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Anthropogenic litter in a Mediterranean coastal wetland: A heterogeneous spatial pattern of historical deposition

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ABSTRACT

Coastal wetlands represent areas that can testify historical accumulation of litter. We analyzed the anthropogenic litter deposited on the channel bottom of a coastal wetland area that experienced water stress due to extreme summer dryness after about 20 years. We hypothesize that the litter accumulated in the different areas over the years reflects the different social user categories (i.e., fishermen, beach users, hunters) and exposure to meteo-marine events. Our findings highlight that historically accumulated litter is composed of plastics (78.8 %), clothes (8.9 %), and glass (4.9 %). Moreover, litter concentration averages 53.6 items/ha in the 8 sectors. The most found categories were common household items (25.4 %), diverse (professional and consumer) items (24.2 %), and food and beverages packaging (21.4 %). Finally, litter diversity indices and the Detrended Correspondence Analysis showed sector and litter type similarities. We reported for the first time the presence of litter accumulated for 20 years testifying non-more occurring recreational activities.

1. Introduction

Coastal wetlands are vulnerable ecosystems of high ecological value and provide important ecosystem services (Barbier, 2019; Newton et al., 2020). Nevertheless, these ecosystems are impacted by a high number of different anthropogenic threats, including different types of water and soil pollution (Kennish, 2002; Battisti et al., 2008; Painting et al., 2020; Rodríguez-Santalla and Navarro, 2021; Ertaş et al., 2022). More particularly, coastal wetlands are still poorly studied regarding the pattern of deposition of anthropogenic litter (e.g., Cresta and Battisti, 2021; Gallitelli et al., 2021, 2023a), when compared to coastal dunes and littorals (e.g., Alshawafi et al., 2017; Poeta et al., 2014, 2016; Giovacchini et al., 2018; Prevenios et al., 2018; Mutlu et al., 2020; Bergmann et al., 2015). These dynamic environments may be characterized by the progressive accumulation of litter which, once deposited, settles on the bottom of ponds and canals, without being moved by natural meteo-marine events or removed by clean-ups. Therefore, coastal wetlands represent areas that can testify to the historical accumulation of litter, both in quantitative and qualitative terms (types of litter and origin), since, here, there are no clean-up activities (sensu Battisti et al., 2020) carried out regularly. This characterization of anthropogenic litter may be possible only when exceptional events, such as water stress resulting from extreme summer drought or land reclamation actions, bring to light these materials sedimented over the years.

This study analyzes the anthropogenic litter deposited on the bottom of the channels of a coastal wetland area that after about 20 years has experienced water stress-induced both by a period of extreme summer dryness and by management actions designed to deepen the reservoir channels. These events allowed for the systematic remediation of a large part of the wetland area from anthropogenic litter deposited over the years. Given that this wetland represents a site currently frequented by different social targets (i.e., beachgoers, fishermen) and, historically, by waterfowl hunters (until about 20 years ago), our goal was to characterize the different types of litter, highlighting any spatial patterns associated with attendance by different social targets. Moreover, the coastal wetland area is located to a few meters from the coastline: therefore, it may be affected by the input of material from the sea. Therefore, we hypothesize that the litter accumulated in the different

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areas over the years reflects the different social categories of users (i.e., fishermen, beach users, hunters) as well as exposure to meteo-marine events (in the areas adjacent to the sea). In addition to the characterization by categories, we applied indices of litter diversity (Battisti et al., 2017, 2018) to analyze the level of heterogeneity in litter and its implication for wetland management.

2. Materials and methods

2.1. Study area

The study area was located in the "Torre Flavia wetland" nature reserve (municipalities of Cerveteri and Ladispoli; Lazio, central Italy; 41°58′ N, 12°03′ E), a small coastal wetland (40 ha) on the Tyrrhenian coast (Special Protection Area according to the Directive 2009/147/EC 'Birds'; code IT6030020), relict of a larger wetland drained and transformed by land reclamation (Battisti, 2006; Fig. 1). At a landscape scale, this area represents a remnant fragment of wetland inside an agricultural and urbanized matrix. At a local scale, it shows a seminatural heterogeneity with a dominance of *Phragmites australis* reedbeds and ponds used for fish farming from 1938 (mainly managing stocks of *A. anguilla* and three species of mullets, *Mugil cephalus*, *Chelon saliens*, *Chelon ramada*). From 2004, activities of fish stock management like flooding, reedbed mowing and burning (Battisti et al., 2009a, 2009b) were completely abandoned. Near the reedbeds, there are flooded meadows with *Carex hirta*, *Juncus acutus* and Cyperaceae corresponding to the *Juncetalia maritimi* habitat type according to the "Habitat" Directive 92/43/EC (Guidi, 2006; Fanelli and Bianco, 2007). The water flooding the wetland is mainly of meteoric and sea storm origin (Battisti, 2006). Along the coastline patches of the EU Habitat type "Embryonic shifting dunes" (code 2110) are present (Guidi, 2006; Ioni et al., 2020). The climate is xeric-meso-Mediterranean (Blasi and Michetti, 2005). For details on chemistry and water quality: Sabia et al. (2018); for morphodynamics of the coastal landscape, see Raffi et al. (2018) and Davoli et al. (2019). For a faunal arrangement: Battisti et al. (2021).

