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Understanding through drone image analysis the interactions between geomorphology, vegetation and marine debris along a sandy spit

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Highlights

- UAV images were used to map the different eco-geomorphological thematic classes and the ML items
- ML items were observed along the spit system, in particular on the upper beach and salt marsh
- Waves and wind transports are the main dominant pathways explaining the distribution of the ML
- Vegetation is an important factor for the deposition of the marine litter
- Cleaning activities should be developed for salt marsh environment

Understanding through drone image analysis the interactions between geomorphology, vegetation and marine debris along a sandy spit

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Abstract

Marine litter (ML) is recognized as one of the main socio-economic and environmental concerns and monitoring operations have been realized worldwide in order to collect information on the types, quantities and distribution of marine debris. In this study we used Unmanned Aerial Vehicles (UAV) images to map the presence of marine litter on a coastal spit in relation to geomorphological aspects and vegetation. Our results show that ML are present all over the system, but concentrate in the beach wrack, dunes, and saltmarshes, highlighting the role of the vegetation in trapping ML. Moreover, ML will most probably remain trapped by the saltmarsh vegetation, given that they are not visible and not easily accessible, will not be removed, while cleaning operations may remove the ML present in the beach wrack. Finally, our results provide useful information to support decision makers for improving beach cleaning activities in the Po Delta areas.

Keywords

Marine litter distribution, habitat classification, physical processes, vegetation trapping, retention times, Barbamarco lagoon.

I- Introduction

Human pressures on the coastal zones and oceans have increased substantially in the last decades. As it has been mentioned by Batista et al. (2014), the effects of human activities on the oceans have been well documented, in particular since 1950s. Currently, it is widely recognized that the increase in coastal and marine activities has adversely affected the coastal and marine environment as well as ecosystem goods and services (Galgani et al., 2013, Kay and Alder, 1999). As a matter of fact, human exploitation and overexploitation constitute the greatest threat to the coastal and marine environment, generating considerable quantities of waste as wood, metals, glass, plastics, rubber, textiles and paper (UNEP, 2005, UNEA, 2019), which could contaminate the marine environment as recognized by the EU Marine Strategy Framework Directive (MSFD, 2008/56/EC) that provide an framework within which EU Member States take action in relation of the 11 descriptors in order to achieve or maintain good environmental status (GES) of their marine waters. In particular, Descriptor 10 (D 10) concerns marine litter and more specifically criteria 10.1

mentions that “The composition, amount and spatial distribution of litter on the coastline, in the surface layer of the water column, and on the seabed, are at levels that do not cause harm to the coastal and marine environment”.

From this brief overview, marine litter, which is defined as “items that have been deliberately discarded, unintentionally lost, or transported by winds and rivers, into the sea and on beaches’’ (United Nations Environment Programme, UNEP, 2009), is recognized as one of the main socio-economic and environmental concerns (Newman et al., 2015, UN Environment, 2017). Marine litter includes metals, glass, ceramics, textiles, paper and timber, and can affect organisms at different levels of biological organization and habitats in a number of ways and impacts negatively the economy of tourism, fisheries, aquaculture or energy supply (Werner and O’Brien, 2018; Lusher et al., 2017), but has also significant implications toward human welfare (Panti et al., 2019; Wright et al., 2013).

An additional relevant issue regarding the marine litter is related to its composition, with plastic items representing between 61 to 87% (Barboza et al., 2019; Galgani et al., 2019). The importance of plastics is mainly related to their durability and lightweight allowing their transport via wind, wastewater and rivers when they have been littered (Li et al., 2016). Moreover, Jambeck et al. (2015) calculated that between 4.8 and 12.7 million metric tons enter the ocean. They emphasized that the amount of inland plastic waste available to enter the ocean may increase by an order of magnitude by 2025 if no efficient measures are applied. Indeed, the world production of plastic was 348 million tons in 2017 and is expected to double in the next two decades (Lebreton and Andrady, 2019).

In addition, marine litter and plastics originate from land-based activities or sea-based activities. The first one, representing approximately 80% of marine litter, includes recreational use of the coast, general public litter, industry, ports and unprotected landfills and dumps located near the coast, but also sewage overflows, introduction by accidental loss and extreme events (Galgani et al., 2015, Melo Nobreet al., 2021). According to the same authors, the sea-based activities include commercial shipping, ferries and liners, both commercial and recreational fishing vessels, military and research fleets, pleasure boats and offshore installations.

