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# Difference between invasive alien and native vegetation in trapping beach litter: A focus on a typical sandy beach of W-Mediterranean Basin

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ABSTRACT

Beach litter is one of the most pervasive pollution issues in coastal environments worldwide. In this study, we aim to assess the amount and distribution of beach litter on Porto Paglia beach, its entrapment across psammophilous habitats, and whether the invasive *Carpobrotus acinaciformis* (L.) L.Bolus plays a different role in trapping litter than native vegetation. To this end, two seasonal samplings (in spring and autumn) were conducted using a paired sampling method that considers plots in all coastal habitats with and without *C. acinaciformis*. Our results confirm that the main beach litter category is plastic, and that its distribution varies across habitats: the white dune seems to play a greater role in trapping and filtering beach litter, reducing its amount in the backdune. A correlation was found between the Naturalness index (N) and the beach litter amount, supporting the finding that invaded habitats trap beach litter better than native ones.

## 1. Introduction

Marine litter is a growing global problem that threaten marine, coastal, and freshwater ecosystems, and its impacts are systematically overlooked (De Sá et al., 2018; Gallitelli et al., 2020; Poeta et al., 2022). This component is defined as "any persistent, manufactured, or processed solid material discarded, disposed of, or abandoned in the marine and coastal environment"; moreover, this is a complex issue that has global implications for human activities in addition to marine and coastal ecosystems (UNEP, 2009). Beach litter (hereafter BL), which is the fraction of marine litter that washes ashore due to wind, sea currents, and wave action, is one of the clearest signs of the presence of marine litter (Poeta et al., 2016; Prevenios et al., 2018; González-Fernández et al., 2021).

Due to the abundance of both sea and land sources of litter, the coastal area has become a hotspot for litter accumulation (Rangel-Buitrago et al., 2018; Nelms et al., 2020; Turner et al., 2021). In general, BL and plastic pollution come mainly from land-based sources (UNEP, 2018) and the main sources included industrial outfalls, agriculture, building and construction, mismanaged municipal solid waste, and a wide variety of personal care, pharmaceutical and healthcare products, including the personal protective equipment used during the COVID-19 pandemic (UNEP, 2018; Adyel, 2020; UNEP, 2021). Major contributors to marine sources of BL include shipping and offshore operations (i.e., packaging, cargo, paints, end-of-life dismantling, ballast water), fisheries and aquaculture (i.e., sealants, storage boxes, packaging, buoys, ropes, lines, and nets), ship-based tourism (i.e., packaging, personal goods), and legal and illegal dumping at sea (UNEP, 2021). Although BL is composed of a wide variety of materials, plastic items are the most prevalent, such as fragments, bottles, bags, caps/lids (UNEP/MAP, 2015). In addition, the accumulation of BL on coastal dune systems is directly linked to natural factors such as winds, currents, tides, waves and river flows (UNEP, 2021); these factors, in addition to being interconnected, are all related to beach morphology and vegetation.

Due to the high rate of BL accumulation, which is often non-biodegradable, in marine and coastal ecosystems, scientists' awareness of the nature and impact of BL has increased dramatically worldwide. Indeed, it has been demonstrated that BL accumulation can affect a wide range of ecological domains, from biological populations and communities to biogeochemical cycles, functioning in different ways and applying selective pressure on all elements of biodiversity and associated ecosystem services (Ruimin et al., 2019; Catarino et al., 2021; Bai et al., 2022). For example, BL pollution can cause direct or indirect damage to marine biota through entanglement or ingestion. After ingestion, several negative effects may occur including suffocation and starvation (Anbumani and Kakkar, 2018; Sun et al., 2019), physiological disorders (Au et al., 2015; Anbumani and Kakkar, 2018) and behavioural alterations (Green et al., 2017). In addition, the entanglement

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alters feeding capacity and increase biological stress and tissue lacerations (Angiolillo et al., 2015; de Carvalho-Souza et al., 2018; D'Alessandro et al., 2020). However, despite numerous studies on the effects of litter on marine animals and ecosystems, surprisingly, so far, only a few studies on vascular plants and coastal habitats are available in the literature to date.

This general picture is similar to that of the Mediterranean Basin. The Mediterranean Sea is one of the areas most affected by plastic waste (Fossi et al., 2017; Baini et al., 2018; Kazour et al., 2019). In fact, it has an annual pollution of 230,000 tons of plastic and for this reason it was recently renamed *Mare Plasticum* (Boucher and Billard, 2020). Coastal dunes, in particular, are considered hotspots of plastic pollution (Poeta et al., 2014), with an average of 60–80 % of items consisting of plastic, and in some places this percentage reaches over 95 % (Gregory and Andrady, 2003; OSPAR Commission, 2007). However, for a long time, coastal dunes have received far less attention than the consequences of BL, especially when considering the effects on psammophilous plant species and communities.

Coastal sand dunes are located in the transition zones between terrestrial and marine ecosystems, making them one of the patchiest landscapes on Earth (e.g., Carranza et al., 2008; Maun, 2009; Fenu et al., 2013; Malavasi et al., 2018). These ecosystems are influenced by a wide range of variables that, on one hand, determine their instability (i.e., groundwater flow, local hydrodynamics, beach morphology, prevailing winds, and waves), on the other hand, stabilise the sand dunes, such as the effects of the peculiar flora and biotic communities (Martínez and Psuty, 2004; Maun, 2009; Fenu et al., 2013; Pinna et al., 2015, 2019). Mediterranean coastal dune systems are characterised by high degrees of complexity and originality at both the species and community levels; these unique ecological features also make coastal dune systems particularly fragile environments (e.g., Carranza et al., 2008; Fenu et al., 2012, 2013; Calderisi et al., 2021; Prisco et al., 2021); in particular, coastal dune systems in the Mediterranean Basin seem to be those that have experienced a greater reduction in the last decades (Delbosc et al., 2021; Prisco et al., 2021). As a result, these dynamic environments host highly specialised vascular flora composed of plants that have a wide range of biological adaptations and responses to the significant environmental stresses typical of coastal dunes (Maun, 2009; Fenu et al., 2012, 2013; Pinna et al., 2015). It has been demonstrated that psammophilous vegetation plays a prominent role in BL trapping. In fact, distinct vegetation types have been found to play a role in trapping BL of different sizes (e.g., Andriolo et al., 2021; Gallitelli et al., 2023). For example, plants can influence the dispersal of litter along the beaches and facilitate the deposition of litter (e.g., Debrot et al., 2013; Martin et al., 2019; Battisti et al., 2020). Many BL items, due to their weight, rest in the sand in correspondence with the upper beach or with the embryo dunes and, successively, may be buried by wind, tides, and/or waves (Menicagli et al., 2019; Andriolo and Gonçalves, 2022). In addition, the root structure of the dune vegetation contributes to the retention and burial of BL (de Francesco et al., 2019). Moreover, coastal plants can either be negatively damaged or opportunistically use litter (e.g., Poeta et al., 2017; Menicagli et al., 2019, 2020). Indeed, dune plants may represent indicators of BL accumulation (Corbau et al., 2023).

