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# Natural Protected Areas as Special Sentinels of Littering on Coastal Dune Vegetation

**Maria Carla de Francesco, Maria Laura Carranza *, Marco Varricchione, Francesco Pio Tozzi and Angela Stanisci**

EnvixLab, Department of Biosciences and Territory, University of Molise, C. da Fonte Lappone, 86090 Pesche, and Via Duca degli Abruzzi, 86039 Termoli, Italy; maria.defrancesco@unimol.it (M.C.d.F.); m.varricchione@studenti.unimol.it (M.V.); f.tozzi@studenti.unimol.it (F.P.T.); stanisci@unimol.it (A.S.)

* Correspondence: carranza@unimol.it

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**Abstract:** Beach litter threatens coastal dunes integrity across the world. European countries are committed to improving the environmental status of the marine and coastal environment by 2020, and to do this, they need to reduce the gap of knowledge about litter accumulation patterns in coastal environments. We analyzed the distribution pattern of waste, differentiated by material and origin, in the coastal dune vegetation mosaic along protected natural areas in the Adriatic seashore (central Italy). Litter data were collected following a random stratified procedure. We registered litter occurrence on 180 (2 × 2 m) sampling plots randomly distributed in the different habitats of European conservation concern mapped for the analyzed protected areas. Litter was classified by origin and material, and their abundance on different habitats was explored by multivariate ordination techniques and tested by nonparametric ANOVA followed by Mann-Whitney pairwise post-hoc tests. Most of the plots included at least one waste element being plastic. Plastic was the most abundant material, and fishing and touristic the most polluting activities. Waste distribution varies across coastal dune vegetation types and involves the back dune zone too. Our results stress the need for (a) specific cleaning tasks able to preserve the ecological value of coastal dune habitats and (b) actions aimed at preventing litter production and accumulation.

**Keywords:** Adriatic coast; beach litter sampling; coastal dune vegetation zonation; Habitats Directive (HD-92/43/EEC); litter origin and material; Marine Strategy Framework Directive (MSFD-2008/56/EEC); Conservation and prevention actions

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## 1. Introduction

The presence of macro litter on sandy beaches and dunes represents a widespread and very serious environmental stress impinging coastal areas of the world [1,2]. Macro beach litter is made up of accumulated debris between 2.5 cm and 100 cm long [3], is non-biodegradable and highly fragmentable waste, accidentally or intentionally abandoned in coastal dunes. The origin of marine and beach litter is heterogeneous as it comes from several sources [4,5] involving both the emerged land and marine realms [6]. Land wastes on coastal areas may derive from recreational activities (e.g., bathing, sunbathing, picnics) [7], as well as from polluted rivers, municipal drainage systems, ephemeral streams and sewage [8], from domestic, agricultural or industrial activities, and from refuse dumps located near beaches [9]. On the other hand, marine sources of debris include commercial and recreational fisheries [10], as well as navigation activities (merchant ships, passenger ferries, and recreational boats) [11]. Concerning the material that constitutes coastal accumulated waste, plastic is the most abundant [12–14]. A recent review based on litter data extracted existing reports (Regional Sea Conventions) and an ad hoc analysis of a beach litter data set from the year 2016 underline that plastic waste represents over 80% of marine litter items accumulated on European beaches [15]. Specifically, single-use plastic waste represents a large part of marine beach litter, and for this reason, they have been recently targeted in the EU Strategy for Plastics in the Circular Economy promulgated in the year 2018 [15].

The global trend of sandy beach pollution due to litter accumulation has detrimental effects on the coastal blue economy [8]. Besides reducing the aesthetic value of coastal dunes with the consequent failure of touristic activities [16,17], litter adds economic cost for waste removal that must be carried out by specialized personnel and machinery [1,13]. Besides, macro litter can put public safety at risk, as sharp objects, such as broken glass and rusted metals, can cause injuries to beach users, and the fishing nets and abandoned peaks can trap divers. Finally, contaminating litter, such as sanitary waste, can compromise public health through the transmission and spread of diseases [18].

Beach litter has also negative consequences on coastal biodiversity and ecosystem functioning [19–21]. Macro litter can injure the fauna by trapping terrestrial Gastropods and non-flying Coleoptera [22] or can alter the diet of several coastal species such as turtles, sea mammals, sea birds [20,23], filter feeders, invertebrates, and fishes [24,25]. The ingestion of plastic waste may kill individuals by suffocation [26–28], expose them to toxic substances contained or absorbed by the plastic [29,30], and promote malnutrition and/or starvation [31], since a stomach full of litter gives an animal a sense of satiety.

Despite the number of studies analyzing the impact of litter on animal species, there are still few studies dealing with the incidence and consequences of beach litter on plant communities and species [21,32]. A seminal work evidenced the detrimental effects of litter on germination rates and seedlings growth of some coastal dune vascular plants [32] and how the accumulation of chemical substances in the soil could create favorable conditions for the settlement and spread of alien plant species [33]. The incidence of beach litter accumulation on the Caribbean [34] and Antarctic [35] coasts have been recently addressed. Recent local studies also depicted a variety of trends of litter accumulation in the coastal dunes [32,36], but new research efforts are still necessary to better understand this phenomenon in wider sectors and geographic areas. As far as we know, the accumulation of beach litter on the Mediterranean coastal dunes, specifically in the Adriatic basin, has not yet been sufficiently studied, and updated information about the trend of accumulation along the coastal dune gradient is still incomplete [37].