Once entered the ocean, marine litter sinks to the bottom or floats on the ocean surface depending on its density. Floating litter tend to accumulate on beach-dune ecosystems characterized by multiple anthropogenic pressures and environmental factor that may contribute to their contamination as highlighted by different studies conducted across the globe (Santos et al., 2009; Munari et al., 2016; Corbau et al., 2021 Araújo et al., 2018; Poeta et al., 2016; Velez et al., 2019). Most of these studies, based on field surveys or volunteer cleaning initiatives, aim to identify the origin and destination of litter mostly to manage the problems they cause (Asensio-Montesinos et al., 2019; Nachite et al., 2019; Araújo et al., 2018; Santos et al., 2009).

These studies have also highlighted the importance to develop faster and cheaper monitoring techniques compared to traditional sampling techniques, which are generally considered time consuming and require strong human effort (Gonçalves et al., 2020; Escobar-Sánchez et al., 2021). Indeed, the traditional beach monitoring is based on visual census methods and marine litter items larger than 2.5 cm are counted and collected along different transects (Cheshire et al., 2009; OSPAR, 2010). In this context, the use of aerial surveys, with Unmanned Aerial Vehicles (UAVs), could be a valuable aid as they result 40 times faster compared to a standard visual-census approach (Martin et al., 2018). In addition, they can be used to support integrated coastal zone management since they acquire high-resolution remote-sensing data at a lower cost and increased operational flexibility (Kandrot et al., 2020; Castellanos-Galindo et al., 2019; Klemas, 2015, López & Mulero-Pázmány, 2019; Taddia et al., 2019; Nardin et al., 2021). Taddia et al. (2019), for instance, used UAV-acquired images to assess the evolution of embryo dunes over a two-year time frame in the Po River Delta (Italy). More recently, they have also been used to assess coastal and marine pollution (Kandrot et al., 2020) and marine litter (Salgado-Hernanz et al., 2021; Andriolo et al., 2020; Taddia et al., 2021; Andriolo and Gonçalves, 2022).

Moreover, UAV imageries were used to map and classify marine litter reporting that manual image screening has a variable detection rate (from 62% in Martin et al., 2018; to 98% in Fallati et al., 2019) depending on several factors like operator abilities. Taddia et al. (2021), for instance, easily identified larger items such as plastic bottles and white pieces on orthomosaics, flat objects were recognized through their colour, while transparent items were not distinguishable. Lo et al. (2020) found that the identification of marine litter on UAV imageries depends on their size and the highest percentage of accuracy in litter identification was 75%. For instance, Escobar-Sanchez et al. (2021) found that litter sizes >2.5 cm are the minimum size detectable (flight height 10 m), while Martin et al. (2018) found that items <4cm are misidentified. Consequently, considering that UAV imageries provide indications on marine litter accumulation and abundance, this study focuses on the marine litter deposited along a sandy spit and on examining its distribution in relation to eco-geomorphological aspects. In addition, we provide information and recommendations for litter monitoring and cleaning operations.

II- Materials and method

2.1- Study area

The studied area, the lagoon of Barbamarco, belongs to the Po delta, which covers an area of about 400 km^2 and extends seaward for about 25 km. In the delta, the main river course (Po di Venezia) is divided into five active branches: Po di Maistra, Po di Pila, Po di Tolle, Po di Gnocca or di Donzella and Po di Goro (Figure 1). The final part of the Po di Pila splits into three branches that are, from North to South, Busa di Tramontana, Busa Dritta and Busa di Scirocco.

The Barbamarco lagoon is located between the Po di Maistra and the Po Busa di Tramontana, and has a triangular covering of about 800 ha. The lagoon is separated from the sea by two spits and a barrier island. Our study focuses on the northern spit, which is locally called Scanno di Bocassette (Figure 1). The two inlets are sediment sinks, trapping alongshore moving sediment as a result of current and waves. Riverine freshwater enters the lagoon in the northern part from the Po di Maistra and from the Busa di Tramontana in the southern corner (Ramirez and Imberger, 2002; Maciu et al., 2018). The spit also protects the lagoon and the hinterland from marine flooding.