These ecosystems are currently among the most threatened worldwide and are prone to significant biodiversity loss due to habitat degradation or simplification (e.g., Brown and McLachlan, 2002; Delbosc et al., 2021; Prisco et al., 2021; Pinna et al., 2022) and related to biological invasions (Díaz et al., 2019; Pyšek et al., 2020; Mugnai et al., 2022). Pollution, mechanical beach cleaning, off-road vehicle transit, hydraulic and harbour infrastructure construction, land use transformations primarily associated with agricultural activities, urban development, industrial areas (e.g., refineries), tourism, and afforestation activities have significantly impacted coastal dunes over time (e.g., Prisco et al., 2013; Ciccarelli et al., 2017; Pinna et al., 2022).

As one of the most vulnerable ecosystems, coastal dunes are among those in Europe most frequently invaded by invasive alien plants (Chytrý et al., 2008, 2009; Giulio et al., 2020). Along the Mediterranean coasts, the spread of invasive alien plants is favoured by human pressures, which leads to habitat fragmentation, reducing the plasticity and evolutionary potential of native plants (Giulio et al., 2020). Among the invasive alien plants that threaten the Mediterranean coastal dunes, *Carpobrotus acinaciformis* (L.) L.Bolus is currently considered one of the most pervasive invasive plants (Vilà et al., 2006; Novoa et al., 2013; Mugnai et al., 2022). Considering the ecological adaptability of its mating system, high seed production, and strong clonality (Roiloa et al., 2014; Roiloa, 2019), *C. acinaciformis* significantly affects the diversity, structure, and dynamics of native vegetation in non-native environments (Campoy et al., 2018).

Although the ecological role and the effects of the spread of invasive species along Mediterranean coasts have been extensively studied, little is known about the BL trapping capacity of the invaded habitats compared to the natural ones. In light of these considerations, the goal of this study is to determine if invasive coastal vegetation (specifically, the invasive alien plant *C. acinaciformis*) plays a different role in BL trapping than native psammophilous vegetation in a typical Mediterranean dune system. To achieve this main goal, the specific aims of this study are to: (1) count and classify BL on the beach; (2) analyse how BL is distributed in the different habitats of the dune system; (3) determine the relationship between habitat conservation status and the abundance of BL; and (4) investigate if there are differences between native habitats and *C. acinaciformis* invaded habitats and evaluate whether there is a seasonal effect on the different distribution, composition, and abundance of BL.

## 2. Materials and methods

### 2.1. Study area

With a surface area of c. 24,089 km$^2$, including about 300 satellite islands and islets, Sardinia is the second largest island in the Mediterranean Basin after Sicily (Pinna et al., 2019); the island's 1896 km of coastline (> 20 % of the Italy's coast) is made up of 24 % low, sandy, and pebbly shorelines (Atzeni et al., 2000).

Our study focused on the coastal dunes of Porto Paglia located in the Southern part of the Marina of Gonnesa (SW Sardinia; Fig. 1). This coastal site is approximately 820 m long, and it extends ca. 100 m to the inland, covering an area of ca. 27,000 m$^2$. This dune system is characterised by a slightly pronounced profile, with consolidated dunes reaching a maximum height <1 m.

The Cambrian succession in SW Sardinia is stratigraphically divided into three main groups: Nebida, Gonnesa and Iglesias. The Gonnesa Group (Lower-Middle Cambrian) is characterised by distinctive carbonatic deep-sea sediments and is separated into two groups based on trilobite content: the Santa Barbara Formation (mostly dolomitized rocks) and the San Giovanni Formation (fully karstified limestones) (Arisci et al., 2003). Different generations of dunes deposited from the middle to early Pleistocene form the Porto Paglia deposits (Orrù and Ulzega, 1986).

Available climatic data show a typical Mediterranean annual pattern of temperature and precipitation with a long dry summer (>2 months). This location has a western aspect, representing the greatest exposure to the mistral and west winds, which are considered the two main winds of the W-Mediterranean Basin (Ruti et al., 2008). Waves are mainly generated by the action of the mistral; the biggest yearly significant wave heights vary from 4 to 6 m, with maximum values of 8 m and a peak period of about 12 s (Corsini et al., 2006).

The study area encompasses the entire sandy dune system, which is colonised by the psammophilous vegetation. In general, the vegetation zonation follows the typical Mediterranean Sea-inland ecological gradient (Fenu et al., 2012, 2013), from annual and pioneer plant species typical of the areas closest to the shoreline (such as *Cakile maritima*