2.2. Litter sampling protocol

During the summer of 2022, the entire wetland reservoir was drained to allow for some deepening restoration of the canals, which, since 2004 had never been subjected to this stress (Battisti, 2006). This allowed us to carry out a fine-grained litter clean-up over the entire area (about 80,000 m^2 of 'sectors' or polygonal ponds placed between the canals). However, to enable standardized data collection, a sampling design was made by identifying 8 sectors of standard size and shape (i.e., 1 ha = 10,000 m^2 each one; Fig. 1), within which the litter was quantified and characterized.

In detail, along each sector, two operators collected any type of litter larger than 2.5 cm, considered as 'macrolitter' (i.e., litter >2.5 cm, according to Galgani et al., n.d). The collected material was placed in a sterile bag and stored for classification (at the Department of Science, Roma III University). After, we obtained the total number of anthropogenic litter items for each sector (corresponding to a value of density as n. litter items/ha, see below).

To characterize the anthropogenic litter, we used three different criteria. A first coarse-grained classification considers the type of materials. We divided the items into plastics, glass, cloth, rubber, metal, paper, and others and then into specific categories (Table S1).

A second classification followed the criteria of categories coded in the Marine Strategy Frame Directive Guidelines (hereafter, MSFD; see

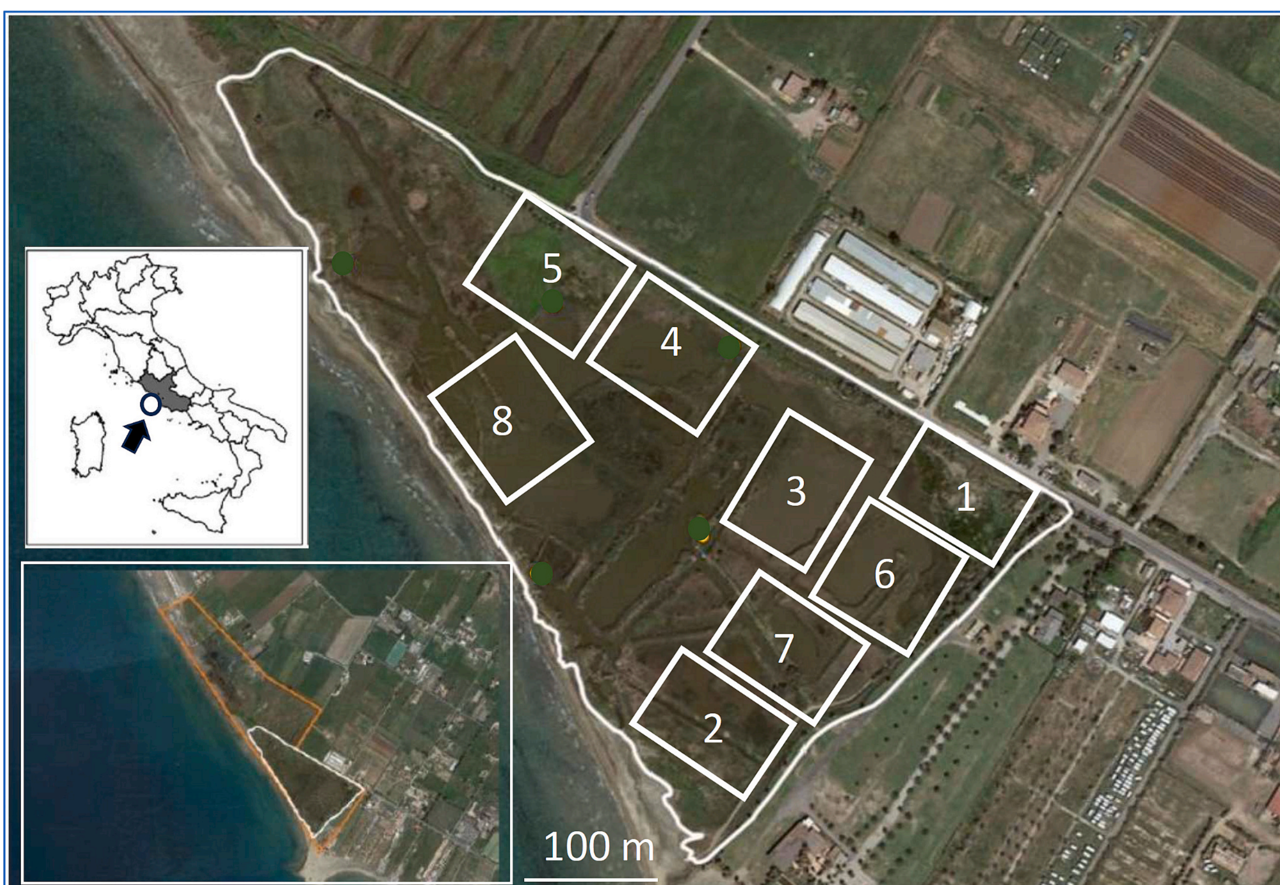

Fig. 1. Map of the study area ('Torre Flavia' wetland; Latium, central Italy; source: Google Maps). The 8 investigated sectors have been reported. On the left: the location along the Italian peninsula.

"Guidance on Monitoring of Marine Litter in European Seas", Galgani et al., 2013, check-list in Supplementary materials: Tables S2 and S3).

Finally, a third classification, aimed to understand the source of litter, followed Bruge et al. (2018). In this case (see Table S4 in Supplementary materials), we considered the main sources of litter (from tourism, industry, household items, professional, sewage debris), i.e. common household items (CHI), fisheries and mariculture gear (FMT), recreational fishing and hunting (RFH), food and beverages packaging (FOO), industrial packaging and construction debris (IPCD), smoking related items (SMO), sewage-related debris (SRD), diverse (professional and consumer; DIV), unknown (UNK).