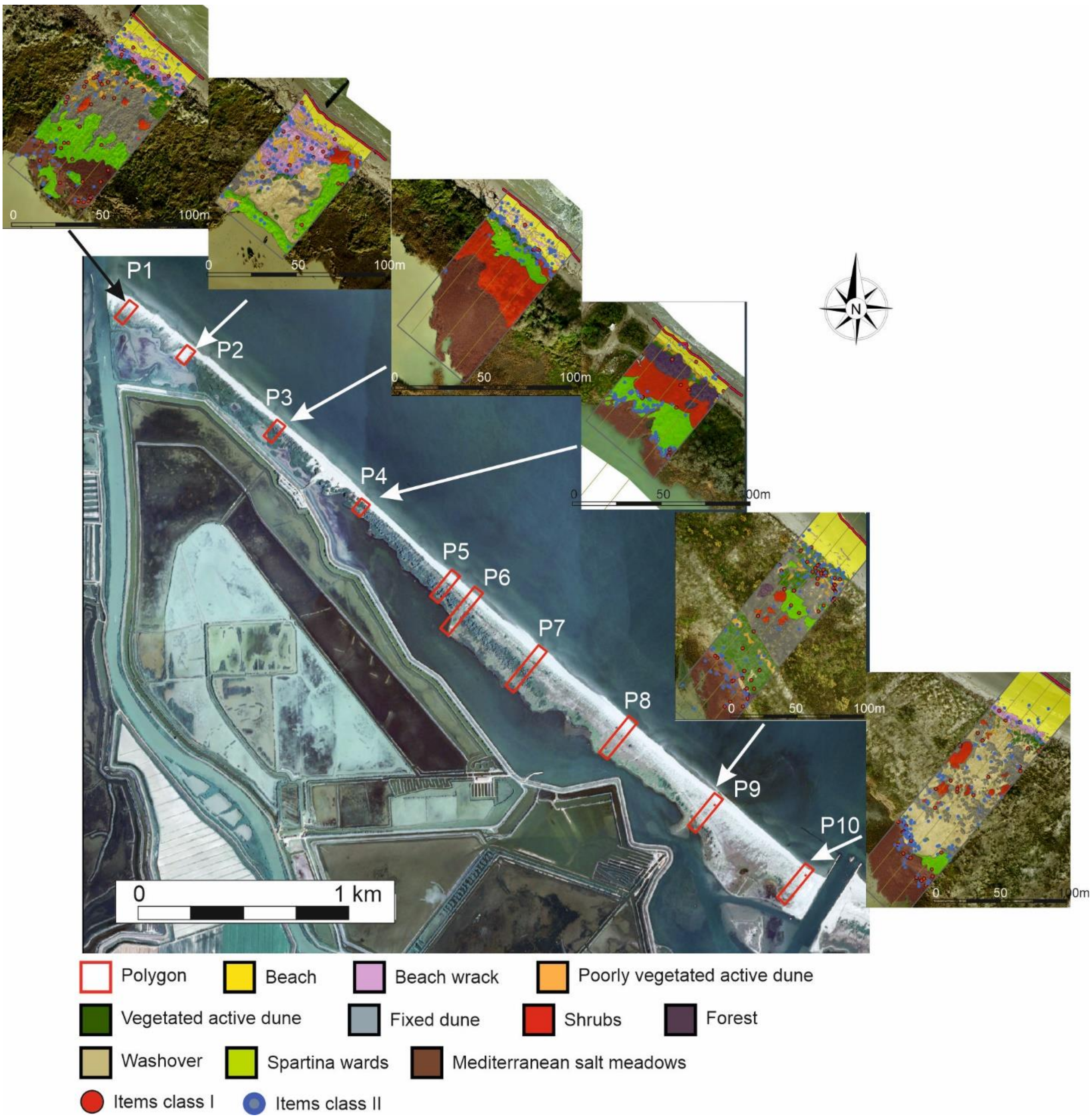

Figure 1: a) Study area, b) details of the polygons analyzed (P1, P2, P3, P4, P9 and P10)

In the lagoon, the average water depth is about 0.80 m. The bathymetry is characterized by the presence of channels (with a maximum depth of 5 m) and shoals situated in the central part of the lagoon. The channels in the lagoon are periodically dredged to counteract sediment deposition (Nardin et al., 2022). The lagoon is surrounded by four large fishing valleys about 1,800 hectares and is located in an area with subsidence rates among the largest in the Delta (3 mm/year; Teatini et al., 2011). Offshore, the nearshore is mostly characterized by a low-gradient slope.

The hydrodynamics is mainly forced by the tide and is locally enhanced by riverine inputs and wind (Maciu et al., 2018). The tide is mainly semidiurnal type, with a maximum range of about 1 m during spring tide. Maciu et al. (2018) also reported that the prevailing wind blows intense from the NE sectors (Bora) and also breezes from the West are frequent. The wind data collected at Porto Tolle from 1993 to 2005 (Figure 2) reveal that prevailing and more intense winds are from N45° to N135° and also secondarily from N225° to N292.5°. Furthermore, some significant events of Sirocco wind are also recorded. The average yearly rainfall over the last 25 years is about 730 mm/yr (Maciu et al., 2018).

