The calculation started from the *xmax* for the T2 (54 g), a size not observed in T1 and T3. In fact, the tale enlargement in T2 is higher than in the other 2 transects. Despite this difference, the estimation obtained applying the optimal, maximum, and minimum power-laws shows fitting values (R^2) of 0.880, 0.839 and 0.884 respectively.

4. Discussion

The presence of plastic litter pollution in the coastal-marine environments is recognized worldwide as a threat to biodiversity and ecosystem services (Bonanno and Orlando-Bonaca, 2018). In particular, the Mediterranean Sea is known for hosting a high species biodiversity, including both endemic and alien species (Zangaro et al., 2021; Bariche et al., 2020; Specchia et al., 2020; Pinna et al., 2017; Coll et al., 2010; Myers et al., 2000), and is one of the marine ecosystems most impacted by plastic litter in the world (Consoli et al., 2020).

It is known that the largest plastic litters are destined to degrade into smaller and smaller pieces, mainly through two processes: degradation due to exposure to sunlight, and mechanical degradation due to movement, as well as the synergy of the two processes (Wang et al., 2019).

The degradation of plastic litter increases their danger making them bioavailable and releasing potentially dangerous substances for the ecosystem (Frigione et al., 2021).

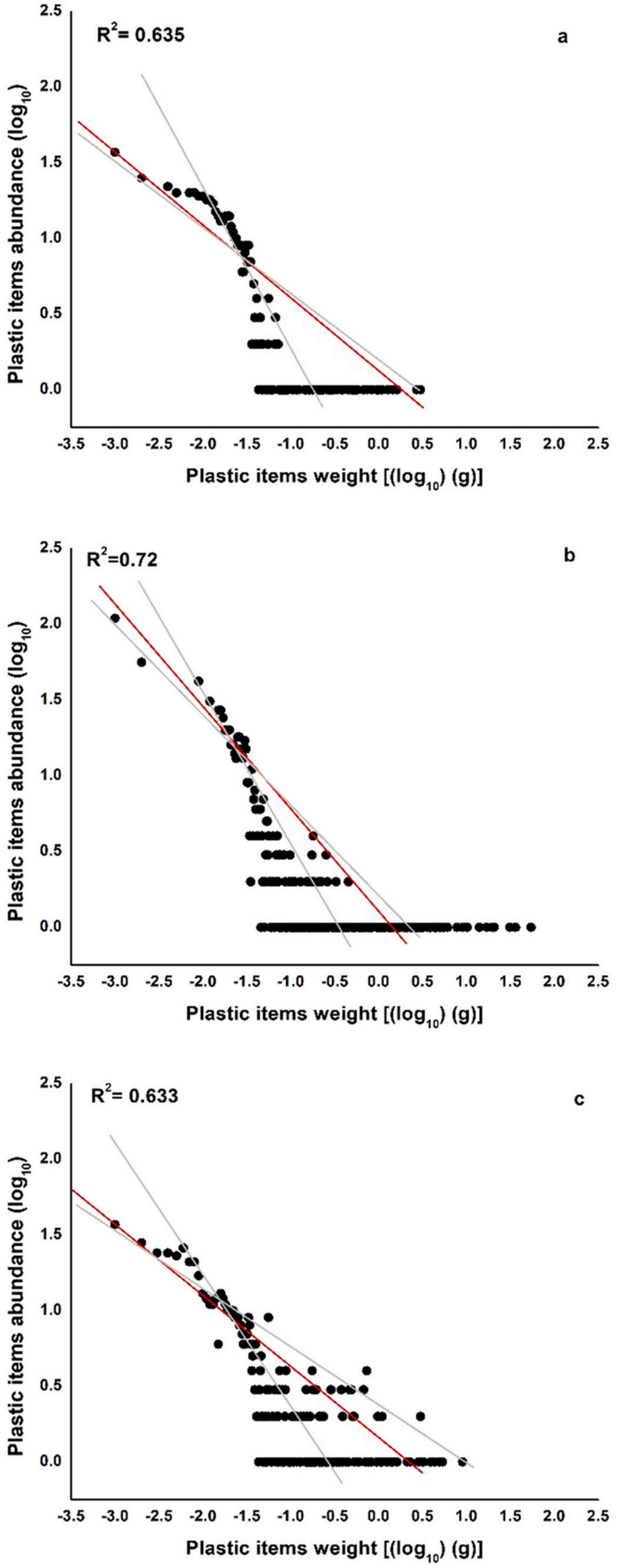

Fig. 6. The power-law distributions are showed for the transect 1 (a), transect 2 (b) and transect 3 (c) respectively. In each graph, the statistical significance is reported. The best fit lines are also reported in the plots (red lines). The grey lines represent the uncertainty range due to the oscillation of the large plastic items. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