2.3. Data analyses

For each sector (and for any category), we obtained the number of litter items, their frequency (n. items/total) and mean density (i.e., averaged n. items/ha).

To compare the median values of density, we performed a non-parametric Kruskal-Wallis test. To compare litter frequencies, we used a χ^2 test. We performed a Detrended Correspondence Analysis (Hill and Gauch Jr., 1980) as an ordination approach to show similarity among sectors and litter type based on the dataset item density/sectors. We performed a cluster analysis (Euclidean distance/pared groups) to classify the similarity among sectors based on the density of MSFD categories in each one. The PAST software was used for the statistical analyses (Hammer et al., 2001). The alpha level was always set to 0.05.

Finally, to obtain information about the litter heterogeneity, we performed a set of uni-variate metrics of diversity, usually used for living communities (Magurran and McGill, 2011) but recently proposed for an application to litter assemblages (see Battisti et al., 2018; Gallitelli et al., 2021). To date, the Shannon-Wiener index (Shannon and Weaver, 1949) and the evenness index (Alatalo, 1981) have been applied to litter to calculate, respectively, the Litter Shannon Index and the Litter evenness (i.e., the pattern in frequency distribution among sectors; see Battisti et al., 2017, 2018).

All the graphs were prepared using GraphPad software (https://www.graphpad.com/).

3. Results

A total of 429 items of macrolitter were collected in the 8 sectors (Fig. 2). Overall, litter concentration averages 53.6 items/ha (±57.3 s.d., min-max: 6–166 items/ha) in the 8 sectors. Concerning litter density, sectors 5 and 6 showed the highest litter density ($n = 166$ and $n = 105$ items/ha, respectively), while 3 and 4 showed the lowest number of macrolitter ($n = 14$ and $n = 6$ items/ha, respectively).

Overall, the total accumulated litter is mostly composed of plastics (78.8 %), clothes (8.9 %), and glass (4.9 %) (see Fig. 3A, Table 1). Particularly, we observed a significant difference in mean density between coarse-grained litter types ($H = 21.76$, $p < 0.001$; Kruskal-Wallis test; Fig. 3B).