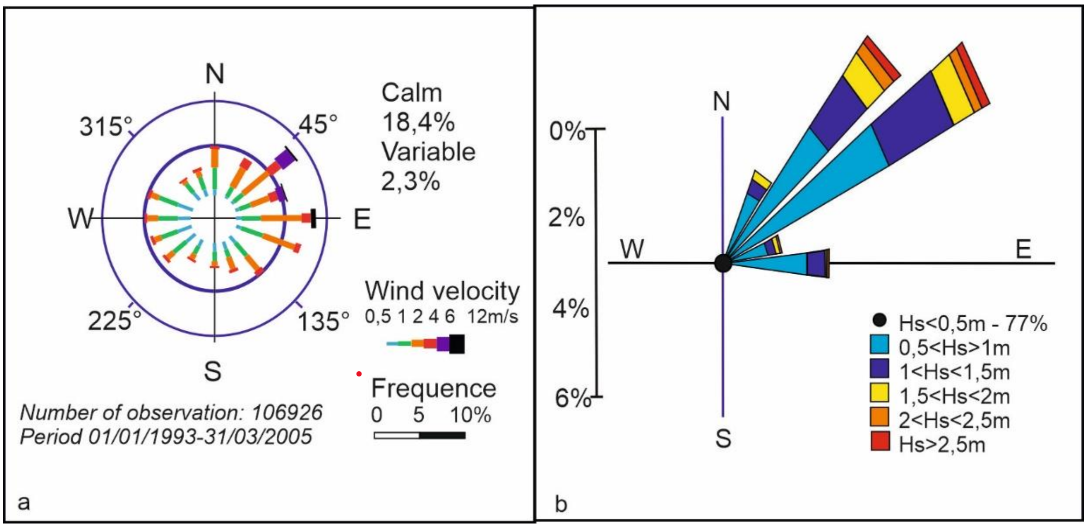

Figure 2: a) Wind Rose (Porto Tolle, 1993-2005); b) Wave Rose (modified from Ruol and Pinato, 2016).

Waves mainly come from N030° to N090, with wave height generally inferior to 4.5 m (Figure 2b). Extreme waves with a 100-years return period data indicates that wave height reaches 4.3 m for Bora event (NE) and only 2.9 m for Scirocco event (SE) (Table 1).

Tp (years)	H_{m0}	Dir (°)		H_{m0}	Dir (°)
1	4.2	055		2.0	089
10	4.3	054		2.5	086
100	4.3	054		2.9	085

Table 1: Nearshore extreme events statistics from NE and SE (after Ruol and Pinato, 2016).

Barbamarco lagoon is subject to flooding event caused by the sea level rise of the Adriatic Sea, wave run up and set up. For example, the contribution to the raising water level due to storm surge in the Adriatic Sea during the exceptional high water of 11/12/2019 reached the measure of 182 cm over the average water level (Ruol and Pinato, 2016). In particular, the sea level accounted for tide, meteorological contribution (storm surge determined by the wind), and the average sea level.

Modelling analysis (Nardin et al., 2022) showed that starting from an average sea level equal to the peak of 182 cm, recorded in the open sea by the Acqua Alta Platform and applying the 2 main wind directions: Bora (North-East) and Sirocco (South-East) might develop a wave set up of about 20 cm on the barrier island.

The Barbamarco lagoon is also characterized by intense anthropic activities related to shellfish farming, aquaculture, fishing and more recently fishing tourism, while landward, agriculture is the main activity. Forest areas are rare, limited to the floodplain areas. The ENEL thermoelectric plant of Polesine Camerini, whose cooling waters are directly discharged into the Canarin lagoon, has an important weight on the economic and ecological balance in the delta area. Avifauna hunting is another activity carried out in the Barbamarco lagoon.

The Barbamarco lagoon belongs to the Veneto Regional Park of the Po Delta (LR 36/1997) and to the Natural Reserve of the Po mouths (Riserva Naturale Bocche di Po, Province of Rovigo, 2008), managed according to the Environmental Plan of the Po Delta (12/2012). Furthermore, Barbamarco lagoon hosts both threatened habitats and animal and plant species and is therefore included in the SPA IT3270023 "Delta del Po" and in the SIC area IT3270017 called "Delta del Po: terminal section and Veneto Delta".

2.2- Method

2.2.1 - Orthophoto realization

A DJI Phantom 4 Pro Obsidian DJI with a high-resolution camera (20 MPixel) was used to detect and reconstruct the geomorphic pattern of the spit of Boccassette. The study was conducted according to the worldwide standard methodology for the application of UAVs (Colomina and Molina, 2014; Cook, 2017; Mancini et al., 2013; Taddia et al., 2019).

