Impact of storms and proximity to entry points on litter accumulation along Mediterranean beaches: management implications

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Highlights

- Impact of storms and entry point proximity on beach litter accrual was assessed.
- Autumn/winter storms are a major driver of beach litter accrual.
- Litter density and beach proximity to major harbors were positively correlated.
- Beach cleaning exerted strong costs on local coastal municipalities.
- Litter mitigation/cleaning actions should be planned at regional coastal scale.

Abstract

Beach litter increasingly threats wildlife and coastal environments worldwide. Moreover, litter affects public health and economic activities forcing local authorities to expensive beach cleaning activities. Most of recent studies have focused on beach litter distribution and potential sources at local and global scale, but the contribution of weather conditions and proximity to entry points in accumulating litter in beaches is still uncertain. This information is critical in planning effective litter management strategies. In this one-year study, we estimated the impact of storm events and waterways runoff on litter abundance and local economy using as a model a managed, peri-urban beach facing a north-western sector of the Mediterranean Sea. We also investigated the relationship between litter composition/density and beach proximity to major/closest harbors/rivers at regional scale by combining our data with data on litter density available in literature.

Autumn/winter storms caused larger litter depositions than spring/summer ones in the peri-urban beach. No preferential accumulation occurred near to waterway mouths. Litter mainly consisted of plastic, and its composition in terms of micro-categories varied over seasons. In total, 367,070 items were deposited along 4.7 km of beach over one year, and the cost for the removal of this waste amounted to approximately 27,600 euros per km/year. At regional scale, beach litter density was positively correlated to the proximity of major harbors while its composition was related to the proximity to both major harbors and rivers.

Results indicate that autumn/winter storms are important drivers of marine litter deposition. They also suggest that beaches in front of the convergence zone of littoral currents and close to major harbors can be particularly subjected to this kind of pollutant. To increase their effectiveness, litter mitigation/cleaning activities should be planned based on predictions of major storm events and performed at spatial scales encompassing at least coastal regional sectors.

1. Introduction

Marine litter is a global environmental problem threatening marine biota and public health. Plastic, the major component of marine litter (up to 90%; Galgani et al., 2015; Morales-Caselles et al., 2021; Scotti et al., 2021), is of particular concern due to its longevity and a wide range of harmful effects on organisms including internal injuries after ingestion, physical entanglement, and growth alterations (Bergmann et al., 2015; Menicagli et al., 2019a,b; Bucci et al., 2020; Menicagli et al., 2020). Plastic can also expose organisms to toxic compounds, such as additives used to manufacture items, and persistent organic pollutants adsorbed from the environment (Oehlmann et al., 2009; Rochman et al., 2013, 2014; Bejgarn et al., 2015; Balestri et al., 2019; Menicagli et al., 2019a). Moreover, marine litter can have adverse social and economic impacts especially on coastal areas as their economy relies on marine resources and tourism. Indeed, currents and waves may deposit large amounts of plastic materials on beaches together with natural wrack (i.e., terrestrial plants, seagrasses, and algae) affecting negatively environmental aesthetics (Ballance et al., 2000; Krelling et al., 2017; Robbe et al., 2021). To maintain tourist attractiveness, coastal municipalities are forced to undertake specific actions to remove litter from beaches and ensure its proper disposal (Cruz et al., 2020; Chubarenko et al., 2021). Therefore, understanding the factors driving the accumulation of litter along beaches is crucial to prioritize management actions aimed at preventing and reducing this kind of pollution.

Modeling studies and field observations indicate that litter enters the oceans from both land-based (e.g., industrial activities, rivers, harbors, and sewage water discharges) and sea-based sources (e.g., fishing activities and shipping; Lebreton et al., 2017; González-Fernández et al., 2021; Morales-Caselles et al., 2021). However, the relative contributions of these sources to beach litter accumulation are still uncertain. Large rivers are considered as major entry points of litter (Lebreton et al., 2017; Schmidt et al., 2017; van Emmerik et al., 2019) as they can transport waste out to the sea due to their high flow rate. Once in the sea, surface currents and winds can distribute the light, floating component of litter (mainly plastic) over wide areas (van Sebille et al., 2020). Instead, the litter transported by small rivers (Galgani et al., 2000), especially heavier, negatively buoyant items, can be retained in coastal areas close to their mouths (Galgani et al., 2015; Morales-Caselles et al., 2021). However, the amount and the distance from river mouths at which litter accumulates is strictly dependent on the intensity of storms and rainfall events (Galgani et al., 2000; van Emmerik et al., 2019). Some studies have found a positive relationship between beach litter abundance and proximity of river mouths (Rech et al., 2014; Willis et al., 2017; Di Febbraro et al., 2021). On the other hand, a recent study failed to detect a positive correlation among beach litter abundance and proximity of rivers and harbors (Masiá et al., 2021). This discrepancy in results indicates that the processes affecting litter distribution along the coastline can be variable and quite complex (Fetisov and Chubarenko, 2021).

The Mediterranean Sea highly suffers from litter pollution as it is an enclosed basin with densely populated and urbanized coastal areas, rivers, and intense shipping traffic (UNEP/MAP, 2017). It has been estimated that the total annual input of plastic in the Mediterranean Sea is approximately 100,000 tons (Liubartseva et al., 2018), and about one third of this input could derive from rivers (Tockner et al., 2009; Ludwig et al., 2010; Verri et al., 2017). At the same time, Mediterranean coasts are destination for a high number of tourists (Andolina et al., 2020); therefore, the presence of litter can negatively impact local economies (Rangel-Buitrago et al., 2018; Cruz et al., 2020). In many countries, beach monitoring activities are periodically carried out as required by European Commission within the Marine Strategy Framework Directive (MSFD) for a comprehensive assessment of the impacts of anthropogenic pressures on marine ecosystems (Galgani et al., 2013). Some studies have focused on quantitative and qualitative beach litter characterization (e.g., Vlachogianni et al., 2018; Fortibuoni et al., 2021). Other studies have attempted to establish a relationship between litter abundance and proximity to entry points such as urban areas (Giovacchini et al., 2018; Di Febbraro et al., 2021) or beach exposure to winds and sea currents (Prevenios et al., 2018; Camedda et al., 2021). Nevertheless, knowledge gaps remain about the impact of storm events as well as of litter input from rivers and harbor-related activities on beach pollution. This is an important management issue since currents and waves associated with storms can accumulate floating litter on beaches even far from entry points (Galgani et al., 2000; Critchell et al., 2015) forcing some local municipalities to face high coasts for beach cleaning (Cruz et al., 2020; Chubarenko et al., 2021).

In this study, we estimated the impact of individual storm events on litter accumulation and local economy using as a model a managed, peri-urban beach facing a sector of the northwestern Mediterranean Sea. We also assessed the relationship between beach litter composition/density and proximity of potential entry points at local (urban area) and regional scale (Tuscany region). To accomplish these objectives, we monitored (i) the amount, typology and distribution of macro-litter accumulated along the study beach and (ii) the number of floating items transported to the sea through runoff of close waterways during storms over one year. We also gathered data of the annual costs required for beach cleaning activities from the local municipality. Then, we combined litter density/composition data obtained from the investigated beach with those relative to other beaches in the same region provided by a national public database, and we related them to beach distance from the closest river and harbor. Sea circulation features at local and Mediterranean sub-region scale were also evaluated. Specifically, we hypothesized that (i) storms would represent a key factor in determining beach pollution, and (ii) beaches closer to entry points would accumulate more litter compared to those located farther away.

2. Materials and methods

2.1. *Study area*

Visual litter surveys were performed along the beach of Marina di Pietrasanta (northern Tuscany (Mediterranean Sea, Italy; Figure 1A). Tuscany faces an ecologically important sector of the Ligurian and Tyrrhenian Seas (western sub-region of the Mediterranean Sea) hosting two regional parks, a national marine protected area and the international Pelagos Sanctuary devoted to the protection of marine mammals. This sector is identified as relatively low-plastic polluted (Liubatseva et al., 2018). However, many coastal areas of the Tuscany are characterized by intense urbanization and presence of coastal protection structures (Bertoni et al., 2021) and major harbors (Carrara, Viareggio, Livorno, Piombino; Figure 1A). Five major rivers (Magra, Serchio, Arno, Cecina, and Ombrone; Figure 1A) and other minor waterways with a torrential regime flow in this region. Moreover, many unmanaged and managed beaches attracting a high number of tourists during the summer period are present along the Tuscany coast.