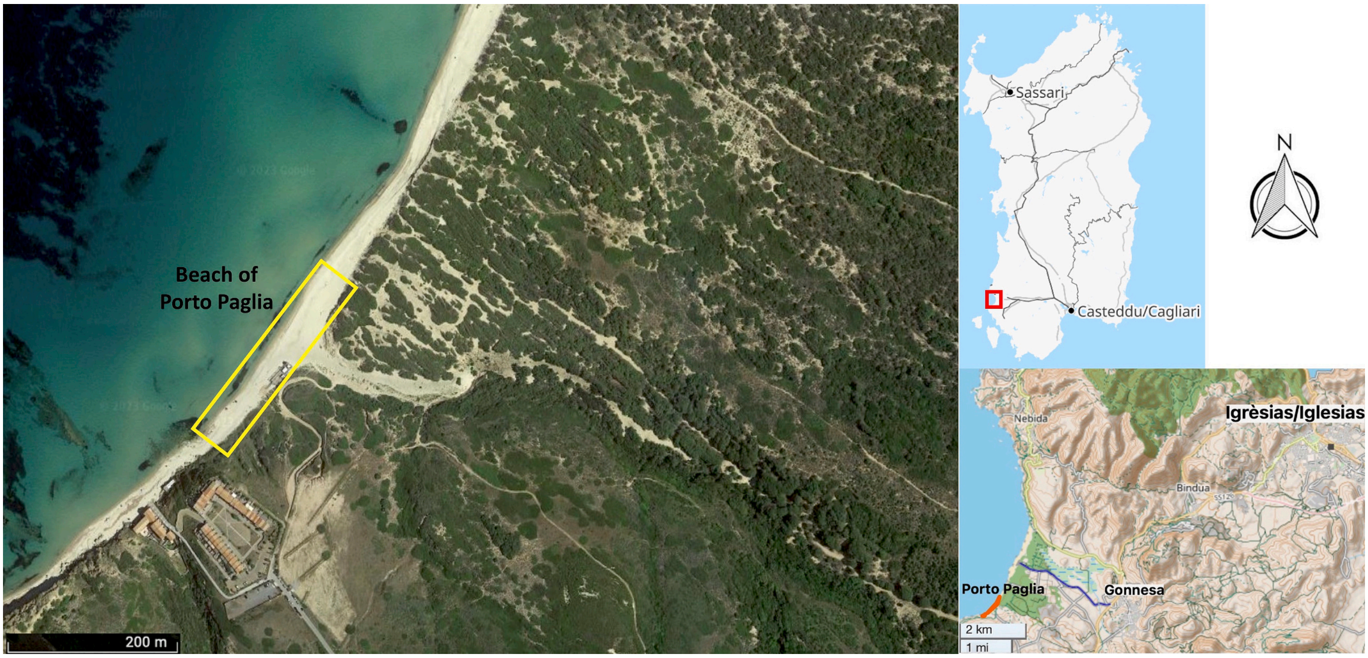


**Fig. 1.** Location of the Porto Paglia beach in Sardinia (W-Mediterranean Basin). The study area in which the surveys were made is indicated in yellow; within this area 39 $m^2$ were monitored. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Scop. subsp. *maritima*), to rhizomatous plants stabilizing the sands (such as *Elymus farctus* (Viv.) Runemark *ex* Melderis; *Sporobolus virginicus* (L.) Kunth; and *Calamagrostis arenaria* (L.) Roth subsp. *arundinacea* (Husn.) Banfi, Galasso & Bartolucci) to shrubby species typical of stabilized dunes (such as *Crucianella maritima* L.; *Juniperus macrocarpa* Sm.; and *Pistacia lentiscus* L.).

### 2.2. Data collection

Starting from the hypothesis that psammophilous vegetation plays a role in trapping BL, the amount and surface-area of BL trapped by native vegetation were assessed to compare with the amount and surface-area trapped by the invasive alien species *C. acinaciformis*. To evaluate these conditions, sampling was conducted using a paired sampling approach, that considered plots with and without *C. acinaciformis*. Moreover, two surveys were conducted, the first in May (hereafter referred to as spring) and the second in October (hereafter referred to as autumn), to evaluate the seasonal effect on the different distribution, composition, and abundance of BL.

BL accumulation was analysed using individual plots randomly placed in the aphitoic zone, as well as adjacent pairs of plots (one invaded and one with natural vegetation), always randomly placed in the coastal dune system, from the embryo dune to the backdune, to sample all EU habitats present in the study area. In particular, near the shoreline, in the unvegetated area, a total of 7 plots, of $1m^2$, were randomly placed. To evaluate the role of *C. acinaciformis* in trapping the BL, 32 plots, always of 1 $m^2$, were randomly placed (16 plots with natural vegetation and 16 plots invaded by *C. acinaciformis*) using the same approach as Gallitelli et al. (2021), adapted to the specific local ecological conditions; plots were selected so that in the invaded ones the *C. acinaciformis* coverage was higher than 60 %, while it was equal to zero in those with natural vegetation. In addition, the invaded plots and the plots with natural vegetation were in close proximity to each other and had similar environmental conditions in terms of sand characteristics and exposure, so we assume that any differences between plots are due to different abilities to trap BL.

For each plot, the distance from the shoreline was measured and the total plant coverage and the relative coverage of each vascular plant have been visually estimated, in percentage.

The superficial BL was identified by viewing only the macrolitter (objects >25 mm in the longest dimension) and the mesolitter (objects between 5 mm and 25 mm in the longest dimension) (UNEP/MAP, 2015; GESAMP, 2019; Fleet et al., 2021). All the BL items present on the plot were counted and categorized using the most recent European manual (Fleet et al., 2021). In addition, the percentage coverage of total BL and of each category of BL were estimated for each plot. Then, each plot was photographed to create orthogonal digital images, which were then used in the laboratory to measure the size of each object.

### 2.3. Data analysis

Based on the floristic surveys conducted for each plot and the presence of diagnostic and characteristic plant species, each plot pair was assigned an EU habitat. The characterization of the psammophilous habitats present in the study areas was based on the types listed in Annex I of the 92/43/EEC EU, using the manuals for the interpretation and monitoring of habitats of community interest in Italy (Biondi et al., 2009; Angelini et al., 2016; see Table S1 in appendix).

To measure total plant species diversity at the plot and habitat level, the $H_{dune}$ index (Grunewald and Schubert, 2007) was calculated according to Pinna et al. (2015, 2019).

Then, starting from $H_{dune}$, the Naturalness index (N) was obtained. The N index was calculated to evaluate the degree of diversity of native and alien plant species at the site level, taking into account the percentage cover of the alien plants in each plot (Grunewald and Schubert, 2007):

$$N = H_{\text{dune}}\ (\text{withoutalienplant}\mathit{species})/H_{\text{dune}}$$

The N index ranges from 0 to 1, where 0 indicates that the plant diversity consists entirely of alien species and 1 indicates the absence of alien plant species in the plant community (Grunewald and Schubert, 2007; Pinna et al., 2015, 2019).

Photographs of each plot were analysed in the laboratory using the ImageJ software (Schneider et al., 2012). The programme was first calibrated using the wooden meters used to delineate the plot as a reference measure, and then the exact size of each object in the plot was acquired. Based on the type and category to which it belongs, each object in the plot was classified as biodegradable or non-biodegradable (hereafter non-bio).

The abundance of BL (both the number of objects and the surface-area occupied) was always reported as the mean ± standard error. The exploratory analysis of the data in relation to the abundance of BL, divided into categories and sub-categories, was carried out by creating histograms that highlighted the main characteristics of BL in the different seasons in the Porto Paglia dune system.

The abundance of BL in the different habitats of the dune system and in the different plots (invaded by *C. acinaciformis* and native) was represented by box plots.

The Kruskal-Wallis One-way Analysis of Variance on Ranks, followed by all pairwise multiple comparison tests, was applied to test for significant differences among habitats in the number of objects and the surface-area occupied by BL. Generalized Linear Models (GLMs) by a stepwise procedure were performed to evaluate the effects of groups (native vegetation vs invaded plots) and seasons (spring vs autumn). Post-hoc tests for pairwise comparisons were conducted using Tukey's Honestly Significant Difference test (HSD). All statistical analyses were performed using Statistica 8.0 software (Statsoft, USA).

## 3. Results

### 3.1. BL characterization in the Porto Paglia dune system

During the two sampling sessions, a total of 614 objects were collected, 324 of them in autumn and the rest in spring. Plastic is the most frequent BL category, with 192 objects in spring and 225 in autumn. The second largest category by number of objects is wood, with a total of 189 objects (92 in spring and 97 in autumn), while the remaining categories (paper, rubber, chemicals, and glass) are represented by only a small number of objects (Fig. 2a).