Reducing this gap of knowledge is crucial for the fulfillment of the Marine Strategy Framework Directive (MSFD) (2008/56/EC; European Commission, 2008) that commits the European states to take actions aimed at improving or maintaining the good environmental status (GES) of the marine environment by 2020 [38]. GES assessment is based on 11 qualitative descriptors (listed in Annex I of the MSFD), and descriptor 10 (D 10) is particularly focused on marine litter. To assure the correct implementation of the MSFD, the EC Directorate-General for the Environment established a Technical Subgroup on Marine Litter (TSG ML) with a role of supporting Member States by providing scientific and technical background for the fulfillment of the requirements stated by the D 10. The work of TSG ML focused on summarizing the information on monitoring protocols and evaluated the relation among GES assessment and environmental targets in order to identify strategies for preventing further inputs of litter and reducing its total amount. From the beginning of the TSG ML, much has been achieved, and new efforts should be addresses to customize the monitoring methods to the different marine and coastal compartments and biota [15,37], to increase the knowledge and information by extending studies to new areas, and to better understand the sources of marine/beach litter [38].

In this context, the present work sets out to explore how the different coastal dune ecosystems are affected by the accumulation of macro litter. Specifically, using a random stratified sampling protocol, we analyze the distribution pattern of waste differentiated by material and source across the coastal dune vegetation mosaic inside seven Protected Natural Areas in the Adriatic seashore (central Italy). We aim to investigate if the accumulation pattern, the composition, and the origin of litter on the mosaic of natural dune habitats is homogeneous or varies between the seashore and the back dunes.

Besides offering a sound baseline for monitoring and comparisons with other coasts, by linking the coastal habitats to litter accumulation patterns, we contribute to the prioritization of conservation actions in this highly vulnerable ecosystem. Knowing the abundances and types of beach litter across the different habitat types should contribute to the identification of effective strategies for litter removal and should support the search for specific solutions claimed by the MSFD directive.

## 2. Materials and Methods

### 2.1. Coastal Dune Ecosystems and Study Site

Coastal dunes are particularly dynamic ecosystems that are characterized by a steep environmental gradient, host a highly specialized flora and fauna [39,40], and provide essential benefits to society [41–43]. Most of the ecosystem services assured by coastal dunes rely on the integrity of eco-morphodynamic processes between dune vegetation and sand [40,44]. Indeed, being adapted to sand burial, psammophilous plants are able to retain sediments, determining dune morphology and stabilization over time [45,46].

In order to preserve coastal ecosystems, the European Union included most of them in the Council Habitats Directive 92/43/EEC (HD, hereafter). The HD claimed the conservation, continuous monitoring, and reporting of the habitats of conservation concern [47], and the protected areas are privileged situations for implementing HD aims. The protected areas along the Italian coast host good examples of well-preserved dune ecosystems [43]. As the mechanical cleaning of beaches compromises the integrity of natural dune eco-morphology [1], the removal of beach litter in protected areas is done with low frequency. The good levels of biodiversity and the paucity of cleaning activities make the natural protected areas excellent candidates for analyzing beach litter composition, origin, and consistency and its relationship with coastal dune natural habitats.

The study was carried out inside a network of natural protected areas (Figure 1, Table 1) along 88 km of the Adriatic coastlines in central Italy (Abruzzo and Molise regions). The analyzed coasts are representative of Mediterranean holocenic dunes and include long continuous sandy beaches that alternate with rocky cliffs and pebble bays [48,49]. Recent dunes (Holocene) generally occupy a narrow strip along the sea-shore and are relatively simple in structure. They are not very high and are characterized by a geo-morphologic gradient where the deposition of sand, pebbles, or organogenic materials, such as fragments of shells, occurs by wave motion and wind [50]. The analyzed Natural Protected Areas host considerable levels of biodiversity, including several species of flora and fauna [51–55] and ecosystems of European conservation concern [51,56,57] (Figure 1, Table 2). Touristic pressure concentrates in the summer months, and the presence of walkways on most of the analyzed protected areas allows tourist to reach the seashore preserving the natural dune habitats. In Figure 2, we report some pictures of the dune fields to give an idea of their width, height, and degree of vegetation coverage. The presence of Natura 2000 sites [43] and Long Term Ecological Research (LTER) observation areas ([40,58], LTER IT20, www.lteritalia.it), together with the low frequency of beach cleaning, make the analyzed coast an excellent training ground to develop methodologies for assessing beach litter composition, origin, and accumulation patterns and their relation to natural habitats.