The beach of Marina di Pietrasanta (4.7 km long with fine sediment) can be classified as peri-urban. Pietrasanta municipality is characterized by a high population density and strong urban development. Tourism is the major local economic activity, with up to 60,000 people staying over at least one night during the summer period (June to September; PDPL, touristic statistics). Two waterways, named Fosso Fiumetto and Fosso Motrone (Figure 1B), that are the output of the drainage basin of the Pietrasanta municipality, discharge inland waters into the sea through the beach (Federigi et al., 2017). The coastline is subjected to storms that can lead to waves high over 4 m (Franco et al., 2003). Wave state is prevalently characterized by West South-West winds, even though the strongest high-energy events come from the South-West (Cipriani et al., 2001). The tidal regime can be classified as microtidal, as the tidal range is usually lower than 30 cm. Our preliminary observations have shown that under typical weather conditions, the abundance of macro-litter items is generally negligible. The items deposited on the beach were regularly removed by operators of the waste collection company, ERSU (Eliminazione Rifiuti Solidi Urbani; www.ersu.it), of Pietrasanta (https://ersu.it/project/impianto-lavarone/). Beach cleaning was done daily during the spring-summer season (from May to September) and after each major storm event in the autumn-winter season. These removal activities provided us the opportunity to quantify the contribution of individual storms events to beach pollution.

2.2 Beach survey, litter input from waterways and management at local scale

To examine the seasonal dynamics of litter accumulation due to storms, three sites along Marina di Pietrasanta beach were selected (Figure 1B): one site was close to the Fosso Motrone (hereafter referred to as Motrone), one site was close to the Fosso Fiumetto (hereafter referred to as Fiumetto), and the remaining one located in an intermediate area between them (hereafter referred to as Pontile). Motrone and Fiumetto were approximately 1.4 km apart from Pontile. In each of the three sites, a 100 m long transect along the strand-line mark parallel to the beach was established, and the initial and final point of each transect was georeferenced using a GPS (Garmin GPSMap 64x). Litter collections were performed in four seasonal surveys, September 2020 (summer), December 2020 (autumn), February 2021 (winter), and April 2021(spring); and hence there were three sites x four seasons collections (=12). Sampling was performed two or three days after the beginning of a storm depending on the end time of the wash-out which typically occurs during the subsiding phase of waves (Fetisov and Chubarenko, 2021), and before litter removal by cleaning operators. We considered only storm events characterized by significant wave height equal or higher than 2.5 m according to Douglas scale (data provided by www.lamma.rete.toscana.it) and South-West or West prevailing direction of winds that resulted in litter deposition at the study beach.

During each survey, litter items with a size greater than 2.5 cm (macro-litter) deposited within a 10 m band on each side of the transects were collected. Thus, a total area of 2,000 m^2 of beach was sampled in each site and season. In accordance with the Marine Strategy Framework Directive guidelines (MSFD, 2013), litter items were categorized in nine macro-categories (Artificial polymers, Rubber, Textile, Paper, Metal, Wood, Glass, Various rubbish, and Unidentified) and 213 micro-categories (G1-G213; Supplementary Material Table S1) to identify potential main litter sources. The presence of macroscopic marine organisms on litter items was also noticed as their colonization indicates a long residency period in the sea (Ryan, 2015). For each sampling date and site, litter abundance was calculated as the total number of collected items, and litter density was expressed as total number of items per square meter of shore (items m^{-2}). The total weight of litter collected in each site in winter was also calculated. Logistic constrains prevented us to weigh litter in other seasons. To estimate the total amount of litter accumulated annually by storms along the entire beach of Marina di Pietrasanta, we gathered data on the direction and intensity of winds registered by the meteorological station of La Spezia (44° 05' 47.79" N and 09° 51' 27.52" E) from September 2020 to May 2021. We computed the number of days in which maximum intensity of winds from West, South-West directions that have exceeded the threshold (29 km/h) defining the category five of the Beafourt scale, corresponding to a sea state of 4 and a wave up to 2.5 m in height, for at least two consecutive days. This number was multiplied by mean number of litter items collected in the three sites across four seasons, and the resulting value was then multiplied by the length of the entire beach of Marina di Pietrasanta (4.7 km). We also gathered available information from ERSU about the typology and total amount of litter collected annually over the period 2014-2020 along the beach and relative cleaning costs.

Our preliminary visual observations of Motrone and Fiumetto water flux revealed that these waterways transported litter to the sea only during rainy periods associated to storms. Indeed, during calm weather conditions, the presence of a floating barrier prevented the drifting inland waste from ending up in the sea (Figure S1). To evaluate the potential contribution of the litter load coming from these waterways to beach litter accumulation during storms, a fixed observation point was established on the riverbank of each of them at a distance from the sea of approximately 300 m for Fosso Motrone and 150 m for Fosso Fiumetto from the sea. According to the available protocols (González et al., 2016; Crosti et al., 2018), we recorded one half an hour video of each of the two waterways in two consecutive days during each storm event, and all visible items (> 2.5 cm) floating along a transect perpendicular to the riverbank established from each fixed point was counted. Total litter waterway input during a storm was calculated as mean number of items counted in each of the two videos multiplied by 96, assuming a constant waterway flux.

Figure 1 Map of the Tuscany region showing (A) the location of the study beach of Marina di Pietrasanta (black square), major rivers (light-blue lines) and major harbors (red dots), (B) the location of sampling sites (red squares) and waterways (yellow arrows), Fosso Motrone and Fosso Fiumetto. (C) the direction of longshore transport direction along Tuscany coast according to Pranzini et al. (2020) (green arrows), the direction of main surface currents of the northern-western Mediterranean sector (dark-blue arrows), the location of the study beach (red dot), and the location of the five beaches (yellow dots) sampled during previous monitoring programs (www.db-strategiamarina.isprambiente.it). two-column fitting image, color only in online version

2.3 Evaluation of the relationship between beach litter and proximity to entry points at regional scale

To examine the relationship between beach litter pollution and proximity to potential litter entry points, we gathered currently available data on litter density and composition on Italian beaches from the public database (Sistema Informativo Centralizzato Dati di Monitoraggio; www.db-strategiamarina.isprambiente.it) of the national Ministry of Ecological Transition (Ministero della Transizione Ecologica) and the Italian Institute for Environmental Protection and Research (Istituto

Superiore per la Protezione e la Ricerca Ambientale, ISPRA). These data were collected during monitoring campaigns performed by Regional Agencies for Environmental Protection (Agenzie Regionali per la Protezione Ambientale, ARPA) along the Italian coasts according to the MSFD guidelines. Briefly, each beach sampling was performed in spring and autumn over the period 2015-2017 along three transects perpendicular to the coast, separated by less than 50 m defined by a 33 m stretch along the strandline to the first barrier, such as dunes, at the back of the shoreline section. For the present study, we extracted data of litter abundance and typology of five beaches located in Tuscany (Figure 1C) which are occasionally cleaned; three peri-urban beaches (Vittoria Apuana, Marina di Vecchiano, Quagliodromo) and two rural beaches (Marina di Castagneto and Collelungo). For each of these beaches we computed the density (number m^{-2}) of all sampled items as well as the density of items belonging to each macro-category averaged across two sampling times (autumn and spring) of each year, and then averaged across three years (2015, 2016, and 2017). For our investigated beach, these densities were calculated as described above, but they referred only to the study year (2020). We also calculated the distance of each of the five beaches and of each our sampling site (Pontile, Fiumetto, and Motrone) from both the closest waterway and closest major river, and both the closest harbor and closest major harbor by using a georeferenced map (www.regione.toscana.it/geoscopio/cartoteca). Rivers with a catchment area greater than 1,600 Km^2 were considered as major rivers, and harbors characterized by commercial traffic were considered as major harbors (Table S2). The geographical coordinates of all beach sites and their distance from rivers and harbors are reported in Table S3. Data on sea surface current circulation of the north-western Mediterranean gathered from published studies show that this sector is dominated by the Tyrrhenian Current and the West Corsican Current that merge to the north of Corsica and enter together the circulation pattern of the Ligurian Sea (Figure 1C; El-Geziry and Bryden, 2010; Micheli et al., 2010). Beaches of Marina di Pietrasanta, Vittoria Apuana, and Marina di Vecchiano are located within a littoral cell (i.e., a segment of coast where the long-shore sediment transport is bounded by either natural or artificial barriers forming a closed system; Bray et al., 1995; Barsanti et al., 2008) approximately 65 km long extending from Livorno harbor to Magra river. This cell is characterized by two littoral currents (Figure 1C), one with a southward direction (from the Magra river mouth to Pietrasanta) and the other one with a northward direction (from the river Arno mouth to Marina di Pietrasanta (Cipriani et al., 2001; Bertoni et al., 2021). Beaches of Marina di Castagneto, Quagliodromo, and Collelungo are located within the southern Tuscany littoral cell (Figure 1C) which is fed by sediments delivered by Albegna river (Pranzini et al., 2020)

