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Assessing beach litter trapping efficiency in Mediterranean sandy coasts: A comparative study between typical and invaded embryonic dunes

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ABSTRACT

Beach litter is one of the most evident indicators of marine litter pollution, an anthropogenic component that can affect and interact with the habitat of coastal dunes. In this study, we aim to assess the role of the Mediterranean embryonic dunes in trapping beach litter. Moreover, we investigate if dunes with native vegetation and those invaded by the alien plant *C. acinaciformis* differ in the trapping of beach litter. To this end, two samplings were carried out in the Tavolara-Punta Coda Cavallo Marine Protected Area, considering four beaches with different morphologies, using a paired sampling method that considers plots in the embryonic dunes and in the same habitat with *C. acinaciformis*. Our results indicate that plastic is the primary type of beach litter and that its distribution varied across the different beaches; especially, the greatest amount was found on pocket beaches. Based on our results, we can conclude that there are no differences between embryonic dunes with native vegetation and their invaded form, but the different beach morphologies may play a role in the distribution of beach litter. These findings may support habitat conservation initiatives such as the eradication of *C. acinaciformis* since it has no additional role in trapping beach litter.

1. Introduction

Coastal dune systems are dynamic ecosystems with high biodiversity that cover most of the world's coastline (e.g., Carranza et al., 2008; Acosta et al., 2009; Maun, 2009; Fenu et al., 2013; Prisco et al., 2021). Due to several factors, including shifting substrate, sand burial, bare spots amid plants, sand porosity, and a lack of organic matter, especially in the early phases of dune growth, these ecosystems are very changeable (Maun, 2009). Important services, including recreation, fresh water supply, and biodiversity protection, may be obtained from these ecosystems (Everard et al., 2010; van Puijenbroek et al., 2017), which can be influenced by a variety of factors. The two key drivers controlling the environmental variance in coastal dunes are soil- and wind-related factors (Frederiksen et al., 2006; Forey et al., 2008; Maun, 2009). Other forces impacting these ecosystems include the flora and biotic communities that live in these habitats, groundwater movement, beach shape, and waves. All these elements contribute to the uniqueness of these ecosystems (Martínez and Psuty, 2004; Acosta et al., 2009; Maun, 2009; Fenu et al., 2013; Ruocco et al., 2014; Conti et al., 2017; Prisco et al., 2021). Coastal habitats are among the most endangered ecosystems worldwide. The ecological functionality of coastal dunes is seriously threatened by pollution, biological invasion, and human activities such as mechanical beach cleaning, hydraulic and harbour infrastructure construction, urban development, and tourism (e.g., Ciccarelli et al., 2017; Pyšek et al., 2020; Prisco et al., 2021; Mugnai et al., 2022; Pinna et al., 2022). Among these threats, marine litter appears to be one of the issues with a greater global distribution range (Poeta et al., 2014). One of the most obvious indicators of this component is beach litter (BL hereinafter), which is the portion of marine litter that is washed ashore due to wind, sea currents, and waves (Cheshire et al., 2009; Poeta et al., 2016). This anthropogenic component reaches the beach through different processes. Then it can interact with the psammophilous plant species and communities of coastal dunes (e.g., Debrot et al., 2013; Poeta et al., 2017; Menicagli et al., 2019a,b; Battisti et al., 2020; Calderisi et al., 2023; Menicagli et al., 2023).

Within the coastal dune ecosystems, environmental factors, such as the coherence and salinity of sandy sediments, wind, salt spray, and wave inundation, create a complex sea-to-inland environmental gradient (Acosta et al., 2013; Fenu et al., 2013; Conti et al., 2017). Only plant species that are able to tolerate these unique conditions can survive near the coast, while other species are more dominant inland. The result is a coastal-specific vegetation succession (Fenu et al., 2012;

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Ruocco et al., 2014; Green and Miller, 2019). Psammophilous plant species and communities occur in a typical zonation along the sea-inland environmental gradient. Following this complex ecological gradient, they establish different dune habitats that represent complex systems with substantial environmental changes (e.g., Maun, 2009; Fenu et al., 2012, 2013; Ruocco et al., 2014; Prisco et al., 2021). Any change in the shape of these ecosystems leads vegetation zonation to be fragmented, with the replacement of the most prevalent phytocoenosis, and, in the most severe situations, the sensitive biocoenosis may disappear entirely (Acosta et al., 2009). The peculiar environmental conditions typical of these ecosystems make these habitats, especially in the Mediterranean Basin, remarkable for their ecological diversity in terms of highly specialised and distinctive flora (e.g., Carranza et al., 2008; Maun, 2009; Fenu et al., 2012, 2013; Ruocco et al., 2014; Pinna et al., 2015; Prisco et al., 2021) and landscape heterogeneity (e.g., Carranza et al., 2010; Drius et al., 2013; Malavasi et al., 2016; Calderisi et al., 2021). Despite that, these psammophilous coastal habitats are widely threatened, especially by BL, since the Mediterranean seabed has an estimated 0.5 billion litter pieces (UNEP/MAP, 2015) and this Sea is one of the most impacted by plastic litter (Cózar et al., 2015; Fossi et al., 2017; Baini et al., 2018; Kazour et al., 2019; Boucher and Billard, 2020). In fact, even if there is a vast range of litter materials in the marine environment, plastic is the most common kind of litter. Its proportion in total marine litter ranges between 60% and 80%, with some sites exceeding 90% (Derraik, 2002).