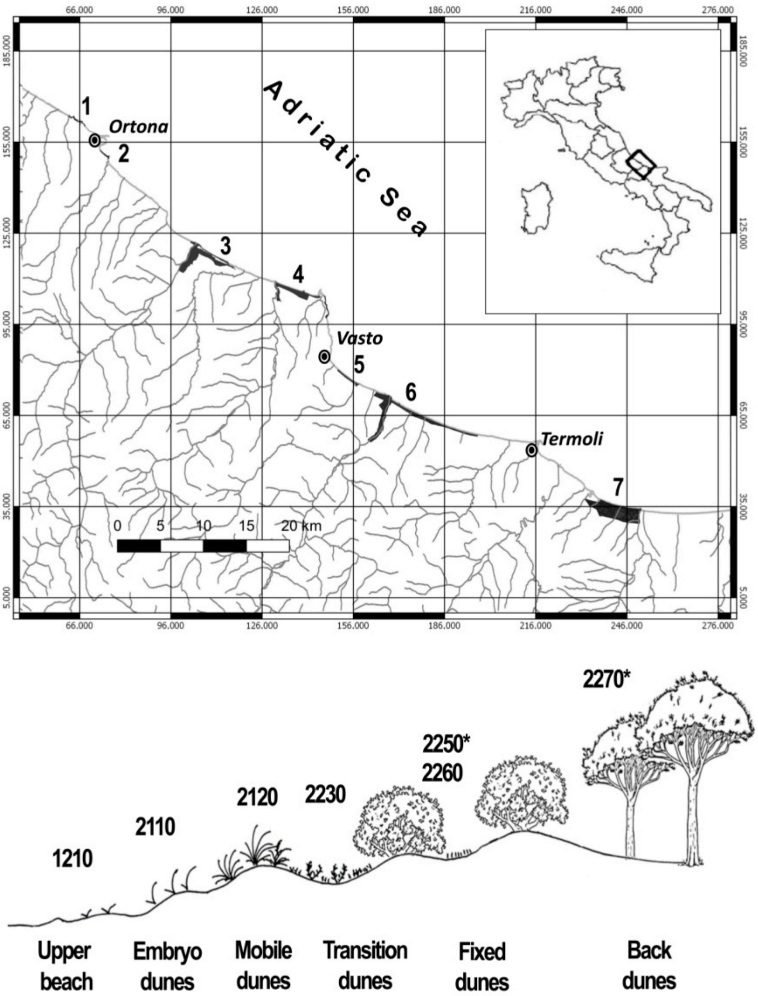



**Figure 1.** Localization of the analyzed Natural Protected Areas along with a schematic profile (redrawn form Drius et al. 2016) describing the typical Mediterranean coastal dune vegetation zonation and the analyzed EU habitat types (HD 92/43/EEC). Numbers in the map refers to ID reported in Table 1. Numbers reported above the profile refers to EU codes. 1210: annual vegetation of drift lines, 2110: embryonic shifting dunes, 2120: shifting dunes along the shoreline with *Ammophila arenaria*, 2230: *Malcolmietalia* dune grasslands, 2250*: coastal dunes with *Juniperus* spp., 2260: *Cisto-Lavanduletalia* dune sclerophyllous scrubs, 2270*: wooded dunes with *Pinus pinea* and/or *Pinus pinaster*.

**Table 1.** List of Protected Areas, with the list of EU habitats (Annex 1 of HD 92/43/EEC, see Table 2) they host, and the number of sampled litter plots collected per EU habitat. ID: refers to protected areas reported in Figure 1. RNR: Regional Natural Reserve; ZSC: Special Area of Conservation.

| Region | ID | Protected Area | EU Habitat Code | Plots |
|---|---|---|---|---|
| Abruzzo | 1 | RNR Punta dell'Acquabella | 1210 | 13 |
| | 2 | RNR Ripari di Giobbe | 1210 | 8 |
| | 3 | ZSC IT7140107 Lecceta di Torino di Sangro-foce del fiume Sangro | 1210 | 10 |
| | 4 | ZSC IT7140108 Punta Aderci-Punta della Penna | 1210 | 15 |
| | 5 | ZSC IT7140109 Marina di Vasto | 1210, 2110, 2120, 2230 | 37 |
| Molise | 6 | ZSC IT7228221 Foce fiume Trigno-Marina di Petacciato | 1210, 2110, 2120, 2230, 2260, 2270* | 43 |
| | 7 | ZSC IT7222217 Foce fiume Saccione-Bonifica Ramitelli | 1210, 2110, 2120, 2230, 2250*, 2260, 2270* | 54 |

**Table 2.** Habitat-types (sensu 92/43/EEC) present in the study area along the sea-inland vegetation zonation. Cod: EU code, Hab: EU habitat name, Zone: Zone of along the dune profile, Sp. Main diagnostic or characteristic species. For a representation of the analyzed EU habitat types (HD 92/43/EEC) and the underlying sea-inland environmental gradient, see the schematic profile reported on Figure 1.

| | **Upper Beach** | **Embryo Dunes** | **Mobile Dunes** | **Transition Dunes** | **Fixed Dunes** | | **Back Dunes** |
|---|---|---|---|---|---|---|---|
| **Cod** | 1210 | 2110 | 2120 | 2230 | 2250* | 2260 | 2270* |
| **Hab** | Annual vegetation of the drift lines | Embryonic shifting dunes | Shifting dunes along the shoreline with *Ammophila arenaria* | Malcolmietalia dune grasslands | Coastal dunes with *Juniperus* spp | Cisto-Lavanduletalia dune sclerophyllous scrubs | Wooded dunes with *Pinus pinea* and/or *Pinus pinaster* |
| **Sp** | *Cakile maritima, Salsola kali, Chamaesyce peplis* | *Elymus farctus, Sporobolus virginicus, Othantus maritimus* | *Ammophila arenaria, Echinophora spinosa, Eryngium maritimum* | *Pancratium maritimum, Silene colorata, Vulpia fasciculata* | *Juniperus oxycedrus,* subsp *macrocarpa* | *Pistacia lentiscus, Rhamnus alaternus* | *Pinus pinea, P. pinaster, P. halepensis* |

(a) Embryo dunes—EC 2110
(b) Mobile dunes—EC 2120
(c) Boardwalk crossing mobile dunes
(d) Fixed dunes—EC 2260

**Figure 2.** Photographs of the dune fields. (**a**) Embryo dune (EC2110: embryonic shifting dunes), (**b**) mobile dunes (EC2120: Shifting dunes along the shoreline with *Ammophila arenaria*), (**c**) boardwalks that allow tourist to reach the seashore preserving the natural dune habitats, EC2260: *Cisto-Lavanduletalia* dune sclerophyllous scrubs.