2.4 Statistical analysis

To investigate how litter abundance varied across seasons, we used a generalized linear mixed-effects model (*glmer.nb* function in the MASS package; Venables and Ripley, 2002) with “Season” (four levels: summer, autumn, winter, and spring) as independent variable, site as random-effects term, and litter abundance as response variable. This model was used because of overdispersion in litter count data (Ver Hoef and Boveng, 2007). A generalized linear mixed-effects model was also used to examine whether a preferential accumulation of litter occurred in Marina di Pietrasanta beach close to the mouth of waterways. In this analysis, “Beach site” (three levels: Motrone, Pontile, Fiumetto) was the independent variable, season was random-effects term, and litter abundance was the response variable. Pairwise comparisons among sites or seasons were performed by using the function *emmeans* (Lenth, 2021). A multivariate one-way permutational analysis of variance (PERMANOVA; Anderson, 2001) was performed to test for differences in litter composition (either in terms of litter macro- or micro-category) among sites or seasons. For micro-categories, we considered only those categories that had at least a 5% contribution to the total litter in at least one site in one sampling occasion. PERMANOVAs were performed using the *adonis* function in the *vegan* package (Oksanen et al., 2019) and setting 999 permutations for the test at an α-level of 0.05. Two-dimensional non-metric multidimensional scaling (n-MDS) ordinations (Clarke, 1993) was employed to ordinate observations in a two-dimensional space. PERMANOVAs and n-MDS were performed on pairwise Bray-Curtis distances between the number of litter items within macro- (or micro-) category and sites (or seasons) after square root transformation (Anderson, 2001). To identify the macro- and micro-categories of litter that most contributed to the differences between levels of the significant factor, a similarity percentage analysis (SIMPER; Clarke and Gorley, 2015) was carried out. A Kruskal-Wallis non-parametric test was used to check differences in the mean total number of litter items transported daily by the two waterways, as data did not meet the normality assumption even after transformations. n-MDS ordinations were also used to visualize data patterns of macro-category litter composition, in terms of item density, and of distances of entry points (closest river, closest harbor, closest major river, and closest major harbor) from the investigated sites (Vittoria Apuana, Marina di Vecchiano, Marina di Castagneto, Quagliodromo, Collelungo, Fiumetto, Pontile, and Motrone). The Bray-Curtis similarity matrix of macro-category litter composition was obtained after square root transformation of data, while the matrix of distances from entry points was based on the Euclidean distance of square root-transformed and normalized data. A SIMPER analysis was carried out to identify the macro-categories contributing most to segregation of sites in multidimensional space. Then, the biological and environmental (BIO-ENV) procedure (Clarke and Gorley, 2015) based on a Spearman rank coefficient (ρ) between the environmental variables (closest river, closest harbor, closest major river, and closest major harbor) and litter macro-category composition was used to determine which variable(s) best explain the pattern of beaches in terms of litter macro-category composition. Lastly, to assess the relationship between total litter density and distances from entry points, Pearson correlation tests were carried out separately for each type of entry point. As beach distance data for major harbor did not meet normal distribution assumption, a Spearman correlation test was performed for this analysis. All statistical analyses were carried out in R environment (R core team, 2018), except that for BIOENV procedure that was conducted with the software PRIMER v.7 (Clarke and Gorley, 2015). Figures were created using the packages *ggplot2* (Wickham, 2016), *cowplot* (Wilke, 2019), and *visreg* (Breheny and Burchett, 2017).

3 Results

3.1 Beach survey, litter input from waterways and management at local scale

Most items deposited on Marina di Pietrasanta beach during our surveys were entangled in natural wrack consisting of terrestrial plants, woods, and fragments of the seagrasses *Posidonia oceanica* L. Delile and *Cymodocea nodosa* Ucria Ascherson (Figure S2). Many items were fragmented plastics, microplastic particles, and polystyrene items and the identification of their origin was not possible (Figure S3). Only three out of the collected items were visibly colonized by macroscopic marine organisms such as serpulids, mollusks, and eggs of unidentified organisms (Figure S3). Importantly, some items reported an expiring date relative to their original food or drink content dating back more than 20 or 30 years ago, although they were not visibly colonized by marine organisms (Figure S3). We also found items related to COVID-19 pandemic, such as surgical and FFP2 masks as well as plastic gloves. The number of litter items collected in the three sites ranged from 112 (0.056 items m^{-2} for Pontile in summer) to 1,489 (0.74 items m^{-2} for Motrone in autumn). In total, 8,520 litter items were collected in an area of 6,000 m^{-2} in four surveys. Litter abundance in winter was significantly greater than in summer and spring and abundance observed in spring did not differ from that in autumn (Figure 2A, Table S4). No significant differences in the mean number of items among sites were found (Figure 2B; Table S5).

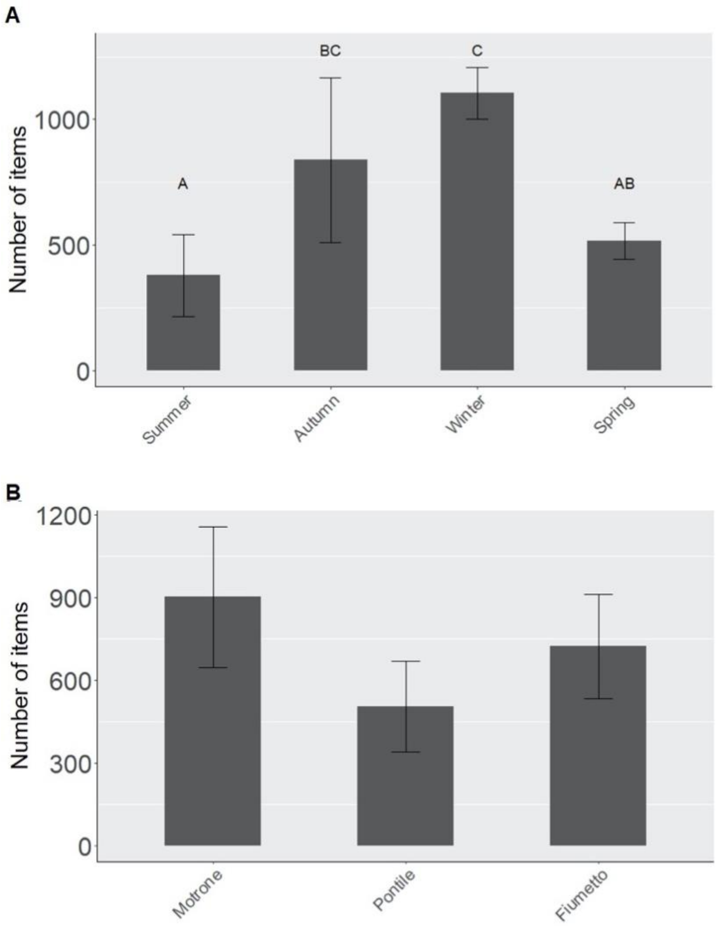

Figure 2 Bar plots showing litter abundance (mean ± SE) in each season averaged across the three sites of Marina di Pietrasanta beach (A) and in each of the three study sites averaged across seasons (B) over a one year. Letters denote significant differences at α-level of 0.05. n = 3 (A) and n = 4 (B).

single-column fitting image, color only in online version

The macro-category of Artificial polymers was the most abundant (7,655 items), followed by Metal (308 items), Rubber (246 items), and Cloths/Textile (186 items). PERMANOVA analysis did not detect significant differences in litter composition at the macro-category level among sites, nor among seasons (Table 1, Table S6), and a clear segregation among sites or seasons was not shown by n-MDSs (Figure 3A,B). PERMANOVA analysis also did not detect significant differences in litter composition at the micro-category level among sites (Table 1). In contrast, significant differences were found among seasons (Table 1) as shown also by their segregation in n-MDS (Figure 3D). SIMPER analysis revealed that Plastic pieces, both hard and soft, together with Polystyrene were the micro-categories that most contributed to these differences (cumulative contribution ranging from 67% to 80%; Table S7). Polystyrene and Shoes and sandals categories were more abundant in autumn than in other seasons. Plastic pieces and Cans categories were more abundant in winter than in other seasons (Table S7). Instead, more items belonging to Plastic Bags, Filaments, and Small bags micro-categories were found in summer and spring than in autumn and winter (Table S7). During the observation period, the threshold of 29 km/h for wind intensity was exceeded 11 times. Thus, considering an average of 710 items stranded per 100 m of beach sector due to a single storm event, the estimated number of items deposited along the entire beach over the study period was approximately 367,070. Based on the mean weight of litter items collected in winter in the three sites was approximately 15 kg, a total of 6.6 tons of litter might have been deposited along the entire beach during the study period.