In recent years, several studies have investigated how litter affects the Mediterranean marine and coastal ecosystems. Many studies have focused on the capacity of marine litter to harm animal species through entanglement and ingestion (e.g., Angiolillo et al., 2015; Deudero and Alomar, 2015; Gall and Thompson, 2015; Galgani et al., 2019; D'Alessandro et al., 2020; Battisti et al., 2023a). Additionally, evaluations have been made on the dispersion of microplastics in the water column, highlighting that the vertical distribution of microplastics changes over time (Chevalier et al., 2023). This variability is influenced not only by the properties of the microplastics (e.g., size, density, etc.), but also by other factors such as wind, seasons, water density, and stratification (Chevalier et al., 2023). Furthermore, the presence of BL on the Mediterranean coasts has been analysed by different studies, revealing that plastic is the most common type of BL observed (e.g., Poeta et al., 2014, 2016; de Francesco et al., 2018; Gjyli et al., 2020; Grini et al., 2022), confirming the global pattern (e.g., Rech et al., 2014; Rangel-Buitrago et al., 2018a; Andriolo et al., 2020, 2021). Additionally, several studies have examined how the distribution of BL varies over time, discovering that this follows a seasonal pattern but obtaining different results from each other. For instance, Menicagli et al. (2022) found that the winter is the season with the greatest accumulation of BL, due to autumn and winter storms, while Poeta et al. (2022) found the highest amount of litter accumulation during the autumn-spring period. Novillo-Sanjuan et al., (2022) evaluated the presence of microplastics on three beaches in Spain and classified them as dirty during the summer and clean, or moderately dirty, during the winter. However, as far as we know, only a few studies have focused on the interactions between BL and the plant species and communities typical of coastal dune systems. Menicagli et al. (2019a,b) used compostable and non-biodegradable bags to assess the effect of BL on seed germination in psammophilous plant species, including *Elymus farctus* (Viv.) Runemark ex Melderis, *Ammophila arenaria* (L.) Link, and *Glaucium flavum* Crantz. These studies have shown that both conventional and compostable bags, once incorporated into sediments, can hinder the growth of newly established seedlings and sexual recruitment, and that their leachates can interfere with mechanisms that control germination, dormancy release, and early growth (Menicagli et al., 2019a,b). As reported by Corbau et al. (2023), psammophilous plants can be considered centres of BL accumulation. In fact, dune vegetation intercepts objects carried by wind and waves along the beach, lengthening resident times and increasing the burial of litter (Cresta and Battisti, 2021; Andriolo and Gonçalves, 2022). In recent years, some studies have reported the ability of psammophilous plant species and communities of coastal dunes to trap BL. For instance, Battisti et al. (2023b) reported how plots in which the psammophilous species *Salsola kali* L. was present appeared to trap a greater quantity of BL and litter with longer lengths compared to plots without vegetation. Ben-Haddad et al. (2023) analysed the ability of the psammophilous species *Cakile maritima* Scop. to trap BL, finding that plots with *C. maritima* contained more plastic litter than those without vegetation. Mancuso et al. (2023) evaluated the role of psammophilous vegetation as a trap for BL, finding that patches with this vegetation were more efficient in entangling BL than the control ones. According to Gallitelli et al. (2023), psammophilous vegetation in foredunes and reedbeds in backdunes may act as sinks for BL. Lastly, Mo et al. (2021) discovered that other psammophilous plants such as *E. farctus*, *Euphorbia paralias* L., and *Echinophora spinosa* L. have a potential role in trapping BL thanks to their habitus and highly branched roots. Considering the typical habitats of Mediterranean coastal dunes, Šilc et al. (2018) demonstrated that there was a noticeable gradient in BL from the sea to the inland, with the largest concentration of litter observed on the foredunes (habitat 2120). Calderisi et al. (2023) found that Mediterranean embryonic dunes and the white dune act by blocking and limiting the amount of BL that is deposited in the backdune. Furthermore, Poeta et al. (2014), analysing coastal dunes located in central Italy, found that the embryonic dunes and mobile dunes contain the most amount of BL, explaining that this could be because in the Mediterranean, even during winter storms, the action of waves and tides rarely extends beyond these habitats.

Nowadays, Mediterranean coastal dunes are characterised by the presence of invasive plant species that constitute a major threat to native plant species and communities. In particular, *Carpobrotus acinaciformis* (L.) L.Bolus (Aizoaceae) is among the most abundant invasive species in the entire Mediterranean Basin (e.g., Brundu, 2013; Campoy et al., 2018; Lazzaro et al., 2020). *Carpobrotus* species invasions have a large negative impact on the ecology of invaded habitats, with considerable alterations in invaded ecosystems at a variety of scales (Vilà et al., 2006; Molinari et al., 2007; Carranza et al., 2010; Santoro et al., 2012). Additionally, these species are significant drivers of soil changes and disruptors of soil geochemical processes (Santoro et al., 2011; Novoa et al., 2013; Vieites-Blanco and González-Prieto, 2018). The effects of the *Carpobrotus* species invasion on the pH of the soil, salt content, moisture content, nutrient content, and microbial activity vary depending on the parameters of the ecosystem before the invasion (Campoy et al., 2018). Due to detrimental effects on germination, survival, growth, and reproduction, *Carpobrotus* species have unfavourable direct consequences on native plants (D'Antonio and Mahall, 1991; Vilà et al., 2006; Conser and Connor, 2009; Affre et al., 2010; Novoa et al., 2013). *Carpobrotus* species directly compete with native plants for available space. Several studies have demonstrated how the invasion of the *Carpobrotus* species alters patterns of native species diversity (Vilà et al., 2006; Santoro et al., 2012; Fried et al., 2014), supporting the theory that its successful establishment most likely occurs through replacement and exclusion of native species rather than coexistence. Previous studies have also shown that habitats with the invasive *C. acinaciformis* can trap more items and items with a larger surface-area than those with native psammophilous vegetation (Gallitelli et al., 2021; Calderisi et al., 2023). However, knowledge on this topic is still insufficient to clarify the potential role of alien plant species in trapping litter compared to native plant species.

Based on these considerations, the aims of this study were (1) to determine the kind and amount of BL present in the embryonic dunes of four typical Mediterranean coastal dunes in Sardinia; (2) to understand, considering that this habitat is often invaded by *C. acinaciformis*, if there were any differences between this habitat and the same habitat invaded by *C. acinaciformis*; (3) to assess if the amount and distribution of BL in the embryonic dunes differed among beaches with different morphologies.