## 2.2. *Sampling Beach Litter across Coastal Dune Habitats*

Litter was sampled across the different EU habitat types on 2 × 2 m plots [13,36] using a stratified random protocol. The spatial distribution of sampled litter plots in the different habitat types was supported by a georeferenced vegetation database available for the study area (RanVegDunes) [59] and habitat maps accessible from Natura 2000 Standard data forms (ftp://ftp.dpn.minambiente.it/Natura2000/TrasmissionECE_2013/schede_mappe). We visited 180 plots and recorded all the litter elements > 2.5 cm (macro-litter) [3]. We sampled each plot only once, and beach litter was registered by the same team of researchers. Sampling was carried out in the vegetative period (April–May 2018), and the list of the main plant species was also recorded in order to further check the correspondence between the litter plots and the EU habitat types. Litter was collected, visually inspected, and registered following the OSPAR protocol (2010; Convention for the protection of the marine environment of the North-East Atlantic). Then, we catalogued beach litter into macro categories of material type and of origin following two basic reports—the OSPAR protocol, developed for the North-Atlantic region and the successive integrations proposed by the UNEP/MAP for the Mediterranean area [60]. Specifically, we classified the recorded items into material types (plastic, polystyrene, glass, paper, aluminum, mixed waste) and into origin categories referring to the source of waste (containers, fishing and boating, food and beverage, packaging, other; see for details UNEP/MAP report [60]). The categories adopted for classifying waste according to the type of material and the origin (source), along with the detailed list of sampled items assigned to each class, are reported in Table 3.

**Table 3.** Litter categories adopted for waste material and origin classification [60] along with the list of items we have recorded for each class. The abundance of polluted plots (N plots: total number of plots polluted per category of material and origin, % plot: percent of polluted plots) and the number of items per class (N items: number of items, % items: percent of items) are also reported.

| | Category | Items | N. Plot | % Plot | N Items | % Items |
|---|---|---|---|---|---|---|
| MATERIAL | Plastic | Bottles cups, pull tabs plastic, plastic bottles, plastic drums, fishing nets plastic, plastic plates, plastic forks, plastic bags, plastic sheets, soap containers, snack cards, straws, food trays, packaging of medicines, monofilament lines. | 113 | 38.0 | 657 | 44.0 |
| | Polystirene | Polystyrene boxes, polystyrene cups. | 88 | 29.6 | 603 | 40.4 |
| | Paper | Paper and cardboard. | 5 | 1.7 | 8 | 0.5 |
| | Glass | Glass bottles. | 19 | 6.4 | 71 | 4.8 |
| | Aluminum | Drink cans. | 13 | 4.4 | 14 | 0.9 |
| | Mixed materials | Cigarette butts, lighters, fluorescent light tubes, light globes, processed timber, rags, clothing, shoes, hats, tableware, toys, tires and inner tubes, rubber/chewing gum, wires, building materials, nappies, cotton buds, syringes, plasters, sanitary pads, foams, strapping bands, buoys, fishing nets not plastic, fishing related, ropes. | 59 | 19.9 | 139 | 9.3 |
| ORIGIN | Containers | Bottle cups, pull tabs plastic, plastic bottles <= 2 l, plastic bottles >2 l, plastic drums>2 l, glass bottles. | 78 | 22.1 | 235 | 15.8 |
| | Fishing and boating | Buoys, fishing nets not plastic, fishing nets plastic, fishing related, monofilament lines, ropes, polystyrene boxes. | 100 | 28.3 | 753 | 50.5 |
| | Food and beverage | Drink and food packages, cups, food trays, drink cans, ice c. sticks, chip forks, plastic plates, straws, snack cards, chips bags. | 48 | 13.6 | 115 | 7.71 |
| | Packaging | Foams, papers and cardboards, plastic bags, plastic sheets, strapping bends, soap containers. | 50 | 14.2 | 134 | 8.98 |
| | Other | Fluorescent light tubes, light globes, processed timber, rags, clothing, shoes, hats, tableware, toys, tires and inner tubes, rubber/chewing gums, wires, building materials. Cigarette packaging, cigarette butts, cigarettes lighters. Sanitary packaging, nappies, cotton buds, syringes, plasters, packaging of medicines, sanitary pads. | 77 | 21.8 | 255 | 17.1 |

*2.3. Data Analysis*

The main trends of litter data collected in the 180 plots across habitat types were first analyzed by multivariate ordination techniques. We ran two Principal Components Analysis (PCA), one on the matrix of plots by material type (180 plots by six material categories: plastic, polystyrene, paper, glass, aluminum, and mixed material) and another on the matrix of plots by origin categories (180 plots by six origin categories: containers, fishing and boating, food and beverage, packaging, and other), and we built the respective bi-plots [61]. PCA finds hypothetical variables (components) summarizing the variance of the original multivariate data [61,62]. These new variables are linear combinations of the original ones. Using PCA, we reduced each data set (plots by material and plots by origin) into two variables (PCAI and PCAII) for plotting purposes and for exploring how these two first components are related with the underlying sea–inland environmental gradient. We projected litter plots into the coordinate system given by the two first components (one PCA diagram for each database) and represented them with different symbols according to the habitat type. We then projected the original variables onto the scatter diagram and built two bi-plots that showed how litter material and litter origin are related with the PCA components and with the different habitat types. Then, in order to test the existence of significant differences in the accumulation rates of litter material and origin categories across the coastal zonation, we compared the frequencies of classified items on the different habitat types using a Kruskal-Wallis nonparametric ANOVA followed by the Mann-Whitney pairwise post-hoc test [62]. We represented the results denoting significant differences by boxplots.