The category of BL which occupies the largest surface-area is represented by wood, with a total of 7615.07 $cm^2$ (1.95 % compared to the sample area), of which 60.21 % were found in spring and 39.79 % in autumn. Plastic covers a total surface-area of 3624.08 $cm^2$ (0.93 % compared to the sample area), of which 41.89 % were found in spring and 58.11 % in autumn. The additional categories found occupy a very small and negligible surface-area (0.04 % compared to the sample area; Fig. 2b).

Considering only plastic items, plastic items and fragments are the most abundant sub-category (Fig. 3a); a total of 150 objects belonging to this category were found (65 in spring and 85 in autumn). Foamed polystyrene is the second most abundant sub-category (104 objects found in the two samplings, 52 objects in each season), followed by the foam rubber sub-category with 87 objects found (40 in spring and 47 in autumn; Fig. 3a, see Table S2 for a detailed description of each sub-category). Objects in these sub-categories are not only the most abundant, but also those occupying the largest surface-area, with a total occupied surface of 1488.19 $cm^2$ (0.38 % compared to the sample area) for plastic items and fragments, of which 37.47 % were found in spring and 62.53 % in autumn; of 819.63 $cm^2$ (0.21 % compared to the sample area) for foamed polystyrene, of which 55.63 % were found in spring and 44.37 % in autumn; and of 245.45 $cm^2$ (0.06 % compared to the sample area) for foam rubber, of which 43.22 % were found in spring and 56.78 % in autumn. The following items are from the sub-category caps/lids drinks, with an occupied surface-area of 234.65 $cm^2$ (0.06 % compared to the total area), of which 82.21 % were found in spring and 17.79 % in autumn. The values for occupied surface-area in the remaining sub-categories are much lower (Fig. 3b).

### 3.2. Patterns of BL distribution across seasons and habitats

In spring (Fig. 4a), for both total objects and non-bio objects, the white dune was the richest habitat, while the backdune was the poorest habitat. The pattern followed by total objects was an increased in the white dune and then a decreased in the backdune, while non-bio objects decreased in the embryo dune, increased in the white dune and decreased in the backdune. The Kruskal-Wallis One-way Analysis of Variance on Rank revealed no statistically significant differences ($p >$ 0.05; see Table S3 for details on the specific values of n and p).

In autumn (Fig. 4b), the upper beach was the richest habitat in term of number of objects, while the backdune was the poorest habitat. The total number of objects followed a decreasing pattern to the backdune, while the number of non-bio objects decreased in the embryo dune, increased in the white dune and decreased in the backdune. However, the Kruskal-Wallis One-way Analysis of Variance on Rank revealed no statistically significant differences ($p > 0.05$; see Table S3 for details on the specific values of n and p).

Considering the surface-area occupied by BL in spring (Fig. 4c), the white dune had the highest surface-area of objects. The habitat with the lowest value was the embryo dune for total surface-area, and the backdune for non-bio surface-area. The total surface-area decreased in the embryo dune, then increased in the white dune and decreased again in the backdune, while non-bio surface-area increased to the white dune and then decreased in the backdune (Fig. 4c). However, the Kruskal-Wallis One-way Analysis of Variance on Rank revealed no statistically significant differences ($p > 0.05$; see Table S4 for details on the specific values of n and p).

In autumn, the habitat with the greatest surface-area values varied between the total surface-area and the non-bio surface-area (Fig. 4d): for

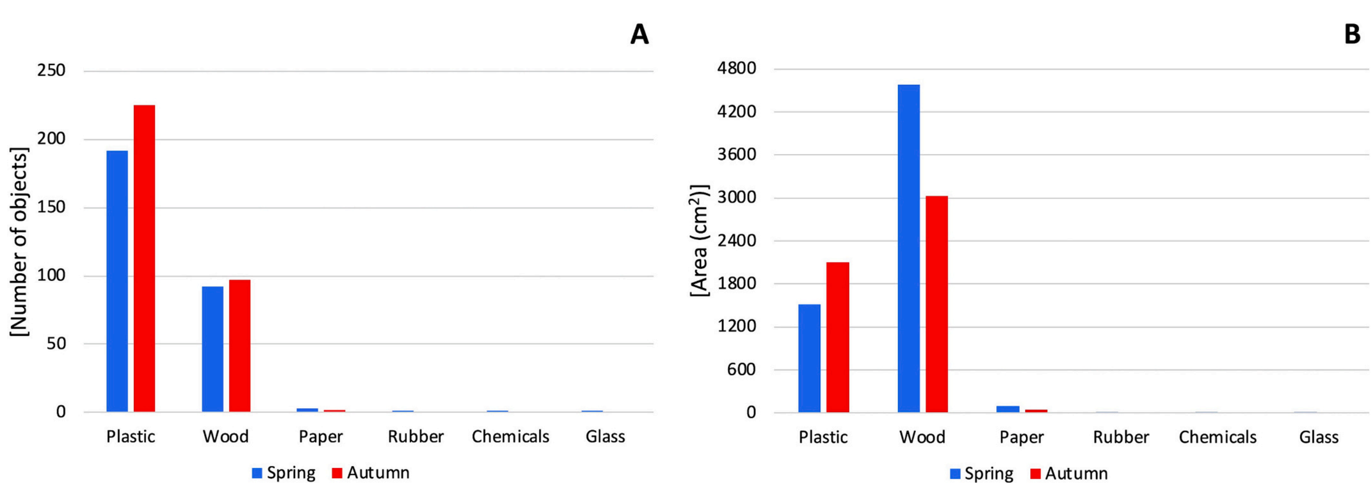


**Fig. 2.** The number of objects for each category of BL during spring and autumn (a); the surface-area of objects for each category of BL during spring and autumn (b).