2. Materials and methods

2.1. Study habitat and study area

The habitat embryonic dunes, as defined by the European Habitats Directive, are characterised by perennial psammophilous herbaceous formations that grow in the embryonic dunes and develop in the Mediterranean macrobioclimate, in the infra- to meso-Mediterranean thermotypes (Biondi et al., 2009). The most engineering species in this habitat is *Elymus farctus* (Viv.) Runemark *ex* Melderis (*Thinopyrum junceum* ≡ *Agropyron junceum* subsp. *mediterraneum* ≡ *Elytrigia juncea*), a rhizomatous Gramineae that manages to increase its rhizome both horizontally and vertically. The result is the formation of a dense network with roots that incorporate the sand particles. Other relevant species that characterise the embryonic dunes are *Sporobolus virginicus* (L.) Kunth, *Otanthus maritimus* (L.) Hoffmanns. & Link, *Medicago marina* L., *Anthemis maritima* L., *Eryngium maritimum* L., *Calystegia soldanella* (L.) Roem. & Schult., *Polygonum maritimum* L., and *Lotus cytisoides* L. (Biondi et al., 2009).

Although it is a pioneer habitat, its organisation is significantly altered along the Mediterranean coasts, and the speed of vegetation recovery after a disturbance is quite fast (Angelini et al., 2016). The factors that negatively affect this habitat are the levelling and mechanical cleaning of the developing dunes, the direct disturbances by humans (e.g., trampling), and the spread of invasive alien species, especially *Carpobrotus* sp. pl.

Our study focused on the embryonic dunes found on the coastal dunes belonging to the Tavolara-Punta Coda Cavallo Marine Protected Area; this Marine Protected Area is in the Gulf of Olbia (NE Sardinia; Fig. 1). This coastal sector is characterised by an alternation of promontories sculpted on the rocks of the intrusive basement and small beaches between one promontory and another. The beaches have been catalogued into two large main groups: the arched or "Pocket Beach" type systems, limited at the ends by rocky outcrops; and the systems set up on coastal strips and ancient beach deposits, often characterised by the presence of a backshore depression or lagoons. The vegetation constituting the embryonic dune in this area can be traced back to the association *Sileno corsicae-Elytrigetum junceae* (Malcuit 1926) Bartolo, Brullo, De Marco, Dinelli, Signorello & Spampinato 1992 corr. Géhu 1996.

To achieve the aims of the study, both the well-developed and conserved embryonic dunes and the presence of the same habitat invaded by *C. acinaciformis* were specifically sought. The field surveys were carried out on the beaches of Murta Maria, Bunthe, Porto Taverna, and Cala Girgolu (Fig. 1 and Fig. 2) because they presented both of these conditions. These four beaches are located close to population centres; furthermore, being in one of the main tourist areas of Sardinia, they are widely frequented, especially in the summer tourist season.

2.2. Data collection

On each of the four investigated beaches, sampling was carried out through the methodology of Calderisi et al. (2023), adapted from previous protocols (Gallitelli et al., 2021; Battisti et al., 2023b). Two samplings, the first in May and the second in October, were conducted using a paired sampling approach, considering plots with and without *C. acinaciformis* following the protocol used in Gallitelli et al. (2021) and Battisti et al. (2023b). Specifically, beach litter (BL) accumulation was analysed using 20 adjacent pairs of plots of 1 × 1 m: 20 plots with natural vegetation and 20 plots invaded by *C. acinaciformis.* In particular, 10 pairs of plots were sampled during the month of May, and, using the coordinates, the same points were sampled in the month of October (Table S1). These plots were randomly placed in the embryonic dunes dominated by *E. farctus*, so that the percentage of *C. acinaciformis* coverage was greater than 60% in the ones that had been invaded and zero in the ones that had natural vegetation (Fig. 2). Moreover, at each site, uninvaded and invaded plots were adjacent or close to each other in similar environmental conditions concerning distance from the shoreline, sand properties, and exposure. We therefore assume that any differences between plots are a result of the presence of *C. acinaciformis*.

Visual estimates have been used to determine the percentages of total plant cover and the relative coverage of each vascular plant in each plot (Fenu et al., 2012, 2013; Pinna et al., 2015). Only the superficial BL was considered distinguishing between the macrolitter (items > 25 mm in the longest dimension) and the mesolitter (items between 5 mm and 25 mm in the longest dimension) (UNEP/MAP, 2015; GESAMP, 2019; Fleet et al., 2021). Using the same approach as Calderisi et al. (2023), each plot was photographed (using the 12MP camera of the iPhone 13 device) to provide orthogonal digital images that were subsequently used in the laboratory to determine the size of each item.

2.3. Data analysis

Using ImageJ software (Schneider et al., 2012), photographs of each plot were evaluated in the laboratory, starting by opening and calibrating the software. To calibrate it, it is necessary to press the "Analyze"

Fig. 1. Location of the Tavolara-Punta Coda Cavallo Marine Protected Area in Sardinia (NE-Sardinia). The precise beaches where the surveys were made (Murta Maria, Bunthe, Porto Taverna, and Cala Girgolu) are indicated with a blue arrow. The two small boxes highlight the global and Mediterranean locations of the study sites.