## 3. Results

*3.1. Litter Material and Origin*

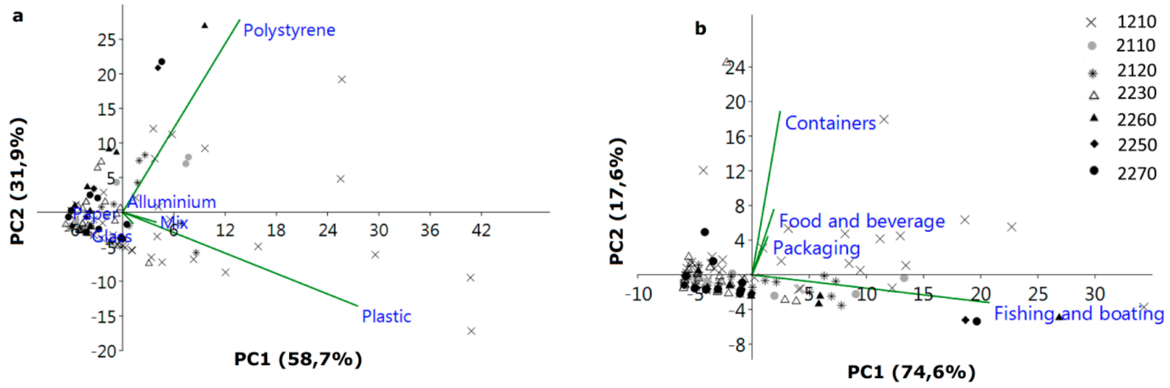
The occurrence of litter elements is quite widespread, as evidenced by the presence of polluting elements on more than four fifths of the inspected plots (Table 3) and by the density of litter items per square meter, which in the sampled plots has a mean value of 2.21 items/m$^2$ and reaches a maximum of 20 items/m$^2$ in an exceptionally polluted site. After analyzing litter density per habitat type, it is interesting to note that the mean values per plot is always above one. The upper beach (EC 1210: annual vegetation of the drift lines) with 3.37 items/m$^2$ registered the higher mean litter density values, followed by the transition dunes (EC 2230: Malcolmietalia dune grasslands) with 2.25 items/m$^2$. Litter density on the other habitats of the zonation ranges between 1 and 2 items/m$^2$.

Most of the plots contain plastic elements and polystyrene, one 10th contains glass, and one third contains mixed materials. Very few plots contain paper or aluminum (Table 3). Concerning the origin of litter (origin categories), containers occurs on about half of the sampled plots, fishing and boating and packaging on more than half, food and beverage on one third, and other elements (e.g., clothes, tableware, toys, tires, building materials, cigarette packaging, sanitary elements) on about two fifths (Table 3).

As regards the number of elements, we found 1492 litter items. Most of them are made of plastic (44%%), followed by polystyrene (40%). We also found a good amount of mixed waste (9.32%), including toys, clothes, shoes, generic sanitary material, wood, various chairs, and so on, with different weights and dimensions. Glass, mainly represented by broken bottles, is less represented (4.76%). Small quantity of aluminum litter (~1%) and paper (0.5%) are found—14 and eight elements, respectively. Most of the recorded litter derives from fishing and boating activities (50.5%), followed by containers (16%), packaging (9%), and food and beverage (7.7%). An interesting amount of litter has other origin (17.1%) and includes fluorescent light tubes, light globes, processed timber, rags, clothing, shoes, hats, tableware, toys, tires and inner tubes, rubber/chewing gums, wires, and building materials (Table 3).

*3.2. Litter Accumulation in EU Habitat Types*

The projection of plots, drawn with different symbols according to the habitat type, in the ordination space denotes a gradient referable to the sea–inland gradient (Figure 3). Furthermore, the bi-plot created by projecting in the same PCA space of the original variables suggested that the gradient on litter material accumulation ranges from shifting dunes on the shoreline (EU 1210), with higher presence of plastic elements, to wooded dunes, typical of the inner sectors of the zonation (EU 2250*, EU 2260, EU 2270*), in which polystyrene items predominate. The PCAI axis is highly correlated with plastic elements accumulation (0.887) and secondarily with polystyrene (0.442); the PCAII is positively correlated with polystyrene accumulation (0.896) and negatively with plastic (−0.437). The first two PCs' axes summarize the 90.6% of total variability (Figure 3a).