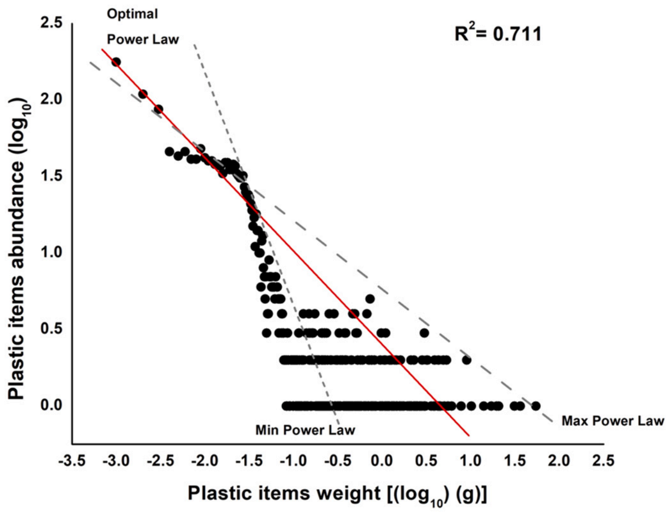

Fig. 7. The power-law is obtained relating the abundance and size (weight) of the plastic items of the overall transects and replicates. In the graph, the statistical significance is reported. The best fit line is also reported in the plot (red line) The grey lines represent the uncertainty range due to the oscillation of the large plastic items. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Unfortunately, the majority of beaches are not managed by administrations able to provide sufficient economic efforts to apply the most developed and expensive models to deal with the phenomenon of beach plastic litter accumulation. A synthetic, cheap, and easy method to calculate information about this issue, would allow the decision makers to estimate, after a parsimonious sampling and data acquisition, the quantity of plastic litter present on beaches, including those items that are not visible through a superficial examination (Harris et al., 2021).

In this research, we have fitted different allometric curves on the weight and abundance of plastic items along 3 transects, measured on a natural, poorly exploited beach. The results show that the power-law distribution is the best model describing the size-abundance relationship of beach plastic items.

Once estimated the optimal, maximum, and minimum power-law models (Fig. 7), it is possible to assess an estimation of the total plastic litter accumulated on the beach. The power-law models describe the amount of plastic litter having a small size (weight) present on the beach in relation to the amount of larger plastic litter. Operationally, the beach manager will first have to estimate the size-abundance relationship proper of its beach. Then, he will proceed to collect and classify in size the largest plastic litter, observable and catalogable through accessible tools (e.g., a sieve and a balance). The size of the plastic litter so observed determines the *xmax* from which make the estimation start according to the power-law relationship previously calculated. According to the applied model (Clauset et al., 2009), the estimation will be concluded at the estimated *xmin* value. Each power-law refers to a determined sampling area, and within it, it contains the abundance gradient (if present) transversal to the beach line. So, the amount of estimated plastic litter, estimated through a single power-law, can be upscaled to the total beach area, obtaining an estimation of the total amount of the beach plastic litter.

This simplified model cannot be easily applied to urban beaches, to beaches with bathing establishments, and to beaches whose management includes nourishment, beach cleaning carried on by volunteers, and seasonally-programmed beach cleaning by local administrations and bathing facilities enterprises because this implies the removal only of the largest plastic items, impairing the efficiency of the model.

The described direct application can be modified through i) the use of discrete classes of the recorded sizes, simplifying the estimation, and/or ii) the repartition of the beach area in sub-areas and estimating a power-law for each sub-area, so that the internal variability of beaches can be considered. In fact, being the beach poorly frequented and poorly managed, to validate the proposed approach it was possible to use two transects to predict the plastic amount of a third transect. Moreover, the analysis did not need an upscaling because the transects represent the same space unit.