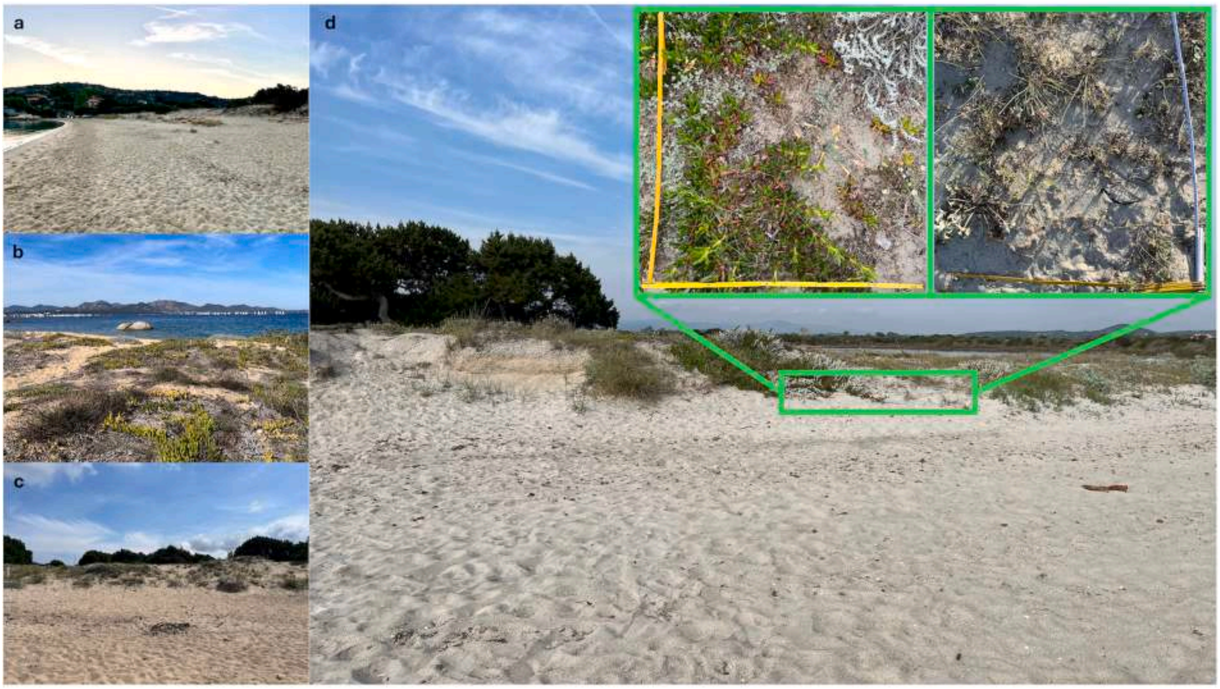
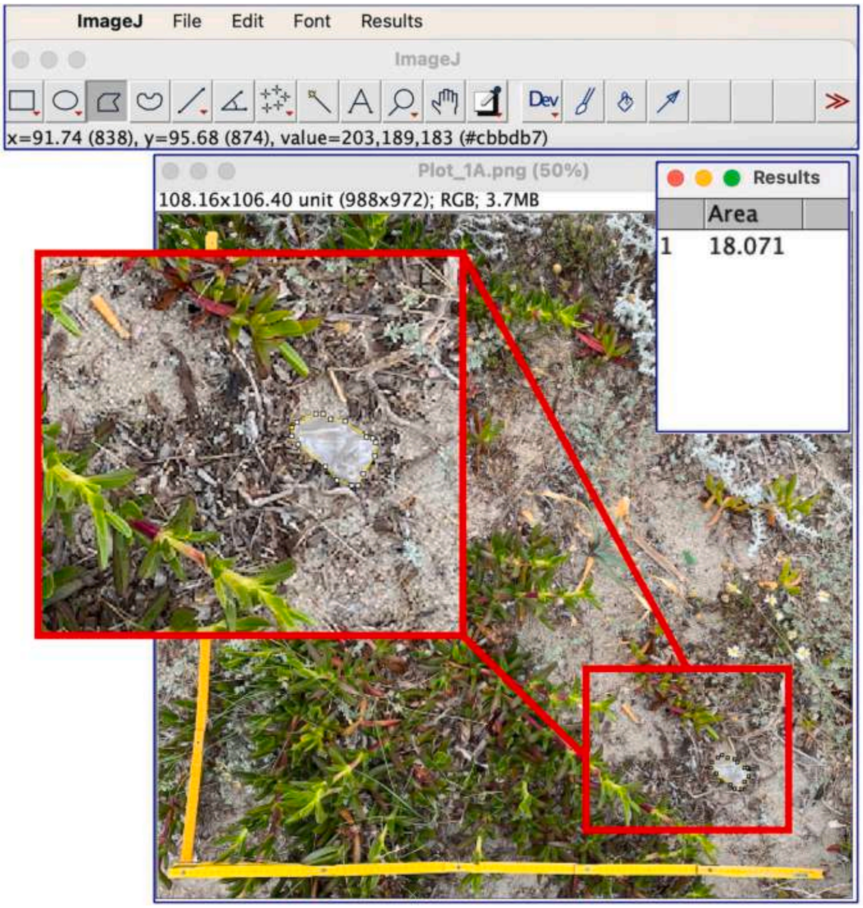


Fig. 2. The dune systems analysed: Cala Girgolu (a), Bunthe (b), Porto Taverna (c), and Murta Maria (d) beaches. The principal photo presents an example of a pair of plots analysed in the field (the Murta Maria dune system).



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x=91.74 (838), y=95.68 (874), value=203,189,183 (#cbbdb7)
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108.16x106.40 unit (988x972); RGB; 3.7MB
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	Area
1	18.071

Fig. 3. An example of a measurement made with ImageJ software in the laboratory. The red rectangle highlights the way in which the perimeter of the object was delimited to obtain its surface-area.

function and then the "Set Scale" option from the menu that appears. Calibration has been performed using the wooden metres used in the field to delimit the plot. This allowed the unit of measurement to be defined to accurately measure the surface-area of each item. After that, using the tools present in the software, such as "Polygon selections" and "Oval", the perimeter of each object present in the plot has been drawn. Once the perimeter has been drawn, by pressing the "Analyze" function and then "Measure", the software provides the precise surface-area occupied by the item. This allowed us to count the items and accurately measure their surface-area (Fig. 3). All the BL items on the plots have been categorised into categories and sub-categories using the most recent European manual (Fleet et al., 2021; Table S2). A category called “Others”, considering both the categories and the sub-categories of BL, was created to contain all the items discovered in the study area particularly low in number.

Regarding the beaches considered in the study, these have been divided into two different groups: the first group consists of Murta Maria and Porto Taverna and has been defined as A, consisting of open beaches with North-East exposure and large dimensions; while the second group consists of Bunthe and Cala Girgolu and has been defined as B, beaches bounded by two promontories, with North exposure and small dimensions, or pocket beaches.