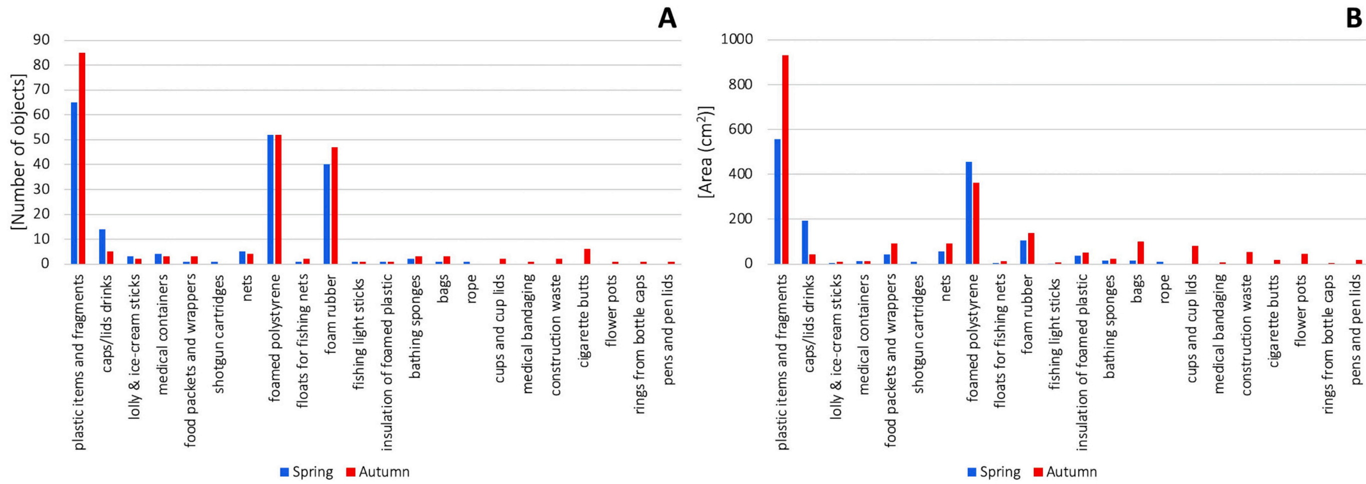


**Fig. 3.** The number of objects for each sub-category of plastic BL during spring and autumn (a); the surface-area of objects for each sub-category of plastic BL during spring and autumn (b). See supplementary materials for detailed information about each sub-category considered in this study.

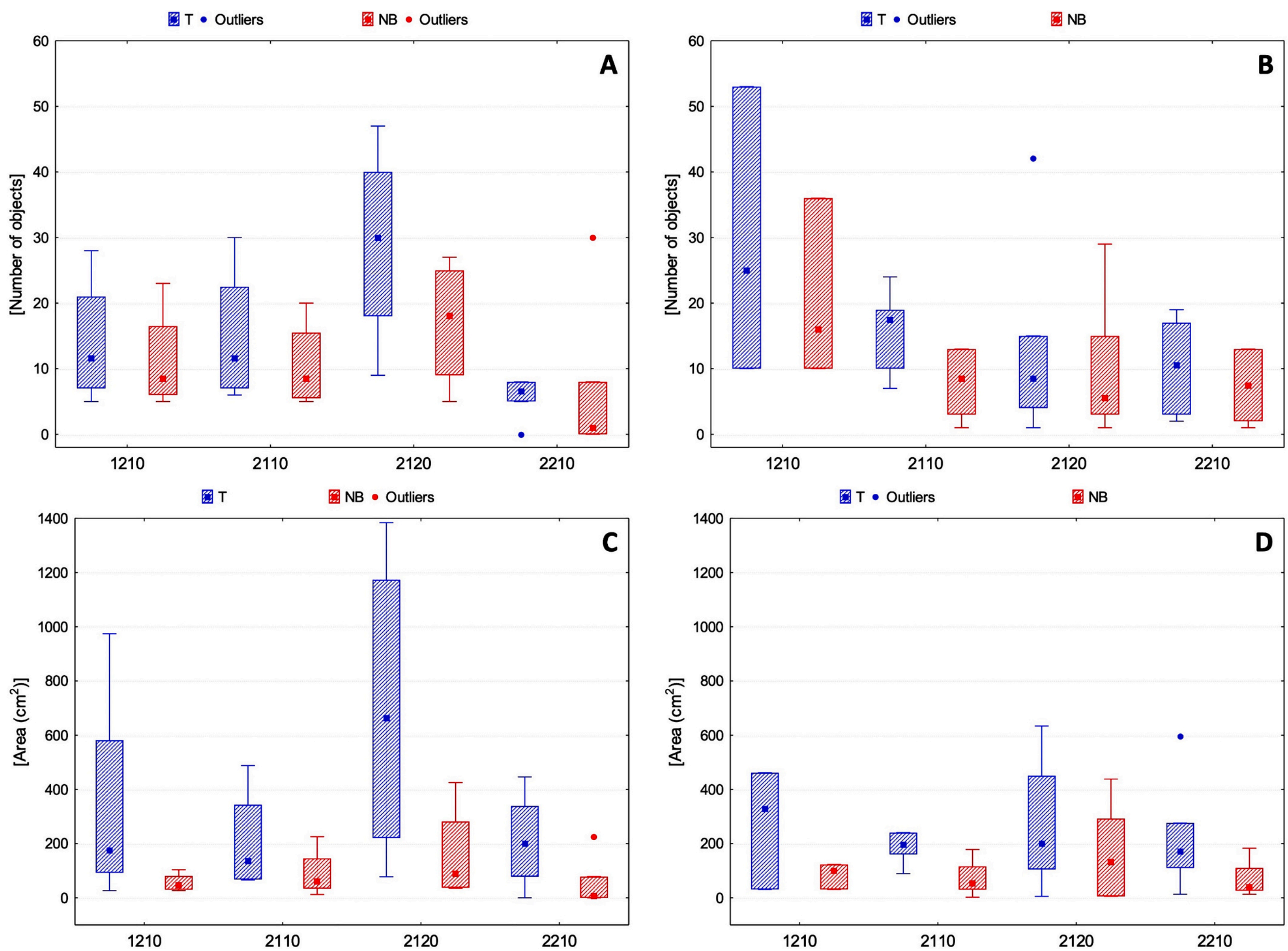


**Fig. 4.** The number of total (T) and non-bio (NB) objects compared to the different habitats found in the dune system of Porto Paglia during spring (a) and autumn (b) and the surface-area of the total (T) and non-bio (NB) objects compared to the different habitats found in the dune system of Porto Paglia during the spring (c) and autumn (d). The boxes show the interquartile range, horizontal bars show median values, vertical bars show top and bottom 25 % quartiles. Habitat codes: 1210 = Upper beach; 2110 = Embryo dune; 2120 = White dune; 2210 = Backdune and Fixed dune (see Table S1 for details).

the total surface-area it was the upper beach and for the non-bio surface-area it was the white dune. The backdune had the lowest values for both the total surface-area and the non-bio surface-area. For the total surface-area and the non-bio surface-area the same pattern emerged: decreased in the embryo dune, increased in the white dune, and decreased in the backdune (Fig. 4d). However, the Kruskal-Wallis One-way Analysis of Variance on Rank revealed no statistically significant differences ($p > 0.05$; see Table S4 for details on the specific values of n and p).