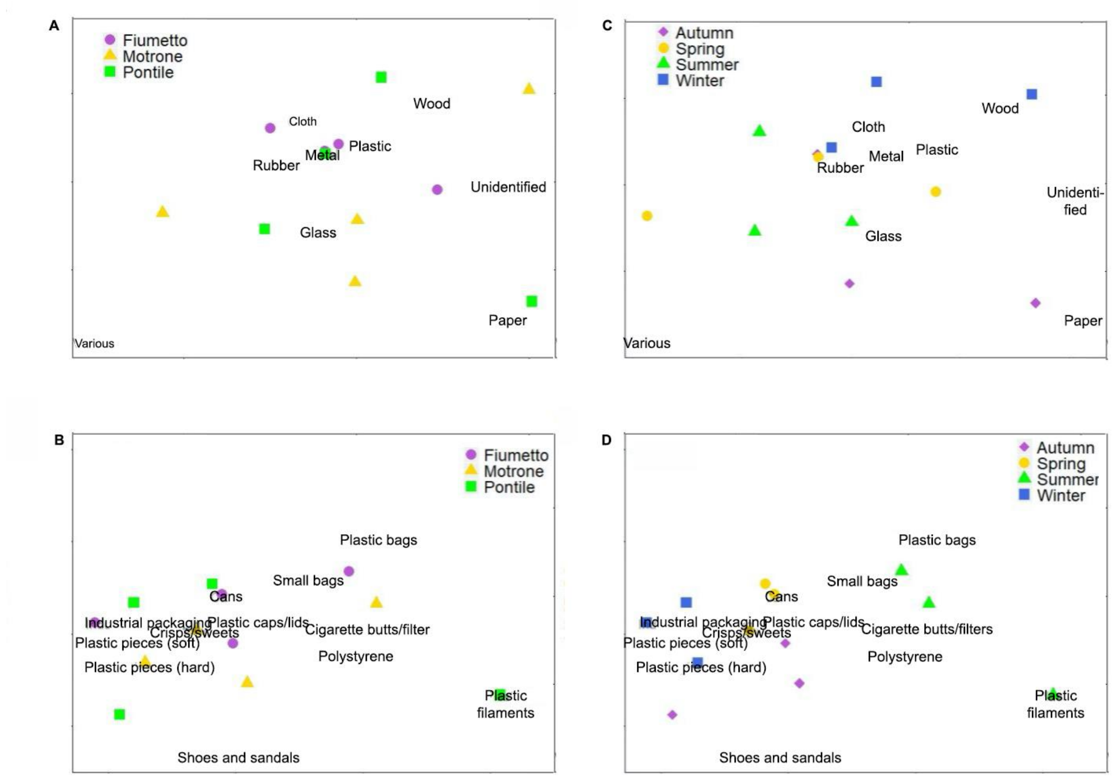

Figure 3 Non-metric multidimensional scaling ordination (n-MDS) of litter composition in terms of macro-categories for sites across seasons (A) and seasons across sites (B), and in terms of micro-categories among sites across seasons (C) and seasons across sites (D). Stress coefficient was lower than 0.2 in all ordinations.

two-column fitting image, color only in online version

Table 1 Results of multivariate analyses (PERMANOVA) on the difference in the composition of litter, in terms of macro- or micro-categories, sampled in Marina di Pietrasanta, among sites (across seasons) and seasons (across sites). Significant results are in bold.

Response variable	Predictor	df	Sum of squares	Mean squares	Pseudo-F	p-value	R^2
Litter Macro-Category	Site	2	0.125	0.063	6.48	0.666	0.13
	Residuals	9	0.871	0.097			
Litter Macro-Category	Season	3	0.443	0.148	2.132	0.107	0.44
	Residuals	8	0.553	0.070			
Litter Micro-Category	Site	2	0.304	0.152	0.751	0.687	0.14
	Residuals	9	1.824	0.203			
Litter Micro-Category	Season	3	1.223	0.408	3.605	**0.001**	0.57
	Residuals	8	0.905	0.113			

During storms, the protective barriers installed along the waterways did not retain all floating items because of substantial water level rising. Visual observations of waterway run-off revealed that up to 4 items passed through these barriers during half an hour. On average, the mean number of items transported to the sea per day by Fiumetto and Motrone was 36 (± 12 SE) and 96 (± 55), respectively. No significant differences in the mean number of transported items between the two waterways were found (chi-square = 0.09, d.f. = 1, p = 0.760). Based on the mean total number of items transported by these waterways in two consecutive days of storm and the number of storms (11) occurring during the study period, a total of 2,904 items (792 for Fiumetto and 2,112 items for Motrone) might have been discharged into the sea, assuming a constant waterway flux.

Based on data provided by ERSU, approximately 11,143 tons (dry weight) of stranded material (corresponding to 1,591 tons per year, Table S8) were collected by mechanical means along the beach of Marina di Pietrasanta from 2014 to 2020. Sand accounted for 68.3% (6,840 tons in total, seven-year average 977 tons) and natural wrack accounted for 29.5% (2,691 tons in total, seven-year average 423 tons) of total weight. Marine litter accounted for the 2.2% of the total weight of collected material. The amount of this litter varied among years, ranging from 0.4 ton to 104.8 tons, corresponding to 31 tons on average per year. Once collected, items of anthropogenic origin were combined with the other waste material produced by the local municipality and properly disposed according to national legislation. Unfortunately, there are no data on the amount of litter items that was recycled. The municipality of Pietrasanta spent on average approximately 130,000 euros per year on average for litter collection and processing, corresponding to 27,600 euros per km/year.

3.2 Evaluation of the relationships between beach litter and proximity to entry points at regional scale

On average, among the investigated beaches of Tuscany Vittoria Apuana, the northernmost beach, showed the highest value (937 ± 348 items, Table S9). However, when accounting for the differences in the beach area surveyed, the Motrone site in Marina di Pietrasanta beach showed the greatest mean litter density 0.53 (± 0.21 items m^{-2}; Table S9). n-MDS plots of macro-category litter composition showed that Motrone, Fiumetto, and Pontile were more similar to Quagliodromo and Vittoria Apuana than to other beaches (Figure 4). Simper analysis revealed that Artificial polymers was the macro-category most contributing to the segregation of Motrone, Fiumetto, Pontile, and Quagliodromo from the other sites, while differences between these two groups of sites were mainly due to Paper/cardboard and Metal with a minor contribution of the other macro-categories (Table S10). n-MDS plots of distances from entry points showed that Fiumetto, Pontile and Motrone were more similar each other than to the other sites (Figure 4). The BIO-ENV results indicated a significant relationship between the similarity matrix of macro-category litter composition and that of distances from entry points (ρ = 0.787, p = 0.003). The single variable that best associated with macro-category composition was the distance from the closest major harbor (ρ = 0.787; Table S11), while the best subset of variables associated with macro-category composition was the combination of distance from the closest major harbor and river (ρ = 0.596; Table S11). A significant correlation between total litter density and the distance from the closest major harbor was also detected (ρ = -0.97, p < 0.005; Figure 5; Table S12).

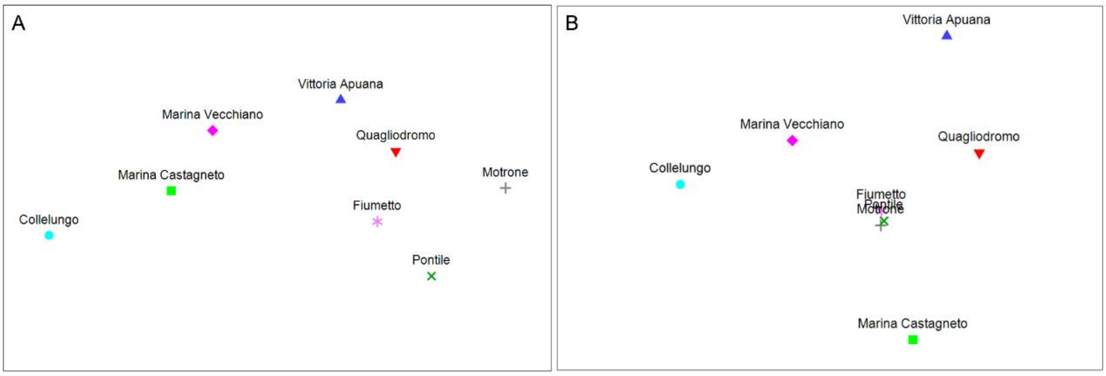

Figure 4 Non-metric multidimensional scaling ordination (n-MDS) of litter macro-category composition (A) and distances from entry points (B) for the study sites of Marina di Pietrasanta (Fiumetto, Pontile, and Motrone) and the sites monitored by ISPRA/ARPA (Vittoria Apuana, Marina di Vecchiano, Marina di Castagneto, Quagliodromo, and Collelungo). Stress coefficient was lower than 0.2 in both ordinations.