Both the number of items and the surface-area occupied by BL items were always reported as the mean ± standard error. To determine whether there was a significant difference in the global data of the trapped BL items in the habitat with native vegetation compared to the habitat with *C. acinaciformis*, a Mann-Whitney U Test was performed. Box plots were used to represent the comparison data. In addition, General Linear Models (GLMs) were performed to test the effect of groups (native vegetation vs. invaded plots), the effect of the different beach morphologies, and the effect of the interaction between groups and beach morphologies on the total BL, on the plastic category, and on the plastic sub-categories. Post-hoc tests for pairwise comparisons were conducted using Fisher’s LSD. The statistical analysis and graphs were performed using Statistica 8.0 software (Statsoft, USA).

3. Results

A total of 190 items were discovered during the sampling in the research area (Fig. 4), the majority of which (110; 57.89%) were in plots invaded by *C. acinaciformis* (Fig. 5a). The items, in total, occupied a surface-area of 2341.72 cm^2 (0.58% compared to the sampled area), 71.26% of these were found in the plots invaded by *C. acinaciformis* (Fig. 5b).

Plots with native vegetation trapped, on average, fewer items (4.00 ± 0.98) than those invaded by *C. acinaciformis* (5.50 ± 1.10) (Fig. 6a). However, no statistically significant differences have been found according to the Mann-Whitney U Test ($p > 0.05$).

On average, in the plots with native vegetation, the surface-area occupied by the beach litter (BL) was minor (33.64 ± 7.53 cm^2) compared to the plots invaded by *C. acinaciformis* (83.44 ± 14.02 cm^2) (Fig. 6b). The Mann-Whitney U Test results in this case showed that this difference was statistically significant ($p < 0.05$).

The litter amount was mostly composed of "Plastic" (74.74%, 142 items) and "Wood" (18.42%, 35 items) categories (Table 1). Overall, "Plastic" occupied the largest area (1270.84 cm^2, 0.32% of the total sampled area), while "Wood" occupied 796.54 cm^2 (0.20% of the total sampled area). The items assigned to the "Others" category comprised 6.84% of the litter amount, occupying 274.36 cm^2 (0.07% of the total sampled area).

The “Plastic” and “Others” categories were found more abundant on invaded plots, whereas “Wood” items were more numerous in the native vegetation plots (Fig. 7a). However, no statistically significant differences were found according to the Mann-Whitney U Test ($p > 0.05$). The General Linear Models (GLMs) results confirmed that there were no statistically significant differences between the plots with native vegetation and those invaded ($p > 0.05$; Figure S1a; Table S3). There was a significant effect of the beach morphologies in relation only to the “Plastic” category ($p < 0.05$; Figure S1c; Table S3). Moreover, the effect of the interaction between groups and beach morphologies was not statistically significant ($p > 0.05$; Figure S1e; Table S3).

The lesser surface-area occupied by BL for all the categories was found in the plots with native vegetation in relation to those invaded (Fig. 7c). The Mann-Whitney U Test showed that the differences

Fig. 4. Examples of beach litter found in the study area.

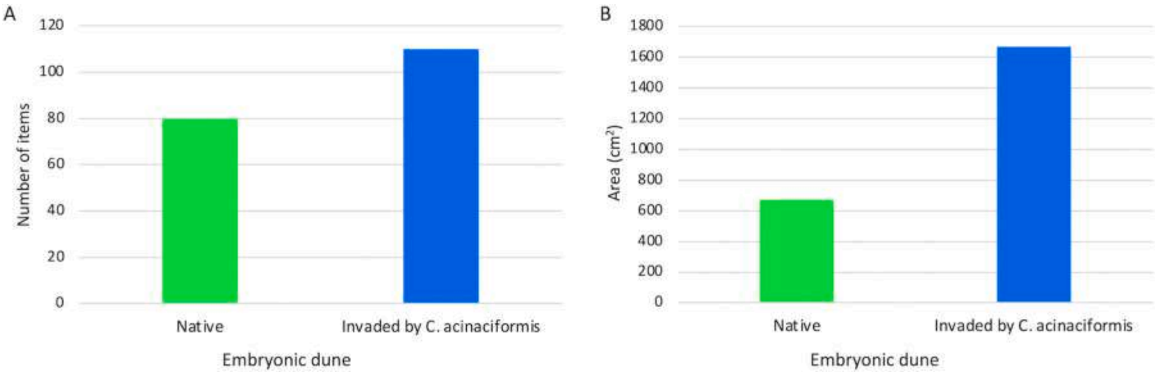

Fig. 5. The number of items (a) and the surface-area of items (b) compared to the embryonic dunes and the embryonic dunes invaded by *C. acinaciformis* in the Tavolara-Punta Coda Cavallo Marine Protected Area.

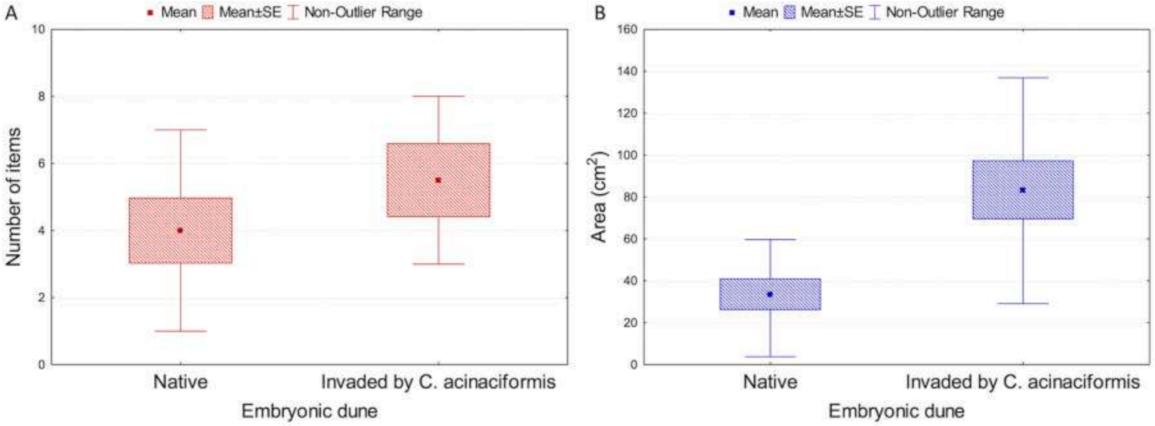

Fig. 6. Boxplots of the number of items (A) and of the surface-area (B) compared to the plots with natural vegetation (Native) and invaded by *C. acinaciformis*. The boxes show the mean ± standard error, and the horizontal bars show the max and min values, except for the outliers.