Following the MSFD categorical criterion, the top 10 categories accounted for 85.1 % of total litter (Fig. 4A and C, Table 1). In detail, plastic bags (code MSFD: G5), shotgun cartridges (G70), and plastic construction waste (G89) represent 26.3 %, 17.8 %, and 14.0 %, respectively (Fig. 4A, Table 1; Supplementary materials Table S3). Differences of median values of top 10 MSFD categories among sectors were significant ($H = 17.79$; $p = 0.013$; Kruskal-Wallis test). Among the source categories, the most found litter categories were CHI (25.4 %), DIV (24.2 %), and FOO (21.4 %; Fig. 4B and D, Table 2; Supplementary materials Table S4). Differences among median values tend to significance ($H = 13.28$; $p = 0.066$; Kruskal-Wallis test) while differences among frequency are significant ($\chi^2 = 228.5$; $p < 0.001$).

Sectors 5, 6 and 8 appeared different when ordering with cluster analysis both considering the MSFD classification and the source classification (Fig. 5). More, the Detrended Correspondence Analysis showed that, considering the MSFD litter categories (Fig. 6A), sector 6 appears characterized by G79, G89, G102, G145, sector 5 by the G70 and G124, the sector 8, by G8 and G200. Considering the source categories, sector 6 appears characterized by the SMO, DIV and CHI, sector 5 by the RFH category and Sector 8 by the IPCD category (Fig. 6B).

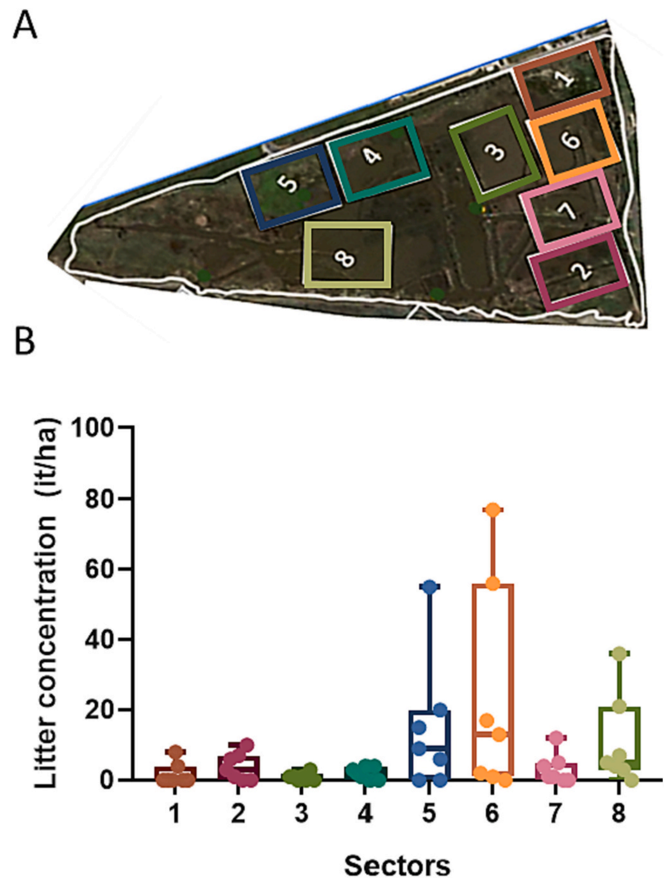

Fig. 2. Litter concentration in the eight sectors (median density of litter, as number of items per hectare, and min-max error range). The sectors are shown above in panel A with litter concentration in sectors in panel B.

Regarding the diversity indices, the Litter Diversity in sectors averaged 1.68 for the Shannon-Wiener index and 0.64 for the Evenness index. Sectors 8 and 6 appeared the most diversified and the least even (Table 3).

4. Discussion

Following strong water stress consequent to a drought summer, we sampled a large amount of recent and historical macrolitter items in a Mediterranean wetland. In this regard, for the first time, we quantified historical litter, accumulated from 20 years ago in the wetland.

As expected, we found mostly plastics, everywhere. This is not new information both at local level (inside the wetland: Cresta and Battisti, 2021; along the surrounding seashore: Gallitelli et al., 2021, 2023a, 2023b; Poeta et al., 2022; Cesarini et al., 2021, 2022; Battisti et al., 2023b) and at regional or continental scale (e.g., Derraik, 2002; Browne et al., 2011; Fanini and Bozzeda, 2018; Oztekin et al., 2020; Ertaş, 2021a, 2021b). The presence of plastics in coastal wetlands may have implications on wildlife, since items may degrade and fragmentate (Kumar et al., 2021; for example, polymers may be ingested by animals or entrapping them: e.g., Battisti et al., 2019; Gallitelli et al., 2022; see also about the implication for dunal plants: Poeta et al., 2017). Part of this litter could be exploited by biota and blocked by dune vegetation (Gallitelli et al., 2021; Battisti et al., 2023a, 2023b; Gallitelli et al.,