### 3.3. Correlations between BL and floristic indices

In spring, the mean values (± standard error) of $H_{dune}$ and N indices, for the entire dune system, are 0.709 ± 0.074 and 0.801 ± 0.081, respectively; the mean value of $H_{dune}$ in the plot invaded by *C. acinaciformis* is higher than the value in the plot without *C. acinaciformis*; instead, the mean value of the N index in the invaded plot is lower than the value in the plots with native vegetation. Considering the different habitats, the highest $H_{dune}$ values are found in the backdune (0.899 ± 0.112), followed by the white dune (0.628 ± 0.058); while the lowest values of the index are found in the embryo dune (0.533 ± 0.104). The highest N values are found in the backdune (0.894 ± 0.070), followed by the white dune (0.800 ± 0.104), while the lowest values are found in the embryo dune (0.686 ± 0.223).

In autumn, the $H_{dune}$ values decrease significantly while the N values remain similar; in fact, the $H_{dune}$ and N indices have mean values (± standard error) of 0.439 ± 0.106 and 0.876 ± 0.044, respectively. The mean value of the $H_{dune}$ in the plot with *C. acinaciformis* is higher than the mean value in the plot without *C. acinaciformis*; while the mean value of the N in the invaded plot is lower than the value in the plots with native vegetation. Considering the different habitats present in the Porto Paglia dune system, the highest $H_{dune}$ values are found in the backdune (0.533 ± 0.124), followed by the embryo dune (0.466 ± 0.061); while the lowest values of the index are found in the white dune (0.362 ± 0.061). The habitats with the highest N values are the white dune (0.935 ± 0.041) and the backdune (0.858 ± 0.102), while the lowest values are in the embryo dune (0.846 ± 0.071).

The $H_{dune}$ values show an inverse correlation with the number of total objects ($r = -0.191$, $p = 0.304$, $n = 32$) and the number of non-bio objects ($r = -0.194$, $p = 0.296$, n = 32). However, these correlations are not statistically significant ($p > 0.05$). Conversely, the inverse correlations between the N values and the number of total objects ($r = -0.397$, $p = 0.027$, n = 32) and the number of non-bio objects ($r = -0.395$, $p = 0.028$, n = 32) are statistically significant ($p < 0.05$; Fig. 5).

### 3.4. Role of C. acinaciformis in trapping BL

For the total objects and the non-bio objects the plot with *C. acinaciformis* shows higher values of BL compared to the plots with native vegetation (Fig. 6a). GLMs results confirmed that the differences between these two groups of plots were statistically significant for both total objects and non-bio objects ($p < 0.05$, n = 32). Conversely, the effect of the season and the interaction of groups and season were not statistically significant for both total objects and non-bio objects ($p > 0.05$, n = 32; Table 1).

Similarly, considering the total surface-area and the non-bio surface-area the plot with *C. acinaciformis* shows higher values for the surface-area occupied by BL compared to the plots with native vegetation (Fig. 6b). GLMs results confirmed that the differences between these two groups of plots were statistically significant for both total surface-area and non-bio surface-area ($p < 0.05$, n = 32); again, the effect of the season and the interaction of groups and season were not statistically significant for total surface-area and non-bio surface-area ($p > 0.05$, n = 32; Table 1).

## 4. Discussion

The coastal habitat has become a hotspot for the accumulation of BL because of the numerous sea and land sources of litter that influence this

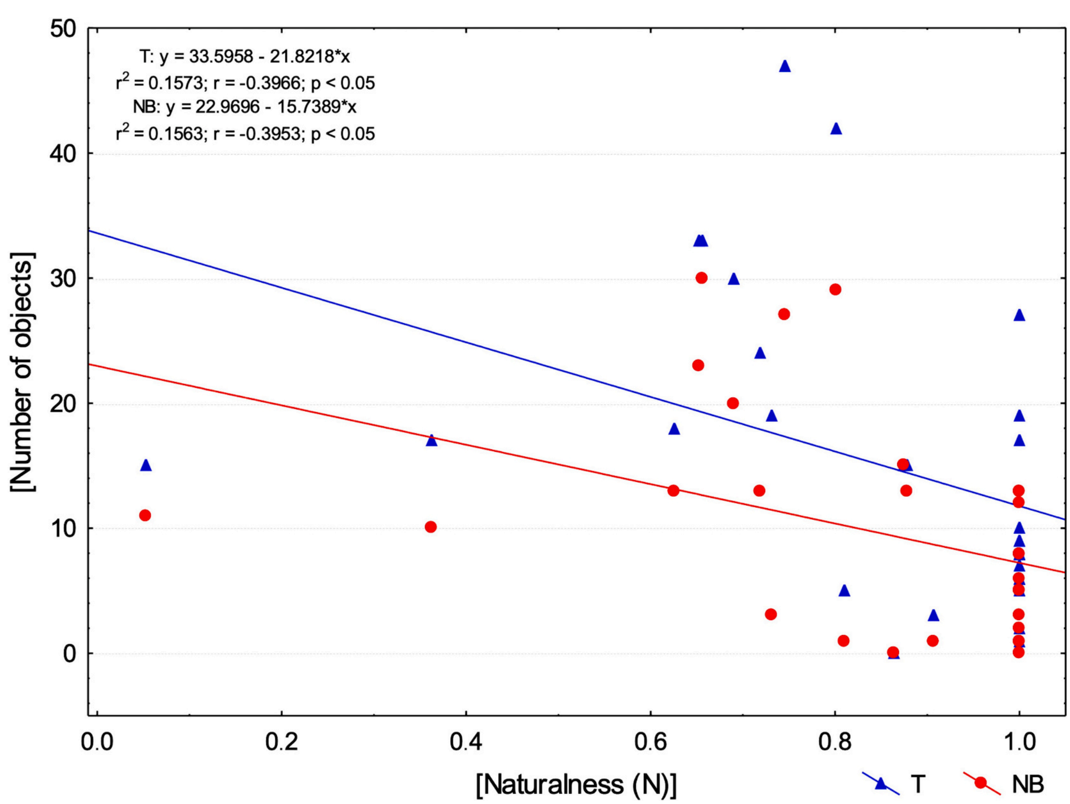


**Fig. 5.** Correlation of the number of total objects (T) and non-bio objects (NB) with the N index's value considering both samplings.