Table 1
Number of items, surface-area, and respective percentages, distinguished between plots with native vegetation and those invaded by *C. acinaciformis*, for each BL category considered.

Categories	No. items		Area occupied (cm^2)	
	Native plots	Invaded plots	Native plots	Invaded plots
Plastic	57 (40.14%)	85 (59.86%)	226.35 (17.81%)	1044.49 (82.19%)
Wood	19 (54.29%)	16 (45.71)	370.84 (46.56%)	425.70 (53.44%)
Others[a]	4 (30.77%)	9 (69.23%)	75.69 (27.59%)	198.67 (72.41%)

[a] Others category includes: Glass/ceramics items, Metal items, Cloth/Textiles items, and Paper items.

between the plots were statistically significant only when the total BL surface-area and the "Plastic" surface-area were considered ($p < 0.05$). These results have been confirmed by the GLMs ($p < 0.05$; Figure S1b; Table S4); instead, the effect of the beach morphologies and the interaction of groups and beach morphologies were not statistically significant ($p > 0.05$, Figure S1d,f; Table S4).

The most abundant plastic sub-category was "Plastic items and fragments" (51.41%, 73 items). Followed by "Cigarette butts" and "Plastic tangled nets/cord" sub-categories, both with 19 items (13.38% each), the "Foamed polystyrene" sub-category (7.75%, 11 items), the "Others" sub-category (7.04%, 10 items), and the "Plastic food packets" sub-category (6.34%, 9 items; Table 2). For the majority of the objects that were found, it was possible to hypothesise a high residence time. Only several, such as "Cigarette butts" and "Plastic tangled nets/cord" sub-categories, were of recent origin since the objects presented a low level of degradation and, regarding the cigarettes, ash could have been seen in some of them.

The sub-categories with the largest surface-area were "Plastic items and fragments" (561.86 cm^2, 0.14% of the total sampled area) and "Plastic tangled nets/cord" (250.66 cm^2, 0.06% of the total sampled area), followed by the "Foamed polystyrene" sub-category (179.75 cm^2, 0.04% of the total sampled area), the "Others" sub-category (171.44 cm^2; 0.04% of the total sampled area), the "Plastic food packets" sub-category (65.96 cm^2; 0.02% of the total sampled area), and the "Cigarette butts" sub-category (41.17 cm^2; 0.01% of the total sampled area; Table 2).

On average, considering all sub-categories except "Others", plots with native vegetation trapped a lesser number of items compared to the invaded ones. As regards the "Others" sub-category, both types of plots trapped the same number of items (Fig. 7b). No statistically significant differences were found according to the Mann-Whitney U Test ($p > 0.05$). The GLM results confirmed that there were no statistically significant differences between the plots with native vegetation and those invaded ($p > 0.05$; Figure S1a; Table S3). Instead, the beach morphologies had a significant effect on the sub-categories "Plastic items and fragments" and "Plastic tangled nets/cord" ($p < 0.05$; Figure S1c; Table S3). Furthermore, none of the plastic sub-categories showed statistically significant effects from the interaction between groups and beach morphologies ($p < 0.05$; Figure S1e; Table S3).

The least amount of surface-area occupied by the plastic sub-category has been found in plots with native vegetation in comparison