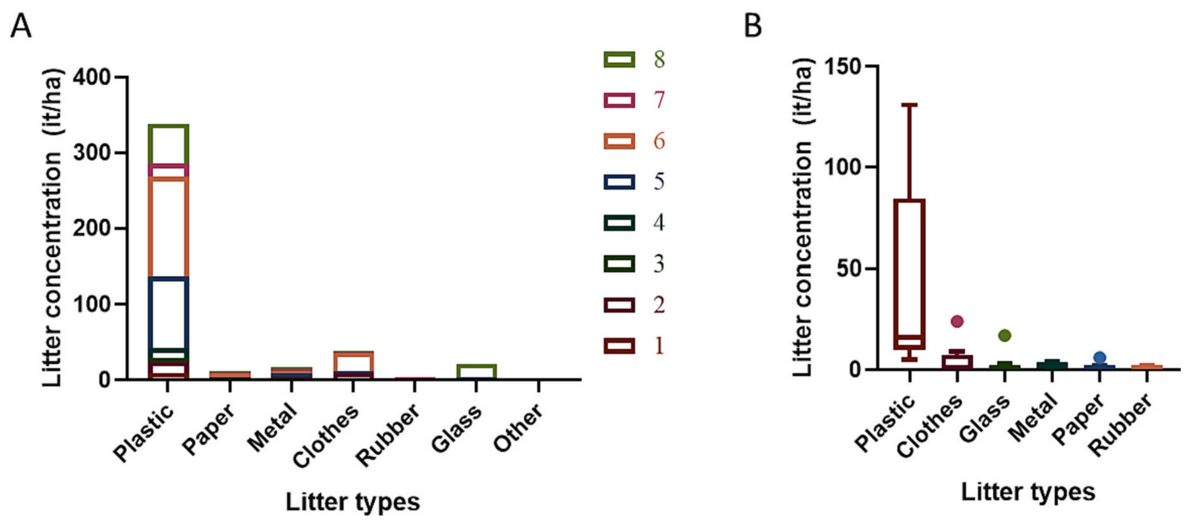

Fig. 3. (A) Litter concentration (items/ha) for each litter type in sectors following the generic classification by Galgani et al. (2013). (B) Tukey box plots of the number of items for different coarse-grained categories, reported as median values among sectors with the minimal and maximal values shown with whiskers. The horizontal line shows the median values and the asterisks report the outliers.

Table 1
The top 10 MSFD categories of litter (mean density among sectors and standard deviation, SD), total number of items (N) and relative frequencies (fr).

	Mean	SD	N	fr
G5	12.0	18.1	96.0	0.20
G70	8.10	18.6	65.0	0.20
G89	6.40	15.6	51.0	0.10
G8	5.60	5.30	45.0	0.10
G79	3.90	5.30	31.0	0.10
G145	3.90	7.80	31.0	0.10
G200	2.40	5.20	19.0	0.00
G124	1.80	3.40	14.0	0.00
G175	0.90	1.40	7.00	0.00
G102	0.60	1.8	5.00	0.00

2023a, 2023b). For instance, beach litter could entangle and threaten the endangered species of coastal birds (such as plovers, see Battisti et al., 2023a) and macro-invertebrates (Poeta et al., 2015). Moreover, the litter on the beach might be entangled by vegetation, representing a resource or a threat to the local biota (Cesarini et al., 2021; Gallitelli et al., 2021, 2023a).

Considering the MSFD classification, the most abundant litter everywhere were the plastic bags (G5) while considering the source classification, common household items (CHI) and diverse litter (DIV) represented the most abundant categories. Other studies in the same study area pointed out that tourism could be one of the large drivers for litter, with polystyrene and plastic items as the most dominant (Poeta et al., 2014, 2022). Therefore, in our study area the role of people (mainly bathers), who abandon garbage in situ, is dominant. Other studies in the literature highlighted the same patterns also in other Mediterranean sites (Prevenios et al., 2018).