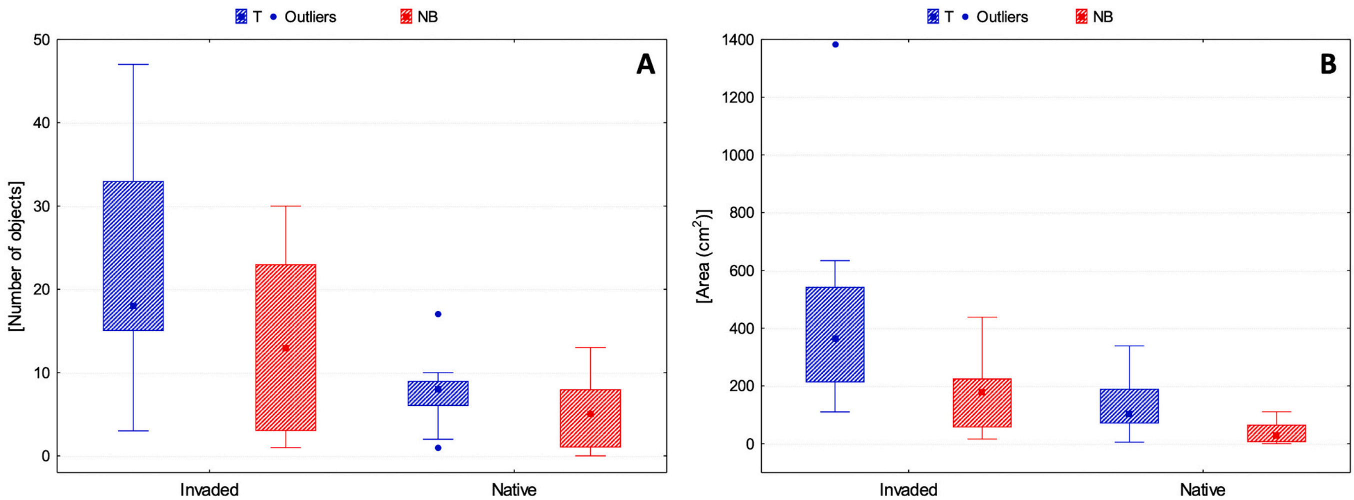


**Fig. 6.** Boxplots of the number of objects (total: T; non-bio: NB) (a) and of the total (T) and non-bio (NB) surface-area (b) compared to the plots containing or not the invasive alien species *C. acinaciformis* (invaded and native, respectively). The boxes show the interquartile range, horizontal bars show median values, vertical bars show top and bottom 25 % quartiles.

**Table 1**
Generalized linear models (GLMs) results for the effect on number of objects and surface-area of groups (native vegetation and invaded plots) and seasons.

| | SS | DF | MS | F | *p value* |
|---|---|---|---|---|---|
| No. objects | | | | | |
| Total | | | | | |
| Intercept | 6636.939 | 1 | 6636.939 | 70.09111 | 0.000000 *** |
| Group | 1462.05 | 1 | 1462.05 | 15.44036 | 0.000562 *** |
| Season | 123.339 | 1 | 123.339 | 1.30255 | 0.264151 |
| Group × Season | 224.45 | 1 | 224.45 | 2.37036 | 0.135742 |
| Error | 2461.944 | 26 | 94.69 | | |
| Non-bio | | | | | |
| Intercept | 2808.45 | 1 | 2808.45 | 52.86388 | 0.000000 *** |
| Group | 724.006 | 1 | 724.006 | 13.62807 | 0.001039 ** |
| Season | 68.45 | 1 | 68.45 | 1.28844 | 0.266691 |
| Group × Season | 144.006 | 1 | 144.006 | 2.71064 | 0.111717 |
| Error | 1381.278 | 26 | 53.126 | | |
| Area | | | | | |
| Total | | | | | |
| Intercept | 2,319,841 | 1 | 2,319,841 | 43.60869 | 0.000001 *** |
| Group | 711,413 | 1 | 711,413 | 13.37323 | 0.001136 ** |
| Season | 50,150 | 1 | 50,150 | 0.94272 | 0.340526 |
| Group × Season | 30,624 | 1 | 30,624 | 0.57568 | 0.454836 |
| Error | 1,383,116 | 26 | 53,197 | | |
| Non-bio | | | | | |
| Intercept | 315,458.6 | 1 | 315,458.6 | 30.8155 | 0.000008 *** |
| Group | 143,384.1 | 1 | 143,384.1 | 14.00644 | 0.000912 *** |
| Season | 90.5 | 1 | 90.5 | 0.00884 | 0.925805 |
| Group × Season | 378.9 | 1 | 378.9 | 0.03701 | 0.848942 |
| Error | 266,162.2 | 26 | 10,237 | | |

SS: sum of squares, DF: degrees of freedom, MS: mean square, F: F test.
** $p < 0.01$.
*** $p < 0.001$.

environment (Rangel-Buitrago et al., 2018; Nelms et al., 2020; Turner et al., 2021). In addition, the psammophilous vegetation along the sandy coast contributes significantly to litter deposition processes (Debrot et al., 2013; Battisti et al., 2020; Gallitelli et al., 2023). The Mediterranean Sea is one of the areas most affected by plastic waste (Fossi et al., 2017; Baini et al., 2018; Kazour et al., 2019). Nevertheless, only a few studies have focused on the issues covered in this study, which characterise for the first time the presence of BL and its relationship with the psammophilous vegetation in a typical Sardinian coastal dune system.

Similarly to what was obtained from Ertaş et al. (2022), the largest number of objects for the Porto Paglia dune system was found in autumn, while other studies find that the season with the most BLs is winter, followed by autumn (e.g., Poeta et al., 2016; Menicagli et al., 2022); it should be underlined that our surveys were conducted on a single day for each season, therefore they may not be fully representative of the trend in the accumulation of BL.

The BL objects belong mainly to plastic and wood categories; as expected, plastic objects are the most numerous, with values comparable to other studies (e.g., Galgani et al., 2013; Poeta et al., 2014; Pasternak et al., 2017; Šilc et al., 2018; Vlachogianni et al., 2018; Mo et al., 2021; Özden et al., 2021). This is easily understandable as plastics are extremely durable, light, and often buoyant, which has led to their widespread use and dominance in coastal areas; these properties allow them to spread over long distances (up to thousands of kilometers) from their point of origin (e.g., Lavers and Bond, 2017; Özden et al., 2021). Within the plastic category, following the classification of Fleet et al. (2021), the most numerous items were plastic items and fragments, foamed polystyrene fragments, foam rubber fragments, and plastic caps, again confirming the result of previous studies (e.g., Poeta et al., 2014; Vlachogianni et al., 2018; Andriolo et al., 2020; Mo et al., 2021; Özden et al., 2021). Wooden objects, although fewer in number, occupy the largest total surface-area; this is mainly due to the large size of this component compared to the plastic items which usually have the smallest size; however, it is important to note that this component, in terms of occupied surface-area, was rarely considered in previous studies analysing the coastal BL on the Mediterranean coasts, for this reason, further studies are needed in order to fully understand this aspect.

Unexpectedly, no cigarette butts were found during spring, which is surprising as this category is ranked first in the Global Coastal Cleanups (Ocean Conservancy, 2010, 2017); this absence could be due to mechanical cleaning of the beach and to the fact that the samples were taken before the tourist season, as detected in other coastal systems (Šilc et al., 2018). Cigarette butts were found in autumn, particularly near the shoreline, a portion of the dune mainly used by bathers in summer.