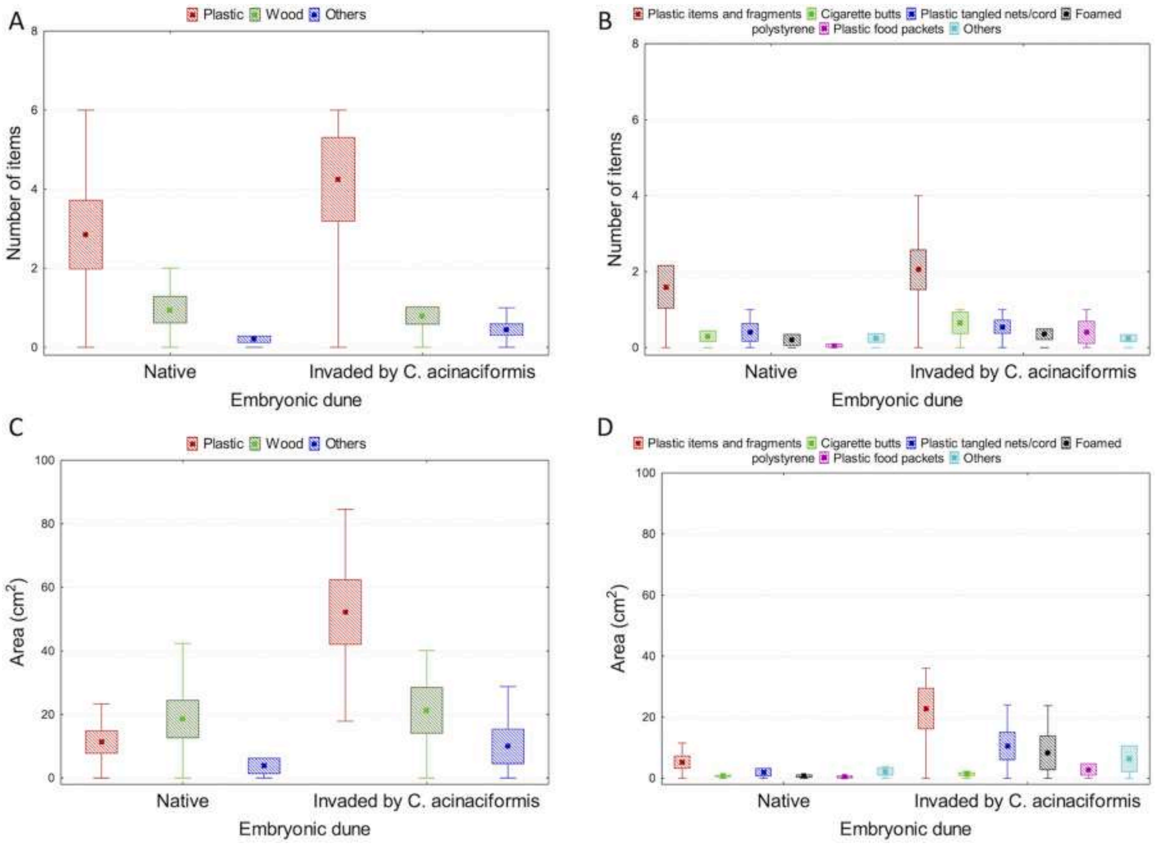

Fig. 7. The number of items in relation to the different BL categories (A) and plastic sub-categories (B) and the surface-area occupied by the items in relation to the different BL categories (C) and plastic sub-categories (D) compared to the plots with natural vegetation (Native) and invaded by *C. acinaciformis*. The boxes show the mean ± standard error, and the horizontal bars show the max and min values, except for the outliers. In A and C, the Others category includes: Glass/ceramics items, Metal items, Cloth/Textiles items, and Paper items. In B and D, the Others sub-category includes: Plastic rings from bottle caps, Plastic caps, Cotton buds, Plastic food containers, Plastic bags, Plastic cups, Plastic straws, and Plastic fenders.

Table 2
Number of items, surface-area, and respective percentages, distinguished between plots with native vegetation and those invaded by *C. acinaciformis*, for each plastic sub-category considered.

Plastic sub-categories	No. items		Area occupied (cm^2)	
	Native plots	Invaded plots	Native plots	Invaded plots
Plastic items and fragments	32 (43.84%)	41 (56.16%)	105.17 (18.72%)	456.69 (81.28%)
Cigarette butts	6 (31.58%)	13 (68.42%)	14.37 (34.92%)	26.80 (65.08%)
Plastic tangled nets/cord	8 (42.11%)	11 (57.89%)	39.54 (15.78%)	211.12 (84.22%)
Foamed polystyrene	4 (36.36%)	7 (63.64%)	14.14 (7.87%)	165.61 (92.13%)
Plastic food packets	1 (11.11%)	8 (88.89%)	8.69 (13.17%)	57.27 (86.83%)
Others[a]	5 (50.00%)	5 (50.00%)	44.44 (25.92%)	127.00 (74.08%)

[a] Others sub-category includes: Plastic rings from bottle caps, Plastic caps, Cotton buds, Plastic food containers, Plastic bags, Plastic cups, Plastic straws, and Plastic fenders.

to those invaded (Fig. 7d). The results of the Mann-Whitney U Test showed that these differences were not statistically significant ($p > 0.05$), while the GLM results showed that the differences between plots with native vegetation and those invaded were statistically significant only considering the surface-area occupied by the “Plastic items and fragments” sub-category ($p < 0.05$; Figure S1b; Table S4). Furthermore, a significant effect of the beach morphologies in relation to the “Plastic tangled nets/cord” sub-category surface-area has been found ($p < 0.05$; Figure S1d; Table S4). Lastly, the effect of the interaction of groups and beach morphologies was not statistically significant for all the plastic sub-categories ($p > 0.05$; Figure S1f; Table S4).

4. Discussion

Although coastal dune systems have become deposits for the accumulation of beach litter (BL) (Rangel-Buitrago et al., 2018b; Nelms et al., 2020; Turner et al., 2021), only few studies have focused on the impact that this anthropogenic component may have on plant species and communities in the Mediterranean ecosystems. This study investigated the presence and abundance of BL in a specific dune habitat, especially the Mediterranean embryonic dunes, a protected habitat among the most threatened in Europe. Several studies evaluating the presence of BL in dune systems found that this habitat has an important role in blocking litter (e.g., Poeta et al., 2014; de Francesco et al., 2018, 2019; Calderisi et al., 2023). It has also been observed that the main structural species of embryonic dunes can trap the BL (Andriolo et al., 2021; Mo et al., 2021). Additionally, this study evaluated the differences between the embryonic dunes and the embryonic dunes invaded by *C. acinaciformis* in trapping BL and whether different beach morphologies could influence the distribution of BL in this habitat.

Our study demonstrates that the embryonic dune and its invaded form trap BL in the same way, as no statistically significant difference has been found, although in the uninvaded habitat fewer items have been found. This conclusion contrasts with the findings of previous research. Calderisi et al. (2023), analysing all the habitats of the Porto

Paglia dune system (SW-Sardinia), showed statistically significant differences between habitats invaded by *C. acinaciformis* and habitats lacking this alien species. Gallitelli et al. (2021), analysing just the embryonic dune habitat at a sandy beach along the Tyrrhenian coast of Central Italy, showed statistically significant differences in the amount of BL trapped by *C. acinaciformis*-invaded habitat compared to the same non-invaded habitat. These deviations from the literature might be attributed to variances in beach exploitation practices as well as differences in beach features, which can lead to disparities in BL accumulation. In fact, not only dune vegetation but also several variables influence the amount, kind, and distribution of BL. These variables include both environmental determinants, such as winds, currents, tides, river flows, and beach morphology, and socioeconomic determinants, such as municipal infrastructure, beach use, social behaviour, and the level of environmental awareness among local and visiting populations (Araùjo and Costa, 2006; Thiel et al., 2013; Poeta et al., 2014). The beaches included in this study have a different exposure than the beaches studied by Calderisi et al. (2023). This might be one of the reasons for the smaller amount of litter discovered in our research area, as well as the lower number of BL caught by the two habitat types (native and invaded by *C. acinaciformis*) and, consequently, these could explain the lack of statistically significant differences. However, to properly comprehend these discrepancies, more research in other areas of study is required.