two-column fitting image, color only in online version

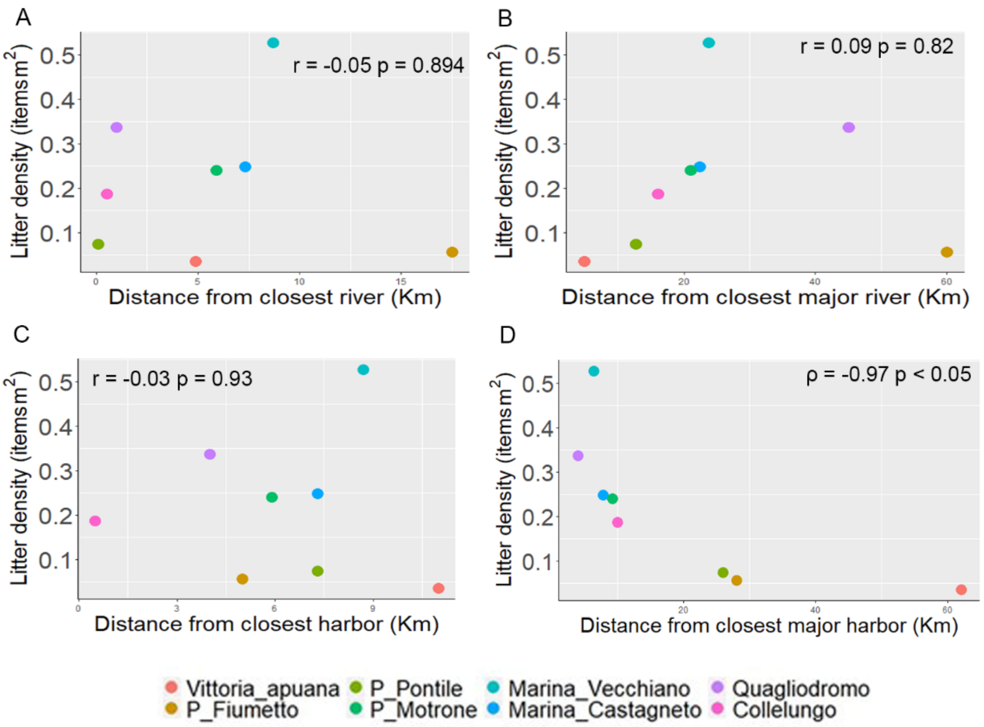

Figure 5 Relationship between litter density measured in the study sites of Marina di Pietrasanta (Fiumetto, Pontile, and Motrone) and in the sites monitored by ISPRA/ARPA (Vittoria Apuana, Marina di Vecchiano, Marina di Castagneto, Quagliodromo, and Collelungo), and their distance from their closest river (A), closest major river (B), closest harbor (C), or closest major harbor (D).

two-column fitting image, color only in online version

4 Discussion

Our study shows that autumn/winter storms can cause large depositions of anthropogenic litter and natural wrack on Mediterranean beaches. The waste introduced through runoff of the waterways closest to Marina di Pietrasanta during these storms did not significantly influence the distribution of litter along the beach. Analysis of published data revealed a clear positive relationship between litter density and beach proximity to the closest major harbor, as well as a significant relationship between litter composition (in terms of macro-category) and beach proximity to the combination of the closest major harbor and river at regional scale.

4.1 Impact of storms and proximity to entry points on litter accumulation on beaches

Previous studies have shown that massive litter deposition events could be directly related to the intensity and direction of winds, wave height, and the duration of the subsiding phase of the storm

(Brunner and Lwiza, 2019; Fetisov and Chubarenko, 2021). Shore geomorphology as well as the speed and direction of currents in the coastal zone can also play a role in washout dynamic (Fetisov and Chubarenko, 2021). In the Mediterranean, the frequency and intensity of storms in autumn/winter are generally greater than in spring/summer (Grabowska et al., 2010; Androulidakis et al., 2015). Our study reveals that wind with West, South-West direction and waves with height up to 2.5 associated to autumn/winter storms resulted in substantial litter deposition during the subsiding phase. This finding is consistent with previous field and modeling studies that showed a higher litter abundance in beaches during bad weather conditions (Rangel-Buitrago et al., 2017, 2018; Prevenios et al., 2018; Critchell et al., 2019; Camedda et al., 2021; Fetisov and Chubarenko, 2021).

In terms of beach pollution level, Marina di Pietrasanta showed a mean value (710 items/100 m) higher than the median level recorded in other Mediterranean beaches (477 items/100 m; Fortibuoni et al., 2021). Greater levels of pollution have been reported for some western Mediterranean beaches (up to 8,150 items/100 m; Fortibuoni et al., 2021). In terms of litter density, the average value recorded in Marina di Pietrasanta (0.34 items m^{-2}) was within the range of that estimated for other Italian beaches (from 0.55 to 0.11 items m^{-2}; Vlachogianni et al., 2018) but it was lower compared to that Ligurian Sea – North-Western Mediterranean beaches (on average 1.06 items m^{-2}; Giovacchini et al., 2018). Litter density in Marina di Pietrasanta beach was greater, except that for Quagliodromo, than values observed for sites monitored by ISPRA/ARPA.

When looking at litter composition, plastic category was the prevalent fraction in the beach of Marina di Pietrasanta. This observation is consistent with estimates of plastic pollution at national (Fortibuoni et al., 2021), Mediterranean (Vlachogianni et al., 2018), and global scales (Morales-Caselles et al., 2021) indicating that this pollutant is the most abundant and ubiquitous type of litter around the world. Regarding the other categories of litter, Metal, Textile, and Rubber where the second, third, and fourth most represented categories, respectively. This is consistent with results of a previous study performed in urban and urbanized sites close to our study beach (Giovacchini et al., 2018) but disagrees with another study conducted at national level showing that Paper/Cardboard, Sanitary waste, and Glass were the most abundant categories after plastic (Fortibuoni et al., 2021). We also found that autumn/winter storms accumulated a larger amount of hard and soft plastic fragments as well as polystyrene pieces than spring/summer ones. The source of plastic fragments is difficult to assess as they originated from the degradation of larger items present in marine environment for a long time (Camedda et al., 2021) while polystyrene pieces could derive from items used in fishing-related activities (Veiga et al., 2016; Giovacchini et al., 2018). In contrast, a greater abundance of plastic bags and small bags was found in spring/summer than in autumn/winter. We hypothesized that these items could be related to an improper waste disposal by visitors during the bathing seasons. The lack of a macroscopic organism colonization on items with an expiring date of 30 years ago collected in the present study could indicate that these items entered marine environment only recently. The presence of pandemic-associated plastic waste washed ashore is consistent with findings of recent studies (Ardusso et al., 2021; Mghili et al., 2022) and supports the idea of the COVID-19 pandemic as an additional source of littered plastics (Peng et al., 2021).

Previous studies suggest that most litter found on beaches originates in land and enters the sea mainly through rivers and coastal activities (Galgani et al., 2015; Morales-Caselles et al., 2021). Thus, greater litter accumulations are expected to occur in beaches closer to major entry points than those further away (Rech et al., 2014; Galgani, 2015; Willis et al., 2017). In our study, a preferential accumulation of litter in the two sites closer to the mouth of the waterways (i.e., Motrone and Fiumetto) was not observed. Based on our estimates, these waterways contributed only partly to beach litter accumulation during storms transporting approximately 12.4% of items found in the sampled area to the sea. Indeed, the protective floating barriers installed near the mouth of these waterways intercepted and retained most of the litter items transported by water flux. This suggests that processes acting at scales greater than peri-urban, such as local current circulation and river run-off could be responsible for beach pollution. Indeed, Marina di Pietrasanta beach lies at the convergence point of two littoral currents which transport sediments from two major rivers, Magra and Arno, allowing this beach to strongly accrete in time (up to 100 m in the past century; Cipriani et al., 2001; Cappucci et al., 2020; Bertoni et al., 2021). Recent studies have shown that these rivers also introduce large quantities of litter into the sea (i.e., more than 26,000 and 263,000 items on average per year, respectively; González-Fernández et al., 2021). Since several shoes and textile industries are in inland areas close to Serchio and Arno rivers, the presence of shoes and sandals stranded on Marina di Pietrasanta beach suggests that a portion of these items entered the sea from these rivers and then accumulated on the beach by sea currents especially during storms. A further support to the role of surface currents in generating pollution is provided by observations of *P. oceanica* fragments found along this beach. Indeed, the closest *P. oceanica* meadows to the beach are tens of kms away (https://www.emodnetseabedhabitats.eu/access-data/launch-map-viewer/), and a previous study demonstrated that *P. oceanica* seeds collected near to Marina di Pietrasanta beach were produced by plants growing in Corsica (French) meadows (Micheli et al., 2010).