In this research, a very relevant issue to consider is the *xmin* value, corresponding, to a size of 2 mm and a weight of 0.001 g. Previous studies have showed that the power-law distribution is more evident for the size range from 1 mm to 10 mm. Therefore, no lower limits were identified in the analysis, but only upper limits were identified related to the observed widening tail. Probably, for this reason, we have observed the enlargement of the curve tails for the heavier plastic items, comprised in the size (weight) range from 0.5 g to 100 g, corresponding to the last 5 quantiles of the observed distributions. It is consistent with the fact that every single plastic item generates a power-law distribution and that, while the smallest dimensions are reachable by any initial plastic item dimension due to the degradation process, the initial dimension is instead independent from the process of degradation. This results in a key information for the application of the estimation methodology since it is way easier and cheaper for the beach manager to collect information about the largest plastic items than about the smallest ones. However, our results better fit to plastics' samplings applied on the same polymers (same specific weight) in the size range from 1 mm to 10 mm per single plastic item, in order to retrieve the same distribution curve. In fact, power-laws can be better estimated using the weight of the plastic items as a proxy for size, but changing the polymers composition (and therefore the specific weight) the distribution curves may differ. Indeed, even if the distribution tails tend to enlarge, fit to a power-law distribution in each of their ranging points, and the exploitation of the largest measures in the estimation allows to have a “maximum” and a “minimum” expected values of the beach plastic litter distribution in relation to the plastic items' abundance.

The results also show: i) an effect of beach zoning on the abundance of plastic litter, with a greater abundance near to the dunes than the other considered beach zones; and ii) the size-abundance distribution of the plastic items in each transect and considering the entire dataset is well described by a power-law model. The first result is consistent with what is known about transversal transport to the beach, in which the deposition process begins in the high tide area and ends close to the dune or beyond it. The effect of the chemical-physical system of continuous deposition and fragmentation of plastic items is at the same time consistent with the estimated power-law distributions. In fact, the power-laws describe a system in which there are several small pieces and few large pieces.

Our results cannot actually be considered a broad generalisation for every beach, but they are considered for a representative case. However, considering the transport/degradation mechanism followed by deposition/degradation, it seems logical to expect the same type of relationship on each beach (Kaandorp et al., 2021). In the case of beach management with bathing establishments and continuous cleaning, it seems correct to expect the removal of larger, visible items, but it is likely to expect a relationship of invariance of scale such a power-law distribution. From a temporal point of view, a succession of the obtained curves would also allow to describe the degradation rates of the plastics. Besides, it is likely to assume that the curves are not influenced by seasonality. In fact, the deposition of beach plastic litter is constant throughout the year regardless of the different hydrodynamic conditions (Fanini and Bozzeda, 2018). The same conclusion was obtained from a capture/recapture study carried out on several Japanese beaches (Kataoka et al., 2013). In both studies, the only relevant variable seems to be space.

In the obtained power laws, a widening of the distribution tails is observed. This is due to the heavier beach plastic items present as a single unit. In any case, the heaviest beach plastic items fall into the last five quantiles of the distribution, and other studies attest to 3% the percentage of litter heavier than 3 g (Schulz et al., 2017). An existing