Understanding the composition of the BL is significant since it provides information on specific litter items and their sources (Šilc et al., 2018). In our study area, the most abundant category was “Plastic”, as found in further research (e.g., Šilc et al., 2018; Vlachogianni et al., 2018; Andriolo et al., 2021; Mo et al., 2021; Özden et al., 2021; Calderisi et al., 2023; Rios-Fuster et al., 2023). It must be considered that distinct countries and even individual beaches within a country have different values for the various sub-categories of plastic (Šilc et al., 2018). The main Plastic sub-categories detected in our study area were “Plastic items and fragments”, “Cigarette butts”, “Plastic tangled nets/cord” and “Foamed polystyrene”, again confirming the results of previous studies (e.g., Šilc et al., 2018; Vlachogianni et al., 2018; Andriolo et al., 2020; Mo et al., 2021; Calderisi et al., 2023). The sub-category “Plastic items and fragments” was mainly made up of plastic fragments of various sizes, which were difficult to identify. This typology of BL, together with the sub-category “Foamed polystyrene”, in agreement with Šilc et al. (2018), is an indicator of “aged” litter, and it is not *in situ* littering; therefore, these sub-categories of BL are not strictly linked to the presence of beachgoers. For this sub-category it is possible to hypothesise a first sea-current-mediated deposition on the shoreline, followed by a second wind-mediated movement to the vegetated dune. Regarding the sub-category "Cigarette butts", it must be taken into consideration that people are, directly or indirectly, a strong determinant of the accumulation of this litter on the beaches (Araújo and Costa, 2019), but the presence of this litter is not always correlated to the cigarettes smoked *in situ* (Novotny et al., 2009). Considering the characteristics of the cigarettes found on the beaches we assessed (good preservation and presence of ash), we can state that beachgoers are the main source of this litter.

Regarding the plastic category, fewer items were found in plots with native vegetation than in the invaded ones, but this difference was not statistically significant. This finding may further support habitat conservation initiatives such as the eradication of *C. acinaciformis* since it has no additional role in trapping BL. However, the effect of the beach morphologies was significant: the pocket beaches had a greater quantity of plastic items than those indicated as open beaches, with North-East exposure and large dimensions; in particular, this was evident for the sub-category “Plastic items and fragments”. In the literature, there is evidence that the different coastal morphology and the different exposure to winds and waves affect BL abundance, distribution, and composition (e.g., Velander and Mocogni, 1998; Williams and Tudor, 2001; Williams et al., 2017). It must be considered that this sub-category of BL ("Plastic items and fragments") is mainly characterised by small objects or fragments; therefore, we can hypothesise that their main origin is connected to sea currents and winds. In this case, we can assume that the exposure only to northern winds and currents, together with the typically closed morphology of the pocket beach, may play a major role in determining the accumulation of BL in the dune system compared to systems with a North-East exposure and larger dimensions.

Considering the surface-area occupied by the “Plastic” category and, especially, by the sub-category “Plastic items and fragments”, a statistically significant difference was found between the plots with native vegetation and those invaded by *C. acinaciformis*. The plots with native vegetation have a smaller surface-area occupied by these categories than the invaded plots. This conclusion lines up with what has been stated in previous studies (Gallitelli et al., 2021; Calderisi et al., 2023). A reasonable explanation could be related to the shape and the developing mode of the considered alien species. This species develops by forming carpets along the sand, resulting in the possible ability of this species to trap larger items than the native vegetation of the embryonic dunes, such as *E. farctus*, which, generally, does not develop in this way.

Another interesting sub-category to consider is “Plastic tangled nets/cord”. In this case, there is a statistically significant effect of the beach morphologies considering the number of items and the surface-area occupied by these items. The pocket beaches, compared to the open beaches with North-East exposure and large dimensions, have a greater number of items belonging to the “Plastic tangled nets/cord” sub-category and a greater surface-area occupied by them. An explanation for this could be the exploitation of these beaches by fishermen. In fact, within this group of beaches, we find some zones particularly quiet for carrying out this activity. Even if this result is in contrast with what was reported by Rangel-Buitrago et al. (2018a), who showed that fishing-related litter is more common in remote or rurally exposed locations, indicating a significant impact from longshore-current movement. However, to further understand the primary origins of this litter, additional investigations that consider a larger number of beaches with varying features are required.

Lastly, it is necessary to consider that some limitations are present in this study. First, our investigation was conducted over a rather short period of time. As a result, more research is needed to properly understand how the distribution of BL differs among psammophilous plants and communities, as well as how other ecological variables might impact this anthropogenic component. These investigations must consider a wider number of beaches, organise manipulative experiments, and use more sophisticated investigative tools, such as drones, which allow a more thorough assessment of BL contamination.

5. Conclusion

Beach litter (BL) is one of the most prevalent pollution concerns in the world’s coastal habitats and one of the most visible signs of marine litter pollution. In this study, we tried to analyse the type and amount of BL on different beaches present in the Mediterranean Basin and to understand the role of other variables, such as the presence of alien species and the different morphologies of the beaches, in influencing this anthropic component.

Based on our findings, plastic was the predominant category in the embryonic dunes, mostly in form of "Plastic items and fragments". This reaffirms the prevalent presence of plastic litter on Mediterranean beaches. We looked at the impact of the alien species *C. acinaciformis* in trapping BL compared to the native vegetation of the embryonic dunes, but we observed no influence from this species, even if the invaded habitat had more litter. Lastly, pocket beaches with North exposure exhibited a higher abundance of plastic items compared to the open beaches with North-East exposure and huge dimensions, suggesting that coastal configuration influences the stranding litter process. This was particularly clear in the sub-category "Plastic items and fragments".

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CRediT authorship contribution statement

Giuseppe Fenu: Writing – original draft, Validation, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Donatella Cogoni:** Writing – review & editing, Data curation. **Giulia Calderisi:** Writing – original draft, Validation, Methodology, Investigation, Formal analysis, Data curation, Conceptualization.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data Availability

Data will be made available on request.

Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.rsma.2024.103532.

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