Studies of the surface sea circulation indicate that the marine area off Tuscany coasts is influenced by currents of the north-western Mediterranean sector (El-Geziry and Bryden, 2010; Micheli et al., 2010) that can accumulate marine litter in this area (Liubatseva et al., 2018). Our study reveals that Tuscany beaches located closer to major harbors exhibited a greater litter density. This finding is consistent with a recent study showing a positive relationship between macro-plastic abundance and proximity of sites with intense fishing activity (Masiá et al., 2021), but it disagrees with studies reporting a greater litter density in beaches near to river mouths (Rech et al., 2014; Willis et al., 2017; Di Febbraro et al., 2021). Nonetheless, our results shows that the combination of proximity to the closest major harbor and river was the best subset of variables explaining the differences in terms of macro-category observed among the investigated beaches, indicating that both these entry points can play an important role in determining litter composition at regional scale. Therefore, we hypothesized that a considerable amount of litter items entering the marine area in front of the investigated coastal area might have been originated from harbor activities and river runoff. These items might have been initially remained in the proximity of entry points and successively been transported during storms by littoral currents toward beaches located in face of their convergence area, such as for example at Marina di Pietrasanta. Further studies should investigate the exact role of littoral currents in distributing and accumulating litter on beach hotspots.

4.2 Beach litter management implications

Cleaning activities are a fundamental tool to maintain beaches free from anthropogenic litter and avoid its further reintroduction in marine environments. Besides anthropogenic litter, some coastal municipalities must manage also beach wrack, which can constitute a relevant portion of all stranded material (for example up to 30% in our study beach). The costs incurred by north European countries for such removal varied (Chubarenko et al., 2021; Robbe et al., 2021) depending on cleaning methodology, personnel costs, infrastructure, machinery types, and tourism activity (Robbe et al., 2021). According to the litter threshold level (20 items per 100 m of beach) established by MSFD Technical Group on Marine Litter (van Loon et al., 2020), the beach monitored in the present study can be considered as polluted, and our estimates indicate that its cleaning requires approximately 130,000 euros per year. Thus, forecasting the time of storm events conducive to massive litter deposition on shores may help to plan effective measures to remove plastics and natural wrack and prevent its reintroduction in the sea. Importantly, this beach, lying at the convergence of two coastal currents, likely receives a high amount of litter originated from distant areas. Indeed, these currents run along two regions (Liguria and Tuscany), four coastal Provinces (La Spezia, Massa-Carrara, Lucca, and Pisa) and nine municipalities (Sarzana, Carrara, Massa, Forte dei Marmi, Pietrasanta, Camaiore, Viareggio, Vecchiano, and Pisa) of Italy. Therefore, beach cleaning management should benefit from an integrated-holistic approach involving multiple authorities. For example, the costs of litter handling should be ideally partitioned among all the authorities belonging to the littoral cell, or they should be managed at regional level, or alternatively they could be internalized via taxes and fees (Robbe et al., 2021). In addition, for a correct beach management, cleaning activities should be performed manually and on-demand to minimize their impact on beaches. Due to the ecological role played by wrack in beach ecosystems, this material should not be removed from where it deposited naturally (Robbe et al., 2021). However, in areas where this approach is not feasible, mechanical cleaning actions should be carried out considering how to manage not only all collected items but also the large amount of sand removed accidentally (up to 70% in dry weight of all material in the study beach). For example, wrack can be disposed appropriately for further use (e.g., soil fertilization and energy production), while a fraction of plastics could be recycled in a virtuous way to cut back its greenhouse gas emissions according to circular economy principles (Löhr et al., 2017; Kumartasli and Avinc, 2020). On the other hand, sand could be used as a valuable resource (Robbe et al., 2021), for example it could be redistributed in areas suffering erosion in nature-based projects for coastal protection (Chubarenko et al, 2021). Yet, the potential presence of microplastics within the sand and their effects should not be overlooked. Other effective solutions to tackle beach litter problem include the installation of barriers along water bodies and rivers to prevent floating urban/industrial waste or waste from coastal activities entering the sea during storms, as well as educational and outreach programs for harbor users to reduce the accidental/intentional waste dispersal.

5. Conclusions

Our study provides a quantitative estimate of the impact of single storm events on the environmental quality of Mediterranean beaches and local economy. It also reveals a positive relationship between the degree of pollution of beaches along the investigated coastal sector and their proximity to major harbors and to a less extent to rivers. These results suggests that the accumulation of marine litter on beaches can be driven by storms, and its abundance and composition can depend on the interplay between anthropogenic activities related to these entry points, littoral currents, and Mediterranean Sea region circulation features. Therefore, the problem of beach pollution management cannot be entirely delegated to individual municipalities, but it needs to be tackled at least at regional scale by multiple public and private entities, and volunteer associations.

CRediT authorship contribution statement

Virginia Menicagli: Investigation, Formal analysis, and Writing - Review and Editing **Davide De Battisti**: Investigation, Formal analysis, and Writing - Review and Editing. **Elena Balestri**: Conceptualization, Investigation, Formal analysis, Data curation, and Writing - Review and Editing. **Ileana Federigi**: Writing - Review and Editing. **Ferruccio Maltagliati**: Writing - Review and Editing. **Marco Verani**: Writing - Review and Editing. **Alberto Castelli**: Writing - Review and Editing. **Annalaura Carducci**: Project administration (equally contributed), Funding acquisition, and Writing - Review and Editing. **Claudio Lardicci**: Conceptualization, Project administration (equally contributed), Resources, and Writing - Review and Editing.

Declaration of competing interest

The authors declare no known competing financial interests or personal relationships that could have influenced the present work.

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References

Anderson, M.J., 2001. A new method for non-parametric multivariate analysis of variance. Austral. Ecol. 26, 32–46. https://doi.org/10.1111/j.1442-9993.2001.01070.pp.x

Andolina, C., Signa, G., Tomasello, A., Mazzola, A., Vizzini, S., 2021. Environmental effects of tourism and its seasonality on Mediterranean islands: the contribution of the Interreg MED BLUEISLANDS project to build up an approach towards sustainable tourism. Environ. Dev. Sustain., 23, 8601–8612. https://doi.org/10.1007/s10668-020-00984-8

Androulidakis, Y.S., Kombiadou, K.D., Makris, C.V., Baltikas, V.N., Krestenitis, Y.N., 2015. Storm surges in the Mediterranean Sea: Variability and trends under future climatic conditions. Dyn, 71, 56-82. http://dx.doi.org/10.1016/j.dynatmoce.2015.06.001

Ardusso, M., Forero-López, A.D., Buzzi, N.S., Spetter, C.V., Fernández-Severini, M.D., 2021. COVID-19 pandemic repercussions on plastic and antiviral polymeric textile causing pollution on beaches and coasts of South America. Sci. Total Environ. 763,144365. https://doi.org/10.1016/j.scitotenv.2020.144365

Balestri, E., Menicagli, V., Ligorini, V., Fulignati, S., Raspolli Galletti, A.M., Lardicci, C., 2019. Phytotoxicity assessment of conventional and biodegradable plastic bags using seed germination test. Ecol. Indic., 102, 569-580. https://doi.org/10.1016/j.ecolind.2019.03.005

Ballance, A., Ryan, P.G., Turpie, J.K., 2000. How much is a clean beach worth? The impact of litter on beach users in the Cape Peninsula, South Africa. S. Afr. J. Sci., 96, 210-213. https://hdl.handle.net/10520/AJA00382353_8975

Barsanti, M., Calda, N., Valloni, R., 2008. Definizione operativa delle unitá di trasporto litorale. Atti convegno coste prevenire, programmare, pianificare. Maratea, 15-17 Maggio, 2008. Collana studi e ricerche dell'Autoritá Interregionale del bacino della Basilicata, 9, 205-212.

Bejgarn, S., MacLeod, M., Bogdal, C., Breitholtz, M., 2015. Toxicity of leachate from weathering plastics: An exploratory screening study with *Nitocra spinipes*. Chemosphere, 132, 114-119. https://doi.org/10.1016/j.chemosphere.2015.03.010

Bergmann, M., Gutow, L., Klages, M., 2015. Marine Anthropogenic Litter. SpringerOpen. https://doi.org/10.1007/978-3-319-16510-3

Bertoni, D., Bini, M., Luppichini, M., Cipriani, L.E., Carli, A., Sarti, G., 2021. Anthropogenic impact on beach heterogeneity within a littoral cell (Northern Tuscany, Italy). J. Mar. Sci. Eng., 9, 151. https://doi.org/10.3390/jmse9020151

Bray, M., Carter, D.J., Hook, J.M., 1995. Littoral cell definition and budgets for central Southern England. J. Coast. Res. 11.

Breheny, P., Burchett, W., 2017. Visualization of Regression Models Using visreg. The R Journal, 9, 56-71.