The surveys were conducted in the period December 2019-January 2020, under appropriate meteorological conditions. Considering the drone battery autonomy and accounting for the required image resolution for having a fair representation of macro-litter, the flight altitude was 80 m over an area of about 0.8 km^2 (4.4 km long, 0.1 to 0.4 km wide). The overlap used for the missions was 80% along the longitudinal direction and 60% in the transversal direction. Consequently, nine flights were necessary to map the full extent of the study area and to achieve the desired spatial resolution of 3 cm. About 2,300 photos were acquired in a nadir setting (perpendicular to the direction of the flight). In addition, 27 ground control points (GCPs) were placed in the area surveyed. The measurement of the GCPs was performed using a Hiper-SR Topcon model with a double frequency (L1 and L2) GNSS providing a centimetre accuracy. The GPS was used in NRTK modality through the connection to the NETGEO permanent station network within the ETRF2000-(2008) reference system.

The collected images were successively processed using Agisoft Metashape, based on the SfM (Structure from Motion) algorithm. The process consists in the following steps: 1) image alignment, 2) generation of the initial dense cloud point (sparse dense cloud), 3) georeferencing of the model, 4) optimizing the image alignment using the GCPs, 5) generation of high-resolution dense point cloud and 6) generation of orthomosaic and digital surface model. Imagery spatial resolution, expressed in ground sample distance (GSD), was a value between 9 and 12 cm.

The DSM model returns the elevation calculated at each pixel excluding the areas covered by dense vegetation and water. Therefore, the LIDAR orthophoto acquired in 2018 by the Veneto region was used to obtain the elevation information in the area covered by the vegetation assuming that these areas should be stable. In addition, in order to analyse the relationship between the coastal processes and the marine litter deposition pattern, the short-term evolution of the shoreline was assessed by comparing the 2018 lidar orthophoto with the UAV DSM model (2019), while the medium-term shoreline evolution was obtained by confronting two Lidar datasets (2009-2018) provided by the Veneto region. Similarly, the foot-dune line evolution was also analysed using the same dataset (2009-2018, and 2018-2019). The foot-dune line position was identified by considering the limit of the vegetation, elevation contours and slope variation.

2.2.2 - Orthophoto analysis

The framework to determine marine macro-litter covering at least 2x2 pixels (6*6 cm) abundance and categories on coastal dunes were built in two main steps:

- Visual procedure to identify the geomorphological sectors and features of the spit using the orthophotos and DSM (section 2.b.1);
- Manual observation and screening on the orthophoto in a GIS environment to mark the marine litter items. From hereinafter, we refer to this method as Manual image Screening (section 2.b.2).

The orthophotos were uploaded in a GIS environment and the analysis was performed on 10 polygons drawn in Arcgis Pro. The polygons are 50 meters wide, extending from the shoreline to the lagoon, and consequently, their dimensions are variable depending on the width of the spit. Furthermore, they were placed randomly along the northern spit of Barbamarco. The distance between two successive polygons is generally about 500 meters, but some polygons were closer (Polygons 1 and 2, and Polygons 5 and 6, Figure 1). The main characteristics of the polygons are reported in Table 1.

2.2.3 - Eco-geomorphological mapping

The identification and mapping of eco-geomorphological thematic classes (land use) for each polygon was done by comparing textural, spatial, spectral, and contextual features of the eco-geomorphological elements, through visual photo interpretation on the scale of 1:3,000. These data were analysed together with observations made during field visits, and ten land coverage classes were defined, which are:

- Beach
- Beach wrack
- Poorly vegetated active dune: embryonic dune and foredune with low vegetation density or without vegetation
- Vegetated active dune, which includes foredune and yellow dune
- Fixed dune corresponding to grey dune
- Shrubs corresponding to stable dunes covered by shrubs
- Forest corresponding to a stable dune covered by forest
- Washover
- Spartina swards: High salt marsh
- Mediterranean salt meadows: Low salt marsh.

In addition, for each polygon three topographic profiles were also elaborated using the specific function "profile" within Arcgis Pro.

2.2.4 - Marine litter mapping

The identification of the marine litter on each polygon was performed using a method similar to the method described by Taddia et al. (2021), and marine litter items were mapped using two levels of confidence, which are:

- CL 1: the operator is sure that both the detection and the classification of the item are correct; a description of the item is provided during the mapping process;
- CL 2: the operator is sure that the item is litter, but unsure about the type (difficult to classify); a description of the item may be provided during the mapping process.

For each object recognized as a marine litter item, a point was manually added at the center of the item, while a polygon was drawn to shape the item in order to obtain their areas and perimeters using the command calculate geometry in ArcGIS pro. To perform these operations, two shapefiles were created: point and polygon. In addition to the level of confidence (CL1 and CL2), information regarding the items was added, namely the object/category, when identified, and the colour. When it was not possible to assign a specific category to the marine litter items, this element was characterized as "not identified". The final outputs were a marine litter distribution map associated to attribute tables.