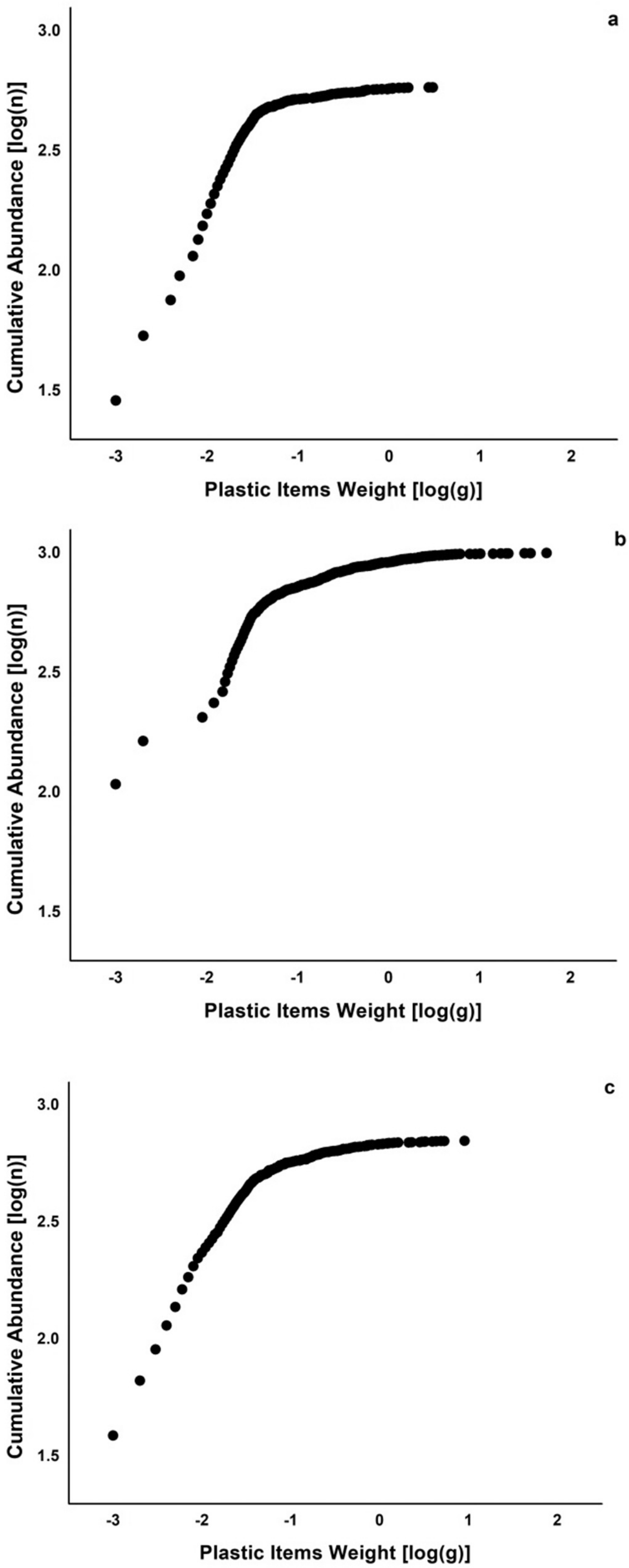

Fig. 8. The cumulative distributions of the retrieved plastic items are showed for the transect 1 (a), transect 2 (b) and transect 3 (c) respectively.

deterministic model to quantify beach plastic litter is proposed by OSPAR (Schulz et al., 2017), which however requires a large amount of information and strong effort for the data acquisition that is not possible for all beaches. Another recent study (Kaandorp et al., 2021) presented a simplified fragmentation model that confirms the transport/degradation/deposition model described in our study, confirming that the plastic litter stranded on beaches like Aquatina di Frigole beach follow self-organization rules well described by the fragmentation model and expressed by the power-law distributions (Turcotte et al., 2002; Kaandorp et al., 2021).

The modelling of plastic litter distribution with the range of items size from large dimensions also visible through satellites (e.g., buoys) until very small fragments (e.g., micro- and nano-plastics) requires a great effort to define the boundary conditions and the transport and degradation functions (Turrell, 2018). Also, a further effort to adapt the model built to the specific site conditions of the beaches is needed.

The use of a power-law distribution describing the system properties allows to bypass these issues and to predictively interact with a complex system through a statistical relationship that can be described with few parameters.

The application of power-laws for understanding complex systems' phenomena occurs in a wide range of natural systems, such as river deltas vegetal patch size, animal size distributions and other natural systems (Tidu et al., 2004; Buchanan, 2008; Taramelli et al., 2017), and can serve as a tool to address the understanding of complexity in a more general framework.

CRediT authorship contribution statement

All the authors contributed in the same way to the conceptualisation, experimental design, methodology, sampling, writing and editing. Funding acquisition by Maurizio Pinna.

Declaration of competing interest

The authors have no conflicts of interest to declare. All co-authors have seen and agree with the contents of the manuscript and there is no financial interest to report. We certify that the submission is original work and is not under review at any other publication.

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