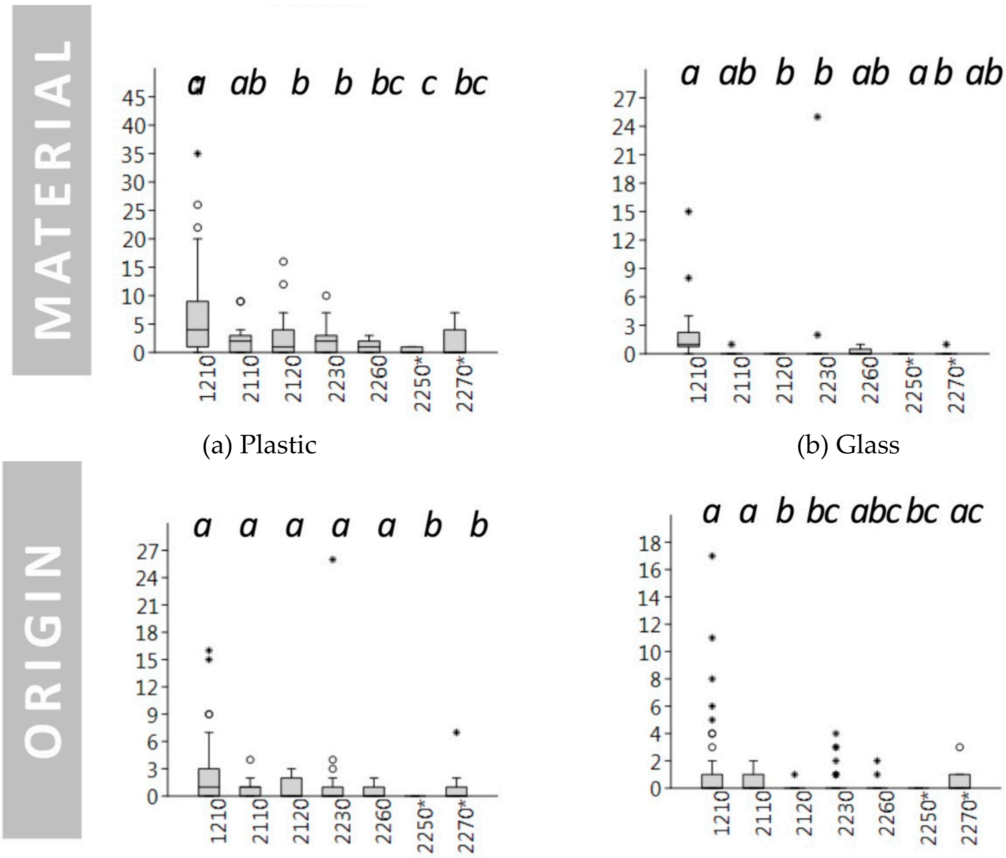



(a) (b)

**Figure 3.** Principal Components Analysis (PCA) bi plots reporting plots per habitat type (symbols) and litter elements classified by material (**a**) and origin categories (**b**). EU codes correspond to 1210: annual vegetation of drift lines (upper beach), 2110: embryonic shifting dunes (embryo dunes), 2120: shifting dunes along the shoreline with *Ammophila arenaria* (mobile dunes), 2230: *Malcolmietalia* dune grasslands (transition dunes), 2250*: coastal dunes with *Juniperus* spp. (fixed dunes), 2260: *Cisto-Lavanduletalia* dune sclerophyllous scrubs (fixed dunes), 2270*: wooded dunes with *Pinus pinea* and/or *Pinus pinaster* (back dunes). For schematic profile representing the sea–inland environmental gradient, see Figure 1.

The PCA analysis of plots accounting of litter origin categories confirms the presence of a sea–inland gradient. The bi-plot evidences a specific pattern of litter accumulation across the habitat zonation, with containers, food and beverage, and packaging most associated with the shoreline habitats (EU 1210) and fishing and boating elements accumulated on both the shoreline habitats (1210) and the woody vegetation of the inner dune sectors (EU 2250*, EU 2260, EU 2270*). The PCAI axis, which explains most of the variability, is highly correlated elements used for fishing and boating activities (0.98693), as the PCAII is correlated with the accumulation of containers (0.89744). The first two PCs summarize the 92.2% of total variability (Figure 3b).

The gradient observed with the PCA analysis is confirmed by the presence of significant differences in waste accumulation patterns across the coastal dune habitats zonation. Significant differences in litter occurrence are evident for plastic and glass (Kruskal-Wallis $p = 9.45E-05$ and $p = 0.04346$ respectively; Figure 4). Plastic waste, the more abundant litter found, presents a decreasing distribution from the shoreline to the inner-dune habitats. Plastic concentrates in the habitat EU 1210 (annual vegetation of drift lines) with the 68% of elements and median (M) = 4, decreases on habitat 2110 (embryonic shifting dunes) (M = 2), and is less present on inner woody habitats (EU 2260: *Cisto-Lavanduletalia* dune sclerophyllous scrubs, EU 2250*: coastal dunes with *Juniperus* spp, EU 2270*: wooded dunes with *Pinus pinea* and/or *Pinus pinaster*) with M~0.5 (Figure 4).




(a) Plastic (b) Glass

(c) Containers (d) Food and beverage

**Figure 4.** Boxplots reporting the number of elements (y axes) per habitat type (x axes) of the different litter categories (only significant differences according with Kruskal-Wallis ANOVA are drawn). Letters correspond to significant differences according with Mann-Whitney pairwise post-hoc test. EU codes correspond to 1210: annual vegetation of drift lines (upper beach), 2110: embryonic shifting dunes (embryo dunes), 2120: shifting dunes along the shoreline with *Ammophila arenaria* (mobile dunes), 2230: *Malcolmietalia* dune grasslands (transition dunes), 2250*: coastal dunes with *Juniperus* spp. (fixed dunes), 2260: *Cisto-Lavanduletalia* dune sclerophyllous scrubs (fixed dunes), 2270*: wooded dunes with *Pinus pinea* and/or *Pinus pinaster* (back dunes). For schematic profile representing the sea-inland environmental gradient see Figure 1. For a complete description of habitats see Table 2.