Successively different geographic processing (intersection) was performed to assess the impact of the vegetation and of geomorphology on the distribution of the marine litter. The operations consisted in intersecting marine litter with elevation and eco-geomorphological classes, calculating the cross-shore distance between the items and the shoreline, and calculating the cross-shore distance between the items and the lagoon.

III- RESULTS

3.1 - Vegetation and topography

The results of the land use cover are reported in Figure 3, and Supl.Mat 1. Figure 3 reports the total distribution of the different land cover classes, and the distribution of the land cover classes for the 10 polygons considering also the cross-shore length of polygons (Polygon 7). It appears that the coverage may be divided in four main zones:

- The beach including the beach wrack (beach and beach wrack, 21%)
- The dune system (Poorly vegetated active dune, Vegetated active dune and Fixed dune, 29%)
- The fixed grassland (shrubs and forest: 14%)
- The salt marsh (Spartina swards and Mediterranean salt meadows, 20%)

In addition, the area is also characterized by the presence of washover at the northern and southern extremity of the spit (Polygons 2, 9 and 10, 6%).

The results of the mapping and in-situ observations indicated that the plant communities are generally disposed parallel to the shoreline and are distributed along with the topographic spit profile, forming the so-called coastal zoning of the vegetation. Furthermore, at the vegetation level, two different types of vegetation were observed: psammophilous vegetation seaward and the halophilous series bordering the lagoon.

However, the distribution of land use is variable when comparing the different coverage of the polygons. Polygons 1 to 4 are narrow compared to the other polygons. In these polygons, the beach covers about 10% of the polygon area, while salt marsh ranges from 40% to 50% except for polygon 2 (about 20%), which is characterized by the presence of a wide beach wrack deposit and washover. In addition, no fixed dune has been identified in Polygons 3 and 4, and active foredune (vegetated or not) is very limited in Polygon 4. Shrubs are also present in Polygons 3 and 4.