Brunner, K., Lwiza, K.M.M., 2019. The impact of storm-induced coastal trapped waves on the transport of marine debris using high-frequency radar data. IEEE/OES Twelfth Current, Waves and Turbulence Measurement (CWTM), 1-5. https://doi.org/10.1109/CWTM43797.2019.8955266

Bucci, K., Tulio, M., Rochman, C.M., 2020. What is known and unknown about the effects of plastic pollution: A meta-analysis and systematic review. Ecol. Appl., 30, e02044. https://doi.org/10.1002/eap.2044

Camedda, A., Coppa, S., Palazzo, L., Marra, S., Massaro, G., Serrentino, F., 2021. Characterization and assessment of micro and macroscopic litter in Sardinian beaches (Western Mediterranean Sea). Water Air Soil Pollut. 232, 41. https://doi.org/10.1007/s11270-021-04993-9

Cappucci, S., Bertoni, D., Cipriani, L.E., Boninsegni, G., Sarti, G., 2020. Assessment of the anthropogenic sediment budget of a littoral cell system (Northern Tuscany, Italy). Water, 12. https://doi.org/10.3390/w12113240

Chubarenko, B., Woelfel, J., Hofmann, J., Aldag, S., Beldowski, J., Burlakovs, J., et al., 2021. Converting beach wrack into a resource as a challenge for the Baltic Sea (an overview). Ocean Coast. Manag., 200,105413. https://doi.org/10.1016/j.ocecoaman.2020.105413

Cipriani, L.E., Ferri, S., Iannotta, P., Paolieri, F., Pranzini, E., 2001. Morfologia e dinamica dei sedimenti del litorale della Toscana settentrionale. Studi Costieri, 4, 119–156.

Clarke, K.R., 1993. Non-parametric multivariate analyses of changes in community structure. Aust. J. Ecol. 18, 117–143. doi: 10.1111/j.1442-9993.1993.tb00438.x

Clarke, K.R., Gorley, R.N., 2015. PRIMER v7: User manual/tutorial.Plymouth, UK: PRIMER-E.

Critchell, K., Grech, A., Schlaefer, J., Andutta, F.P., Lambrechts, J., Wolanski, E. et al., 2015. Modelling the fate of marine debris along a complex shoreline: Lessons from the Great Barrier Reef. Estuar. Coast. Shelf Sci., 167 (Part B), 414-426. https://doi.org/10.1016/j.ecss.2015.10.018

Critchell, K., Hamann, M., Wildermann, N., Grech, A., 2019. Predicting the exposure of coastal species to plastic pollution in a complex island archipelago. Env. Poll. 252 part B, 982-991. https://doi.org/10.1016/j.envpol.2019.06.031

Crosti, R., Arcangeli, A., Campana, I., Paraboschi, M., González-Fernández, D., 2018. 'Down to the river': amount, composition, and economic sector of litter entering the marine compartment, through the Tiber River in the Western Mediterranean Sea. Rend. Lincei Sci. Fis. Nat., 29, 859–866. https://doi.org/10.1007/s12210-018-0747-y

Cruz, C.J., Muñoz-Perez, J.J., Carrasco-Braganza, M.I., Poullet, P., Lopez-Garcia, P., Contreras, A., et al., 2020. Beach cleaning costs. Ocean Coast. Manag., 188, 105118. https://doi.org/10.1016/j.ocecoaman.2020.105118

Di Febbraro, M., Frate, L., de Francesco, M.C., Stanisci, A., Tozzi, F.P., Varricchione, M. et al., 2021. Modelling beach litter accumulation on Mediterranean coastal landscapes: An integrative framework using species distribution models. Land, 10, 54. https://doi.org/10.3390/land10010054

El-Geziry, T.M., Bryden, I.G., 2010. The circulation pattern in the Mediterranean Sea: issues for modeller consideration, J. Oper. Oceanogr., 3, 39-46. https://doi.org/10.1080/1755876X.2010.11020116

Federigi I, Verani M, Carducci A. 2017. Sources of bathing water pollution in northern Tuscany (Italy): Effects of meteorological variables. Mar Pollut Bull. 114, 843-848. https://doi.org/10.1016/j.marpolbul.2016.11.017

Fetisov, S., Chubarenko, I., 2021. Marine litter stormy wash-outs: Developing the neural network to predict them. Pollutants, 1, 156–168. https://doi.org/10.3390/pollutants1030013

Fortibuoni, T., Amadesi, B., Vlachogianni, T., 2021. Composition and abundance of macrolitter along the Italian coastline: The first baseline assessment within the european Marine Strategy Framework Directive. Environ. Poll., 268 (Part A), 115886. https://doi.org/10.1016/j.envpol.2020.115886

Franco, L., Piscopià, R., Corsini, S., Inghilesi. R., 2003. "L'Atlante delle onde nei mari italiani - Italian Wave Atlas." Atti Giornate Italiane di Ingegneria Costiera VII ediz., AIPCN,At: TriesteVolume: 93-104

Galgani, F., 2015. Marine litter, future prospects for research. Front. Mar. Sci., 2, 87. https://doi.org/10.3389/fmars.2015.00087

Galgani, F., Hanke, G., Werner, S., De Vrees, L., 2013. Marine litter within the European Marine Strategy Framework Directive. ICE J. Mar. Sci., 6, 1055-1064. https://doi.org/10.1093/icesjms/fst122

Galgani, F., Leauté, J.P., Moguedet, P., Souplet, A., Verin, Y., Carpentier, A., et al., 2000. Litter on the sea floor along European coasts. Mar. Pollut. Bull. 40, 516–527. https://doi.org/10.1016/S0025-326X(99)00234-9

Giovacchini, A., Merlino, S., Locritani, M., Stroobant, M., 2018. Spatial distribution of marine litter along Italian coastal areas in the Pelagos sanctuary (Ligurian Sea - NW Mediterranean Sea): A focus on natural and urban beaches. Mar. Pollut. Bull., 130, 140-152. https://doi.org/10.1016/j.marpolbul.2018.02.042

González, D., Hanke, G., Tweehuysen, G., Bellert, B., Holzhauer, M., Palatinus, A., et al., 2016. Riverine litter monitoring - Options and recommendations. MSFD GES TG Marine Litter Thematic Report; JRC Technical Report; EUR 28307. https://doi.org/10.2788/461233

González-Fernández, D., Cózar, A., Hanke, G., Viejo, J., Morales-Caselles, C., Bakiu, R., et al., 2021. Floating macrolitter leaked from Europe into the ocean. Nat. Sustain., 4, 474–483. https://doi.org/10.1038/s41893-021-00722-6

Grabowska, K., 2010. Changes in storm frequency in the Mediterranean Sea region. Miscellanea Geographica, 14, 71-78.

Krelling, A.P., Williams, A.T., Turra, A., 2017. Differences in perception and reaction of tourist groups to beach marine debris that can influence a loss of tourism revenue in coastal areas. Mar. Policy, 85, 87-99. http://dx.doi.org/10.1016/j.marpol.2017.08.021

Kumartasli, S., Avinc, O., 2020 Recycling of marine litter and ocean plastics: A vital sustainable solution for increasing ecology and health problem. In: Muthu, S.S., Gardetti, M.A. (eds) Sustainability in the textile and apparel industries. Sustainable textiles: Production, processing, manufacturing & chemistry. Springer, Cham. https://doi.org/10.1007/978-3-030-38013-7_6

Lebreton, L., van der Zwet, J., Damsteeg, J.W., Slat, B., Andrady, A., Reisser, J., 2017. River plastic emissions to the world’s oceans. Nat. Commun., 8, 15611. https://doi.org/10.1038/ncomms15611

Lenth, R.V., 2021. emmeans: Estimated marginal means, aka least-squares means. R package version 1.6.2. https://CRAN.R-project.org/package=emmeans

Liubartseva, S., Coppini, G., Lecci, R., Clementi, E., 2018. Tracking plastics in the Mediterranean: 2D Lagrangian model. Mar. Pollut. Bull., 129, 151-162. https://doi.org/10.1016/j.marpolbul.2018.02.019

Löhr, A., Savelli, H., Beunen, R., Kalz, M., Ragas, A., Van Belleghem, F., 2017. Solutions for global marine litter pollution. Curr. Opin. Environ. Sustain. 28, 90–99. http://dx.doi.org/10.1016/j.cosust.2017.08.009

Ludwig, W., Bouwman, A.F., Dumont, E., Lespinas, F., 2010. Water and nutrient fluxes from major Mediterranean and Black Sea rivers: past and future trends and their implications for the basin-scale budgets. Glob. Biogeochem. Cycles 24, GB0A13. https://doi.org/10.1029/2009GB003594

Masiá, P., Ardura, A., Gaitán, M., Gerber, S., Rayon-Viña, F., Garcia-Vasquez, E., 2021. Maritime ports and beach management as sources of coastal macro-, meso-, and microplastic pollution. Environ. Sci. Pollut. Res., 28, 30722-30731. https://doi.org/10.1007/s11356-021-12821-0

Mghili, B., Analla, M., Aksissou, M., 2022. Face masks related to COVID-19 in the beaches of the Moroccan Mediterranean: An emerging source of plastic pollution. Mar. Pollut. Bull., 174, 113181. https://doi.org/10.1016/j.marpolbul.2021.113181

Menicagli, V., Balestri, E., Lardicci, C., 2019a. Exposure of coastal dune vegetation to plastic bag leachates: A neglected impact of plastic litter. Sci. Total Environ., 683, 737-748. https://doi.org/10.1016/j.scitotenv.2019.05.245