Glass material is less frequent but presents a clear stratification across habitats, with higher presences in the habitat EU 1210 (annual vegetation of drift lines) close to the shoreline (~58% of the observed glass elements), and is particularly rare in some habitats of the inner sectors in correspondence with EU 2250* (coastal dunes with *Juniperus* spp.) and EU 2260 scrubs (*Cisto-Lavanduletalia* dune sclerophyllous scrubs). Glass shows two peaks of presence in the EU 1210 (annual vegetation of drift lines; 58%) and EU 2230 (*Malcolmietalia* dune grasslands; 38%) habitats, respectively, and a low but homogeneous distribution in the other habitats. The first peak, correspondent to habitat EU 1210 (annual vegetation of drift lines), is due to the large stratification of glass elements along the shoreline for their weight that does not allow them to be transported by the wind away from the seashore. Moreover, the peak in correspondence to EU 2230 habitat (*Malcolmietalia* dune grasslands) is probably due to glass waste that arrives not from sea but from other kinds of touristic activities developed inside to Naturalistic Protected Areas (Figure 4). Polystyrene and the rare waste materials, such as aluminum and paper, do not present a significant stratification of accumulation in correspondence of habitat zonation (for paper, this is probably due to the its natural decomposition).

The accumulated waste categorized by origin types also vary across the coastal habitat zonation, with significant differences for containers and for food and beverages litter (Kruskal-Wallis p = 0.009537 and p = 0.003817 respectively). Containers are abundant on all the habitats except for the inner dune woody formations (EU 2250*, coastal dunes with *Juniperus* spp.; EU 2270*, wooded dunes with *Pinus pinea* and/or *Pinus pinaster*). On the other hand, waste derived from food and beverage use tends to concentrate close to the seashore (EU 2110, annual vegetation of drift lines; EU 2120, shifting dunes along the shoreline with *Ammophila arenaria*) (Figure 4).

## 4. Discussion

The analysis of washed-up litter on the network of natural protected areas in the central Adriatic coast provided an accurate description of the type of material and the origin categories of macro-litter accumulated in dune habitats of European conservation concern using an accurate and replicable procedure.

The results derived from random sampling of dune habitats in the Adriatic coast underline the widespread presence of litter, with over the 80% of the inspected plots being polluted. As observed in the marine habitats of other areas of the world such as the Caribbean [34] and the Mediterranean sea, and in the beach and natural sand dunes [22,63], the presence of litter is very consistent.

### *4.1. Litter Material and Origin*

The majority of the plots with washed up waste contains plastic (~70%) and polystyrene (~52%) elements. A high incidence of plastic waste on coastal ecosystems was also observed in other Italian and European areas [15,64], as well as on other coasts across the globe [34,65,66], and such abundance should be due to both the diffuse utilization of plastic [67,68] and the specific characteristics of hard and soft plastic items, such as flotation and high persistence in the environment [24].

On the Adriatic seashore, recreational activities (e.g., bathing, sunbathing, water and beach sports) appeared to be the major source of litter, affecting ~50% of the surveyed plots, results that confirms previous observations on other study coastal areas in Europe [13,15]. Activities connected with recreation were found to pollute the studied beaches with plastic tableware, bottles and bags, glass and aluminum containers, and other litter items.

On the other hand, as in other ecological compartments as the seafloor of the Mediterranean Sea [11], another important marine source of litter that washes up along the sand dunes is navigation and fishing (e.g., shipping, fishery and fish farming), with ~30% of the plots containing buoys, fishing nets, ropes, and polystyrene boxes. Similar values were observed in remote oceanic areas [69,70] and are reported to be higher on other Mediterranean coasts [68]. The relative high abundance of fishery litter in the analyzed area should be due to the protection status and moderate touristic facilities that balance the contributions from other sources in some tracts.

Building materials and metals, except for aluminum, appeared to come from land activities not connected with recreational ones, due to malfunctioning or illegal dumping sites placed along rivers. The examined areas show a stratification of plastic, glass, and polystyrene waste on the habitats along the sea–inland gradient.

### *4.2. Zonation Patterns*

The areas closer to the seashore are mainly polluted by plastic litter (68% of the elements) and glass (58%) coming from both sea (e.g., fishing) and land (e.g., tourist) sources. Several waste items, being heavy, rest into the sand in correspondence of the annual vegetation of drift lines (EU 1210) and tend to be buried [67]. Also, light litter should accumulate on the beach because they are trapped by organic waste as woody posts and dead marsh reeds [21]. In the immediate inner sectors in correspondence with annual vegetation of drift lines (EU 1210), embryonic shifting dunes (EU 2110), shifting dunes along the shoreline with *Ammophila arenaria* (EU 2120), *Malcolmietalia* dune grasslands (EU 2230), plastic litter tends to remain entangled on herbaceous psammophilous vegetation. Indeed, the root structure of dune vegetation has a crucial role on fixing and stabilizing sediments [41,45], and in our case, it also contributes to waste retention and burial.