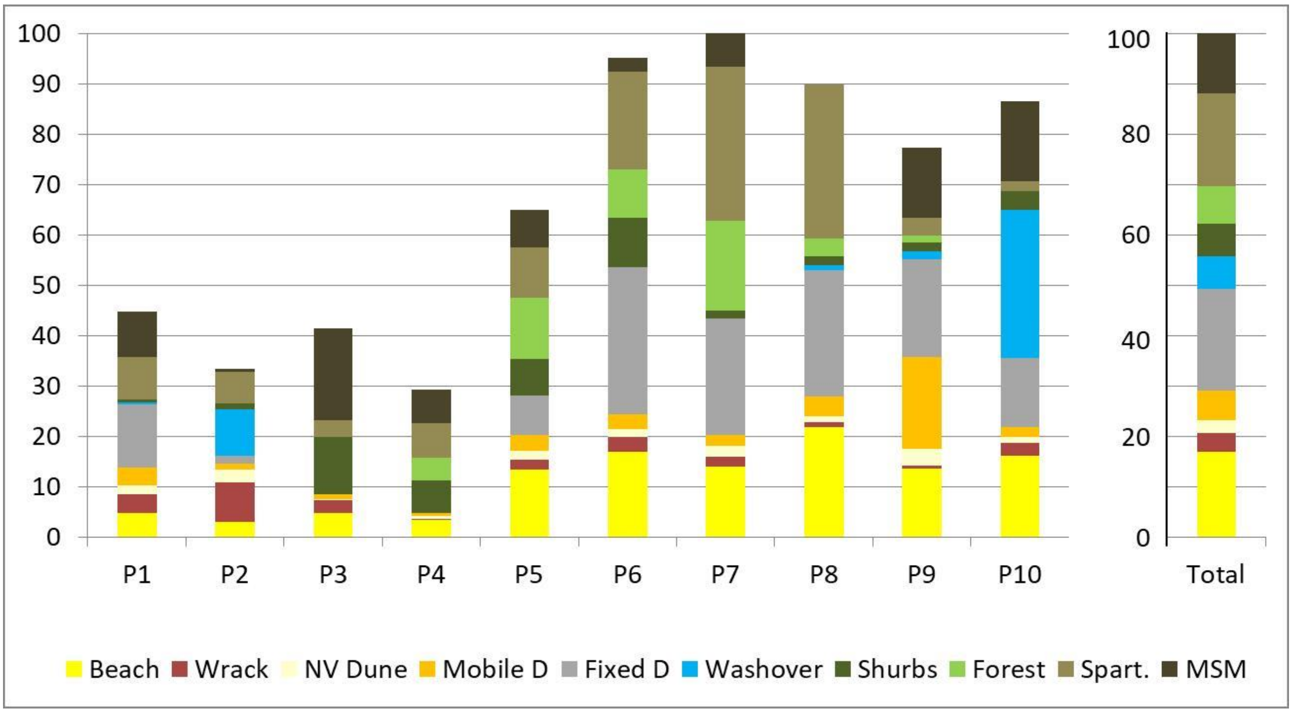

Figure 3: Percentage of the different eco-geomorphological classes for all the 10 polygons (Total) and distribution of the eco-geomorphological classes in the 10 polygons (results have been reported to the maximum cross-shore distance – Polygon 7).

The topographic profiles of these 4 polygons (Figure 4) indicate that the morphologies of Polygons 1, 2 and 3 are similar. The spit widths of these polygons are the narrowest of all the polygons, less than 150 meters. The beach width ranges from 8 to 15 meters while the beach wrack deposition ranges from 1 to 5 meters wide. Dunes are narrow and the profiles reveal low foredune (less than 2 meters high for polygons 2 and 3). The morphologies of the internal part (fixed dunes and saltmarsh) are gently rippled with a height not exceeding 2 meters (generally less than 1.5 m high). The morphology of polygon 4 is however different, characterized by narrow foredune. The morphology of the fixed dunes and saltmarsh is flat, less than 1.5 meters high. The nearshore geomorphology is generally flat, and a sand bar is present in P3 and 4 at 2.5-3 m water depth.

The Polygons 5 to 8 present a classical land cover (geomorphological) succession of the coastal dunes with poorly vegetated active dune, vegetated active dune, fixed dune, shrubs and forest. Further inland spartina swards and Mediterranean salt meadows cover about 25% to 30% of the mapped area.

The spit is wider, generally about 250 meters (P7), except P5 which is only 150 m wide. The beach width is generally 30 meters. Compared to the previous polygons, the active dunes (vegetated or not) are wider, ranging from 15 meters to more than 30 meters, and higher (up to 3.5 meters above sea level, Figure 3 and 4). The fixed dunes are also well developed (reaching 3 meters high) and the saltmarshes present a great topographic variability. However, the internal part of P6 presents a different morphology, lower (less than 2 meters high) and gently undulated. The nearshore morphology is generally gently sloped with the presence of two well-developed bars (at -1.5 m and -3 m water depth), except P8 which presents only one bar (-1 m water depth).

Beach covers about 17-18% of P9 and P10 area, however, while P9 is characterized by well-developed coastal dunes with active dunes (25% of the mapped area) and fixed dunes (25%), active dunes are almost absent (2.5%) in P10 and fixed dunes represent 16% of the mapped area (Figure 3). It should also be noted that beach wrack is almost absent for P9 (less than 1%) and P10 is characterized by a vast zone with scarce vegetation, indicating an old washover (about 34%). Finally, salt marshes (Spartina and Mediterranean salt meadows) represent more than 20 % of the mapped area of P9 and P10. The morphology of these two polygons is different compared to the previous ones. Active dunes of P9 are generally less than 2 m high, while fixed dunes, located further onshore, are generally higher, reaching 3 m high (Figure 4). The wet slack (about 1 m high) is generally flat. In contrast, P10 is characterized by higher fixed dunes, reaching 4 meters high. The saltmarsh is characterized by a gently undulated morphology. The nearshore of P9 is similar to P8 with one well-developed bar (-1m). P10 is also characterized by the presence of a nearshore bar (-1 m) and a channel located about 300 meters from the shoreline.

Regarding the short-term coastal evolution (Supl.Mat 1), the results indicate an almost constant retreat of the shoreline for P1 to P4 and P8 to P10, while a shoreline progression or stability is observed between P5 to P7. The short-term evolution of the foot dune is mainly slightly retreating, with values ranging from 1 to 1.5 m/yr, reaching occasionally 4 m/yr (P9).