However, considering the different sectors, we observed a spatial pattern in litter accumulation, as suggested by the cluster analysis. More particularly, the three sectors (no. 6, 8, and 5) showed a higher distance from the others. More particularly, First, along a path used by bathers, we sampled the highest amount of litter (sector no. 6). Here, the DCA analysis highlighted a prevalence of litter originating by diverse consumers (DIV), mainly domestic (CHI, SMO), as plastic pieces and textiles or bath-linked materials (e.g., G79, G102, G145). This could mostly be due to the activities conducted in this area by people. Second, near the beach (sector no. 8), we sampled mainly litter originating from sea storms and other meteo-marine events accumulated in the wetland near the back dunes (industrial packaging and bottles: G200, G8). In this case, beach litter is mostly carried by marine litter that strands to the beach and then accumulates on the coast or is blocked in back dunes (see Gallitelli et al., 2023a, 2023b for back dune reeds). Third, an inner sector (no. 5) showed a peculiar accumulation of litter linked to the historical activity of poaching, which now is illegal, however, it is not entirely possible to exclude poaching acts also in recent periods. This is due to shotgun cartridges (G70), included among the recreational hunting activity locally carried out until 1997 when the wetland was included in a protected area (Special Protection Area and Regional Natural Monument; Battisti, 2006). Poaching in wetlands represents a direct threat to birds, but also an indirect factor of pressure on wildlife due to lead accumulation (e.g., McIntosh et al., 2023). In this regard, the litter accumulation of shotgun cartridges inside the wetland channels represents an urgent ecological problem (Arcega-Cabrera et al., 2014. Romano et al., 2016; Uhart et al., 2019; Potysz et al., 2023). The analysis using uni-variate metrics evidences also higher diversity of litter in sectors no. 8 (near the beaches) and no. 6 (along the path). This fact may be a consequence of the type of processes originating on this site. Indeed, meteo-marine events along the beaches (sector 8) stranded many different litter types, analogously to people (sector 6) depositing different types of domestic and bathing-related materials.

The litter accumulation by bather people moving through the wetland to reach the beaches is another fact deserving attention, due to implication for wetland management. Litter accumulation by bathers has been largely studied (e.g., Gabrielides et al., 1991; Simeonova and Chuturkova, 2019). In this study, we evidenced a further implication linked to the presence of people crossing through a protected wetland: a large amount of garbage deposited in situ along paths of the nature reserve. Generally, in this protected area a large number of people clean-ups have been carried out using volunteers and operators (Battisti et al., 2016; Battisti and Gippoliti, 2019; Cesarini et al., 2022): these efforts have been focused mainly on beaches. Our results suggest the importance of carrying out beach clean-ups also in the inner sectors of the wetland, at least periodically. This removal may be configured as a true conservation project. Indeed, the accumulation of litter and its progressive degradation and fragmentation can interfere with the food chains (e.g. biomagnification) of the wet ecosystems (Provencher et al., 2019).

In conclusion, an interesting result of our study is that locally different processes may act to determine the local pattern of litter deposition: e.g., meteo-marine events along the seashore, litter deposition by bathers and general people along the path and, finally, historical