Another peculiarity of our study is the lack of plastic cotton buds: this result contrasts to previous studies on different dune systems in central Italy (Poeta et al., 2022) and in northern Sardinia (Corbau et al., 2022). This result is startling, yet based on our knowledge, we have not found a valid justification; therefore, additional research is required to better understand the reason of this peculiarity.

The distribution of the BL across dune habitats follows a similar pattern to the one reported in the literature for Tyrrhenian coastal dunes (Poeta et al., 2014; de Francesco et al., 2018, 2019) and for the Atlantic coast (Andriolo et al., 2021), while only a partial match was found in other dune systems of the Mediterranean (Šilc et al., 2018; Gallitelli et al., 2023). In central Italy, the absence of BL in fixed dune habitats was found to be correlated with the presence of the vegetation typical of these woody habitats, which acts as a barrier against the movement of litter toward inland (Poeta et al., 2014), while the results of our study suggest that the embryo dune and the white dune could have an important role in limiting the accumulation of BL in the backdune and in the fixed dune. In spring, particularly, a greater amount of BL (both for total objects and non-bio objects) has been found in the white dune of Porto Paglia. This result matches the one obtained for some of the Mediterranean coasts (Šilc et al., 2018; Gallitelli et al., 2023), but differs from other studies carried out on the Italian Peninsula, in which the most relevant role was played by the upper beach and the embryo dune (Poeta et al., 2014; de Francesco et al., 2018, 2019). However, it should be noted that the coastal dunes of the central Italian Peninsula are largely different from the Sardinian ones, often reduced in size and presenting a psammophilous zonation that sparsely includes the white dune, which is often fragmented. Our results obtained in autumn are similar to what found by Corbau et al. (2023), at the lagoon of Barbamarco during the winter season, and highlight that most of the BL is on the upper beach. The accumulation of the greatest amount of BL may be caused by storms as well as the previous summer season and thus to the actions of tourists. This result differs from what was found by Andriolo et al. (2021) on the Atlantic coast, where they find more BL in the white dune; this could be justified by the fact that, in this study, the presence of litter in upper beach was not evaluated.

The samplings made during spring and autumn, considering the number of objects (both total and non-bio), show the same result regarding the backdune, which traps the least number of objects. This result is similar to what was found by Corbau et al. (2023), but it is in contrast with what was found by Andriolo et al. (2020) on the central-western coast of Portugal, where the backdune appears to be the habitat with the greatest amount of BL.

For what concerns the number of objects, in spring, the largest surface-area occupied by BL (total and non-bio) is found on the white dune. This could be because the vegetation in this habitat reaches greater heights and, consequently, can trap larger litters. Considering the surface-area occupied by the total objects, the lowest value is found on the embryo dune; while for non-bio objects, the minor surface-area occupied by BL is found in the backdune. These findings, for both the number of objects and the surface-area (especially considering the non-bio BL), confirm what was said previously regarding the ability of the embryo dune and the white dune to limit the accumulation of BL in the backdune. However, due to lack of data in literature, it is difficult to properly discuss it.

In autumn, the largest total surface-area was found on the upper beach, probably because the greatest number of objects were deposited there by the action of waves and people. The main non-bio surface-area was found on the white dune, which still confirms itself as a habitat capable of trapping the BL, even with a large surface, limiting the accumulation of this component in the backdune, in fact, this is the habitat that traps the smallest surface of BL (total and non-bio). However, it is necessary to underline that this result is not sufficient to define a model; further surveys are necessary to fully understand how the distribution of BL varies in relation to the different dune habitats and how other factors, such as waves and wind, can modify the distribution itself.

Thanks to the collection of baseline information on BL it is possible to understand if *C. acinaciformis* plays a different role compared to that of native psammophilous vegetation in trapping BL in the dune system. The plots invaded by *C. acinaciformis* show a greater trapping capacity, as indicated by the numbers of total and non-bio BL, confirming the results in Gallitelli et al. (2021). In literature, there is evidence that other native Mediterranean plant species, such as *Elymus farctus* (Viv.) Runemark ex Melderis and *Euphorbia paralias* L., may have a potential role in trapping BL (e.g., Mo et al., 2021; Gallitelli et al., 2023), however our study indicates that *C. acinaciformis* has a greater trapping capacity than the native plant species. This ability shows a certain correspondence with the diversity indices, $H_{dune}$ and N widely tested on Mediterranean sandy dune systems (Pinna et al., 2015, 2019; Calderisi et al., 2021), calculated in the same plots. In fact, plots with higher overall diversity have a lower number of objects and surface-area occupied by BL, suggesting that the conservation status of a habitat is independent of the presence of BL. Conversely, the N values seem to be associated with the abundance of BL, meaning that an increase in BL reflected a general decrease in the naturalness of vegetation; this finding was also relevant since the correlation found between the index and the number of objects (both total and non-bio) was significant. However, these are still partial results, limited to only one area of study, but they suggest the need to develop more complex indices to characterise the conservation status of the habitats typical of a Mediterranean coastal system. These indices should not be based only on floristic diversity to assess the conservation status of a habitat, but should also consider the presence of BL, for example by combining this index with other indices elaborated to highlight the presence of litter (e.g., the Clean-coast index (CCI) developed by Alkalay et al., 2007).

## 5. Conclusion

One of the most widespread pollution problems in the world's coastal environments is the BL, which negatively impacts ecosystems, biodiversity, and related ecosystem services; consequently, analysing the distribution and build-up of beach litter is essential for managing the coastal zone sustainably (GESAMP, 2019).

In our study, we have tried to respond to this need by analysing a typical Mediterranean coastal dune system in Sardinia, investigating the quantity and distribution of BL across the different habitats, and comparing the role of natural vegetation with the invaded one. We investigated the role of the alien species *C. acinaciformis* in trapping BL, concerning native vegetation and we found an effect of this species. As expected, *C. acinaciformis* has a negative effect on the naturalness of the Mediterranean dune system as it replaces the native vegetation. But paradoxically, this species can be used to trap a large part of the BL during the first step of a dune system restoration project and then removed with the trapped BL. This type of experimental approach can be used in those highly degraded coastal dune systems that need to be restored.

So far, many aspects remain little investigated, and further studies would be needed to investigate the effects of BL on plant species and communities in the Mediterranean coastal environment.

## CRediT authorship contribution statement

Giulia Calderisi: conceptualization, methodology, field investigation, validation, data curation, formal analysis, writing-original draft.

Donatella Cogoni: data curation, writing-review & editing.

Alessandra Loni: field investigation, data curation, writing-review & editing.

Giuseppe Fenu: conceptualization, methodology, field investigation, validation, data curation, formal analysis, writing-original draft.

## 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

The data presented in this study are available on request from the corresponding author.

## Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.marpolbul.2023.115065.

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