The deposition of plastic and polystyrene waste coming from marine sources is not limited to the beach and mobile dunes but reaches the inner fixed dunes with woody vegetation such as *Juniperus macrocarpa* scrub (EU 2250*), *Cisto-Lavanduletalia* dune sclerophyllous scrubs (EU 2260), and wooded dunes with *Pinus pinea* and/or *Pinus pinaster* (EU 2270*). The observed abundance of polystyrene waste in these inner dune habitats is most likely due to the volatility of this material, which is transported by the wind and deposited and fragmented in the fixed and back-dune areas [71].

On the other hand, waste derived from food and beverage tends to concentrate close to the seashore (EU habitats 2110, 2120). Containers are abundant in all the habitats except for the inner woody dune formations (EU habitats 2250*, 2270*). The presence of waste derived from food and beverage in protected areas is most likely related with seaside tourism and the throwaway economy [8], and their littering is mainly due to the long distances that visitors need to walk in protected natural areas before reaching dumpsters and tourists' lack of ecological awareness.

### 4.3. Recommendations and Implications

The presence of macro litter makes coastal dunes touristic and esthetic value drop [17,43] and alters dune substrate characteristics, promoting the invasion of alien species [33,67,72]. Specifically in the Mediterranean, the polystyrene and plastic fragments accumulation inside the fixed dunes scrub represents a persistent pollution that remains in environments of particular naturalistic value, where residual populations of species of European community interest live, such as *Testudo hermanni* and plant communities of conservation and biogeographic interest [47,52,57,73].

In order to prevent or mitigate the negative effects of litter accumulation on natural habitats, it is essential to identify good management practices, such as reducing plastic and promoting a circular plastics economy [71,74] aimed at reducing the marine and beach litter [68,75]. Concerning the analyzed protected areas, periodical manual removal of litter (e.g., every 2–3 months) is advisable [1,22,76]. Litter collection should be implemented along the entire zonation, as removing large or medium waste items prevents the fragmentation of big pieces into smaller ones and the formation of micro litter, which is the most dangerous form when included in the food chain [74]. Furthermore, the periodical manual collection of litter is compatible with the conservation of dune biodiversity [77] and at the same time avoids the accumulation of macro litter that breaks down into smaller pieces that are transported by the wind into the inner dune sectors, where manual removal is very difficult and threatens vertebrate biodiversity [78].

Mechanical cleaning of beach litter should be restricted only to the authorized bathing establishments and on periods that do not alter the nesting period of the fauna present in the analyzed coasts, such as the plover (*Charadrius alexandrines*) [53,55], the Crested lark (*Galerida cristata*), and the *Caretta caretta* [79]. Notice that the utilization of clearing machinery generates a vicious circle due to the systematic removal of both the psammophilous species that are essential for fixing dunes and tons of sand [1]. Indeed, beach cleaning, in addition to litter removal, clears away dune vegetation and levels dune morphology, stripping coastal dunes of its natural capital and the related benefits for the society [43].

Furthermore, in order to prevent the washing up of waste coming from the sea, cleaning activities must be also implemented to remove floating litter and litter accumulated in the seabed (e.g., "fishing for litter" good practice) [75], work that requires of the involvement of the fishermen.

To conclude, it should be useful to improve environmental policy and orient it toward the avoidance or reduction of the utilization of disposable plastic items [17,68] both during terrestrial activities (e.g., picnic, food and beverage containers) and marine ones (avoidance of deposable polystyrene containers for fish stocking), favoring the utilization of biodegradable materials and a proper disposal chain [77].

## 5. Conclusions

The present study, providing an assessment of beach litter accumulation of a network of protected areas along the central Adriatic coast, contributes to increase the knowledge necessary to implement the MSFD (2008/56/EC; European Commission, 2008) and in particular to define adequate strategies aimed at maintaining or improving their good environmental status (GES) at different administrative levels (the local, national, and entire Mediterranean region). Our results also contribute to the activities of the national technological cluster "Blue Italian Growth" (CTN-BIG). Most of the insights and conclusions obtained in this study have been facilitated by the utilization of a sound georeferenced sampling procedures, the collection of litter data according with international protocols (OSPAR and UNEP/MAP), and the utilization of EU habitats maps for defining the sampling strata. The application of those random stratified procedures (a) depicts a representative scenario of the accumulation trends occurring in wide areas, (b) allows the statistical comparison of accumulation patterns among the sampled habitats, (c) offers robust data for multi-temporal comparisons and monitoring, and (d) allows the evaluation of conservation status of habitats and coastal tracts claimed by the TSG ML.

Our results give evidence for the dominance of plastic and polystyrene material and depict that both marine and terrestrial proveniences of litter are very important on the Adriatic coast. Litter tends to be deposited heterogeneously across the sea–inland gradient, impinging dune eco-morphology in a variety of ways, which suggests the need for dedicated cleaning procedures. Among the possible cleaning strategies, the manual picking of litter seems to be the most advisable approach because it is able to extract almost all the materials types deposited on coastal dune ecosystems while respecting dune morphology and avoiding the inevitable loss of sand derived from the utilization of cleaning machinery. Still, measures to prevent litter accumulation on natural habitats are needed. Some examples of these measures include the promotion a circular plastics economy, the implementation of actions aimed at raising the awareness of people that unknowingly contribute to the litter accumulation, the launch of a specific education campaign to fishers and shellfish farmers in relation to marine litter, and the promotion of cleaning activities to remove floating litter and litter accumulated in the seabeds.

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