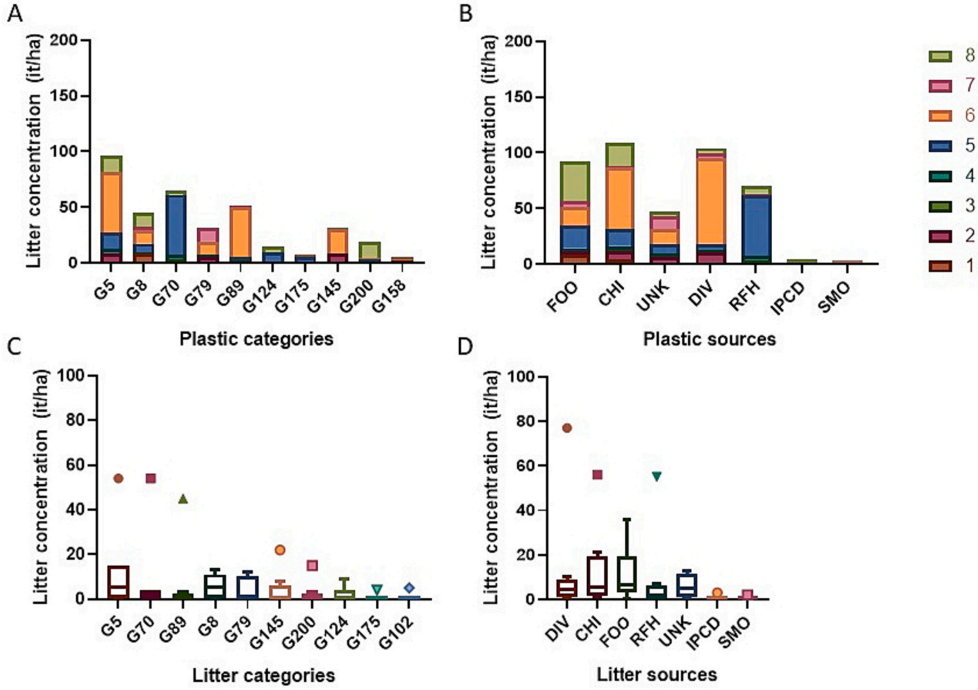

Fig. 4. (A) The top 10 MSFD categories of litter concentration (items/ha) and their source (B) in the 8 sectors. Box plots of the number of items for different MSFD (C) and sources (D) categories (median values among sectors). Tukey box plots of the number of items for different coarse-grained categories reported as median values among sectors with the minimal and maximal values shown with whiskers. The list of categories is available in the Tables S1 and S2 (Supplementary materials). G5 = Plastic bag; G8 = Plastic drink bottles >0.5 l; G70 = Shotgun cartridges; G79 = Plastic pieces 2.5 cm > < 50 cm; G89 = Plastic construction waste; G124 = Polystyrene items; G175 = Cans; G145 = Other textiles (incl. rags); G200 = Glass bottles; G102 = Flip-flops. Source litter categories; and G158 = Paper items. ATP = agricultural tarpaulin and packaging; CHI = common household items; DIV = diverse (professional and consumer); FMT = fisheries and mariculture gear; FOO = food and beverages packaging; IPCD = industrial packaging and construction debris; RFH = recreational fishing and hunting; SMO = smoking related items; SRD = sewage related debris; and UNK = unknown.

Table 2
The source categories of litter (mean density among sectors and standard deviation, SD), total number of items (N) and relative frequencies (fr).

	Mean	SD	N	fr
DIV	13.0	26.1	104	0.20
CHI	13.6	18.5	109	0.30
FOO	11.5	12.2	92.0	0.20
RFH	8.80	18.9	70.0	0.20
UNK	5.90	5.00	47.0	0.10
IPCD	0.50	1.10	4.00	0.00
SMO	0.40	0.70	3.00	0.00
TOT	40.6	56.3	429	1.00

hunting activity in the inner sector of wetland. In this regard, litter clean-ups in wetlands may be important to analyze historical activities (as, in our case, hunting) with implications for wetland management. Our findings could be of large interest if applied to mitigate plastic pollution and lead accumulation. Future studies should investigate the accumulation rate and age of this historical litter. Moreover, the fate and effects of such historical litter should be understood to detect possible sublethal or lethal interaction with coastal biota. In this case, unique and special clean-up activities should be conducted to mitigate plastic pollution in the area.

5. Conclusions

Marine litter is one of the most drivers of contaminants affecting coastal ecosystems. This study reported for the first time the presence of litter accumulated for 20 years on the Mediterranean coast, testifying recreational activities (as, in our case, poaching) non more occurring. In detail, we highlighted a pattern of litter accumulation driven by different sources (e.g., marine events, hunting, bathers, and general people along the path). To date, literature focused on the transport and deposition of litter in coastal areas, without highlighting its fate. This first approach highlights how litter coming from coastal areas might sink and accumulate in these delicate and fragile environments. As the persistence of litter in ecosystems could be of concern for biota and ecosystem functioning, special clean-up activities should be performed like in our study. Those future clean-ups might be configured as a true conservation project as litter clean-ups in wetlands may be important to analyze historical activities with implications for wetland management.

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CRediT authorship contribution statement

Corrado Battisti: Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Resources, Project administration, Methodology, Formal analysis, Conceptualization. **Giulia Cesarini:** Writing – review & editing, Visualization, Validation, Methodology. **Luca Gallitelli:** Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Methodology, Investigation, Formal analysis, Data curation. **Filippo Moretti:** Writing – review & editing, Visualization, Validation, Investigation. **Massimiliano Scalici:** Writing – review & editing, Visualization, Validation, Supervision, Resources.