Menicagli, V., Balestri, E., Vallerini, F., Castelli, A., Lardicci, C., 2019b. Adverse effects of non-biodegradable and compostable plastic bags on the establishment of coastal dune vegetation: First experimental evidence. Environ. Pollut., 252, 188-195. https://doi.org/10.1016/j.envpol.2019.05.108

Menicagli, V., Balestri, E., Vallerini, F., Castelli, A., Lardicci, C., 2020. Combined effect of plastic litter and increased atmospheric nitrogen deposition on vegetative propagules of dune plants: A further threat to coastal ecosystems. Environ. Pollut., 266, 115281. https://doi.org/10.1016/j.envpol.2020.115281

Micheli, C., Spinosa, F., Aliani, S., Gasparini, G.P., Molcard, A., Peirano, A., 2010. Genetic input by *Posidonia oceanica* (L.) Delile fruits dispersed by currents in the Ligurian Sea. Plant Biosyst.,144, 333-339. https://doi.org/10.1080/11263501003764798

Morales-Caselles, C., Viejo, J., Martí, E., González-Fernández, D., Pragnell-Raasch, H., González-Gordillo, I.J., et al., 2021. An inshore–offshore sorting system revealed from global classification of ocean litter. Nat. Sustain. 4, 484–493. https://doi.org/10.1038/s41893-021-00720-8.

MSFD, 2013. MSFD Technical Subgroup on Marine Litter, Guidance on monitoring of marine litter in European seas. European Commission, Luxembourg: Publications Office of the European Union. https://doi.org/10.2788/99475

Oehlmann, J., Schulte-Oehlmann, U., Kloas, W., Jagnytsch, O., Lutz, I., Kusk, K.O., et al., 2009. A critical analysis of the biological impacts of plasticizers on wildlife. Philos. Trans. R. Soc. Lond. B: Biol. Sci. 364, 2047–2062. https://doi.org/10.1098/rstb.2008.0242

Oksanen, J., Guillaume Blanchet, F., Friendly, M., Kindt, R., Legendre, P., McGlinn, D., et al., 2019. "vegan: Community Ecology". R package version 2.5-6.

PDPL database, Database on tourist accommodation. Provincial Department of territorial promotion of Lucca (PDPL). Available online: http://www.comune.lucca.it/flex/cm/pages/ServeBLOB.php/L/IT/IDPagina/16726

Peng, Y., Wu, P., Schartup, A.T., Zhang, Y., 2021. Plastic waste release caused by COVID-19 and its fate in the global ocean. PNAS, 118, e2111530118. https://doi.org/10.1073/pnas.2111530118

Pranzini, E., Cinelli, I., Cipriani, L.E., Anfuso, G., 2020. An integrated coastal sediment management plan: The example of the Tuscany Region (Italy). J. Mar. Sci. Eng., 8, 33. https://doi.org/10.3390/jmse8010033

Prevenios, M., Zeri, C., Tsangaris, C., Liubartseva, S., Fakiris, E., Papatheodorou, G., 2018. Beach litter dynamics on Mediterranean coasts: Distinguishing sources and pathways. Mar. Pollut. Bull., 129, 448-457. https://doi.org/10.1016/j.marpolbul.2017.10.013

Rangel-Buitrago, N., Williams, A., Anfuso, G., Arias, M., Gracia, A.C., 2017. Magnitudes, sources, and management of beach litter along the Atlantico department coastline, Caribbean coast of Colombia. Ocean Coast. Manag., 138, 142-157. https://doi.org/10.1016/j.ocecoaman.2017.01.021

Rangel-Buitrago, N., Castro-Barros, J.D., Gracia, C.A., Villamil Villadiego, J.D., Williams, A.T., 2018. Litter impacts on beach/dune systems along the Atlantico Department, the Caribbean Coastline of Colombia. Mar. Pollut. Bull., 137, 35-44. https://doi.org/10.1016/j.marpolbul.2018.10.009.

Rech, S., Macaya-Caquilpán, V., Pantoja, J.F., Rivadeneira, M.M., Jofre Madariaga, D., Thiel, M., 2014. Rivers as a source of marine litter – A study from the SE Pacific. Mar. Pollut. Bull., 82, 66-75. https://doi.org/10.1016/j.marpolbul.2014.03.019

Robbe, E., Woelfel, J., Balčiūnas, A., Schernewski, G., 2021. An impact assessment of beach wrack and litter on beach ecosystem services to support coastal management at the Baltic Sea. Environ. Manag., 68, 835–859. https://doi.org/10.1007/s00267-021-01533-3

Rochman, C.M., Hoh, E., Kurobe, T., Teh, S.J., 2013. Ingested plastic transfers hazardous chemicals to fish and induces hepatic stress. Sci. Rep., 3, 3263. https://doi.org/10.1038/srep03263

Rochman, C.M., Kurobe, T., Flores, I., Teh, S.J., 2014. Early warning signs of endocrine disruption in adult fish from the ingestion of polyethylene with and without sorbed chemical pollutants from the marine environment. Sci. Total Environ., 493, 656-661. https://doi.org/10.1016/j.scitotenv.2014.06.051

Ryan, P.G., 2015. Does size and buoyancy affect the long-distance transport of floating debris? Environ. Res. Lett. 10, 084019. https://doi.org/10.1088/1748-9326/10/8/084019

Schmidt, C., Krauth, T., Wagner, S., 2017. Export of plastic debris by rivers into the sea. Environ. Sci. Technol., 51, 21, 12246–12253. https://doi.org/10.1021/acs.est.7b02368

Scotti, G., Esposito, V., D'Alessandro, M., Panti, C., Vivona, P., Consoli, P., et al., 2021. Seafloor litter along the Italian coastal zone: An integrated approach to identify sources of marine litter. Waste Manag., 124, 203-212. https://doi.org/10.1016/j.wasman.2021.01.034

Tockner, K., Uehlinger, U., Robinson, C.T., 2009. Rivers of Europe. Academic Press, London.

UNEP/MAP, 2017. Mediterranean quality status report for the Mediterranean – MED QSR 2017. Kenya: United Nations Environment Programme.

van Emmerik, T., Tramoy, R., van Calcar, C., Alligant, S., Treilles, R., Tassin, B., et al., 2019. Seine plastic debris transport tenfolded during increased river discharge. Front. Mar. Sci., 6, 642. https://doi.org/10.3389/fmars.2019.00642

van Loon, W., Hanke, G., Fleet, D., Werner, S., Barry, J., Strand, et al., 2020**.** A European threshold value and assessment method for macro litter on coastlines. EUR 30347 EN**.** Publications Office of the European Union, Luxembourg. https://doi.org/10.2760/54369 van Sebille, E., Aliani, S., Lavander Law, K., Maximenko, N., Alsina, J.M., Bagaev, A., et al., 2020. The physical oceanography of the transport of floating marine debris. Environ. Res. Lett., 15, 023003. https://doi.org/10.1088/1748-9326/ab6d7d

Veiga, J.M., Fleet, D., Kinsey, S., Nilsson, P., Vlachogianni, T., Werner, S., et al., 2016. Identifying sources of marine litter. MSFD GES TG Marine Litter Thematic Report; JRC Technical Report; EUR 28309. https://doi.org/10.2788/018068

Ver Hoef, J.M., Boveng, P.L., 2007. Quasi-poisson vs. negative binomial regression: How should we model overdispersed count data? Ecology, 88, 2766-2772. https://doi.org/10.1890/07-0043.1

Verri, G., Pinardi, N., Oddo, P., Ciliberti, S.A., Coppini, G., 2017. River runoff influences on the Central Mediterranean overturning circulation. Clim. Dyn., 50, 1675-1703. https://doi.org/10.1007/s00382-017-3715-9

Venable, W.N., Ripley, B.D., 2002. Modern applied statistics with S. Fourth Edition. Springer, New York.

Vlachogianni, T., Fortibuoni, T., Ronchi, F., Zeri, C., Mazziotti, C., Tutman, P. et al., 2018. Marine litter on the beaches of the Adriatic and Ionian Seas: An assessment of their abundance, composition and sources. Mar. Pollut. Bull., 131 (Part A), 745-756. https://doi.org/10.1016/j.marpolbul.2018.05.006

Wickham, H., 2016. ggplot2: Elegant Graphics for Data Analysis. Springer-Verlag New York.

Wilke, C.O., 2019. cowplot: Streamlined Plot Theme and Plot Annotations for 'ggplot2'. R package version 1.0.0.

Willis, K., Hardesty, B.D., Kriwoken, L., Wilcox, C., 2017. Differentiating littering, urban runoff and marine transport as sources of marine debris in coastal and estuarine environments. Sci. Rep., 7, 44479. https://doi.org/10.1038/srep44479