Declaration of competing interest

The authors declare that they have no known competing financial

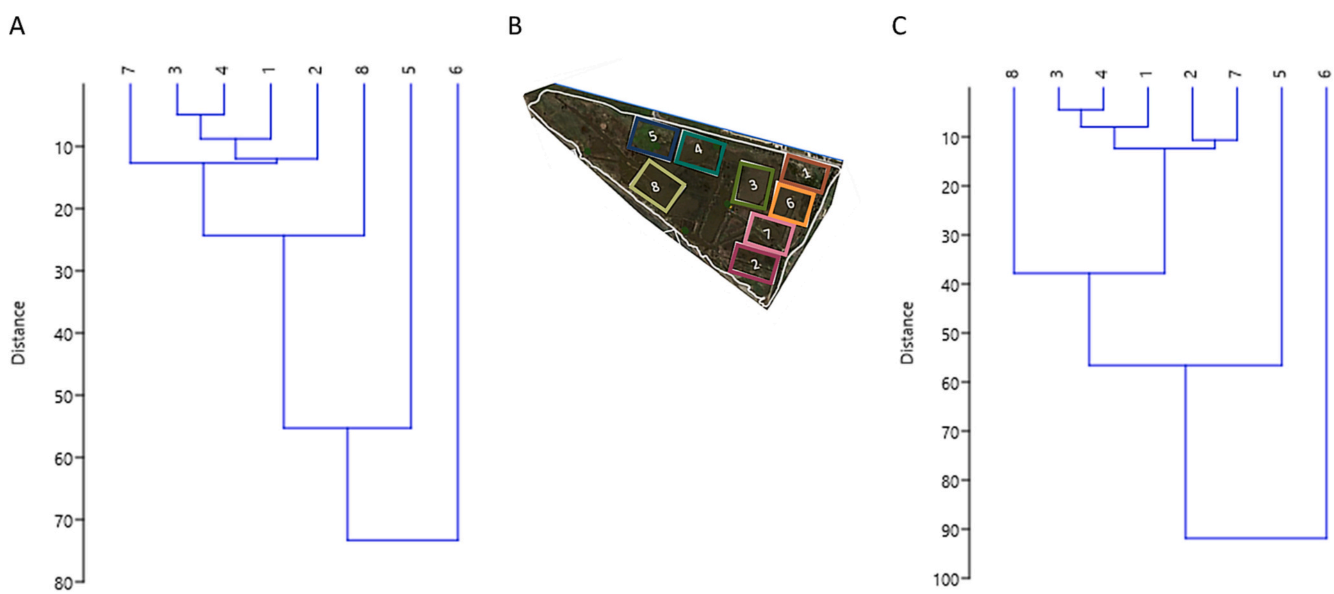

Fig. 5. Cluster analysis (Paired group UPGMA/Euclidean) of the 8 sectors based on the similarity among litter following (A) MSFD classification and (C) source classification with reference to the sectors in the study area (B).

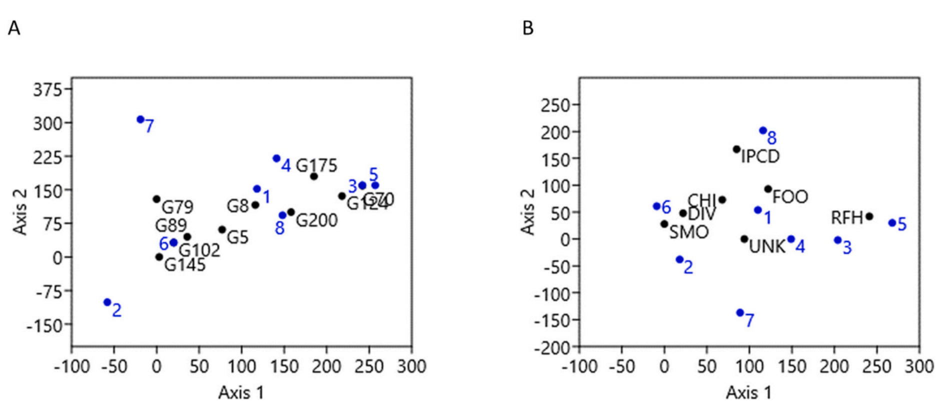

Fig. 6. Detrended Correspondence Analysis among sectors (1–8) and first top 10 MSFD litter categories (A) and litter source categories (B). See Materials and methods and Supplementary materials, for abbreviations.

Table 3
Diversity indices (Shannon-Wiener diversity index, H′ and Evenness) in the 8 sectors.

Indices	1	2	3	4	5	6	7	8
Shannon_H′	0.98	1.75	1.24	1.75	1.67	1.93	1.63	2.47
Evenness_	0.67	0.72	0.87	0.82	0.48	0.38	0.57	0.59

interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

All the data are available in the manuscript and Supplementary materials.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.marpolbul.2024.116163.

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