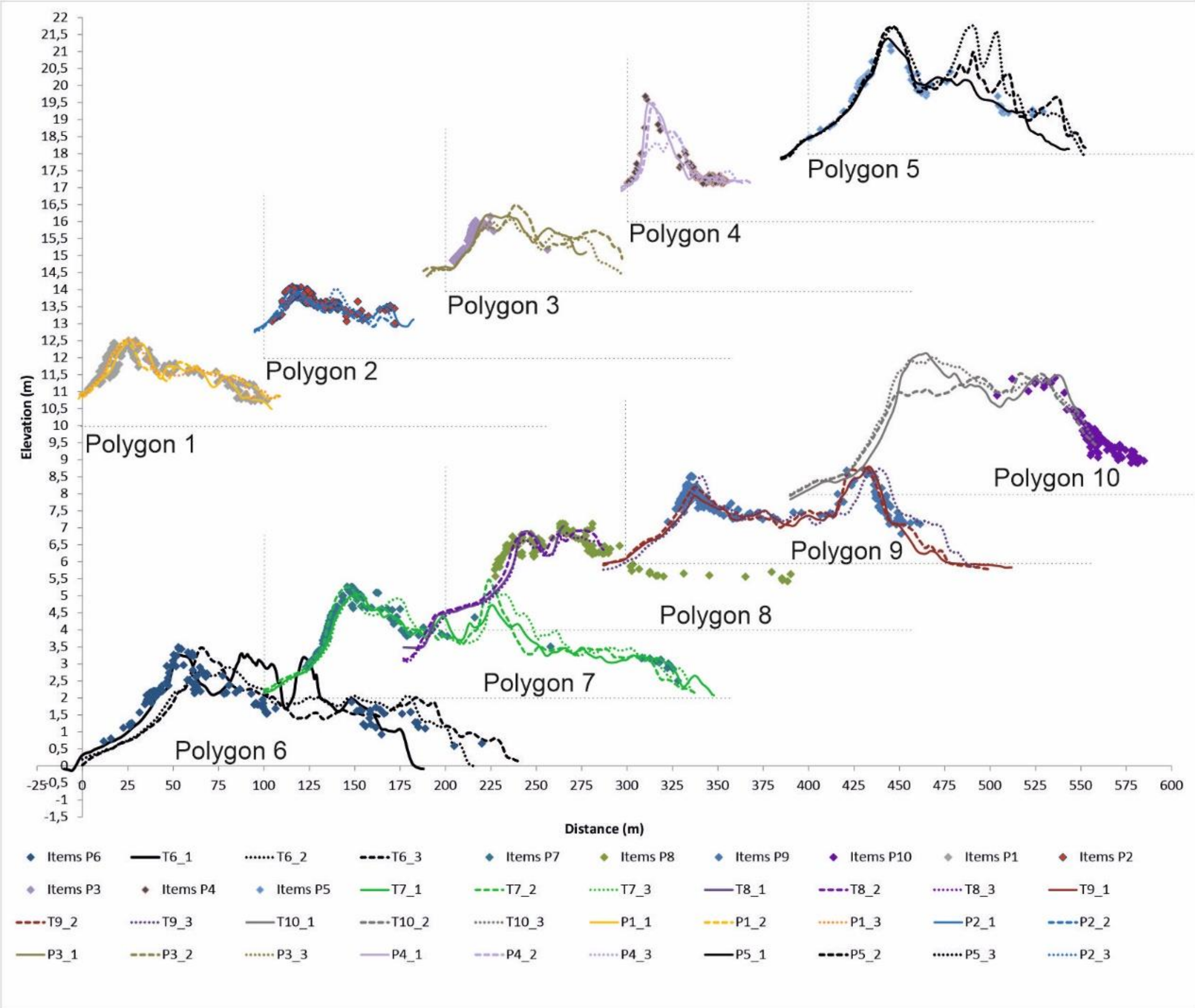

Figure 4: Topographic profiles of the 10 polygons analysed in this study (distance and height are expressed in meters). For each polygon, three profiles have been elaborated.

3.2 - Marine debris

In total 1449 debris items have been mapped in the ten polygons, from which 361 of class 1, with a maximum of 192 items in P8 to a minimum of 100 in P5 (Supl.Mat 1, Table 2). However, if we consider the mapped area, the results indicate a density ranging from a minimum of 0.014 to a maximum of 0.035 debris/m^2 (0.017 to 0.057 items/m^2 if shrubs and forests are not considered), and the area covered by litter was estimated to 130 m^2. The items generally covered an area ranging from 0.001 to 0.35 m^2 (Figure 5). The mean items area is 0.093 m^2 with a standard deviation of 0.135 m^2.

Furthermore, the distribution of the marine litter items indicates that P1 to P4 are characterized by higher density, while fewer items were identified in P5 to P7 (Supl.Mat 1). The results further indicate that, excepting not identified items (especially white items, most frequent), plastic items were the most frequent identifiable items, with polystyrene boxes and fragments found in all polygons (Figure 5). Bottles, buoys and plastic bags were also generally identified in all polygons. In addition, metallic and wood items were also observed, representing up to 4% of the items, while the paper was rarely identified, and textile and construction materials were absent.

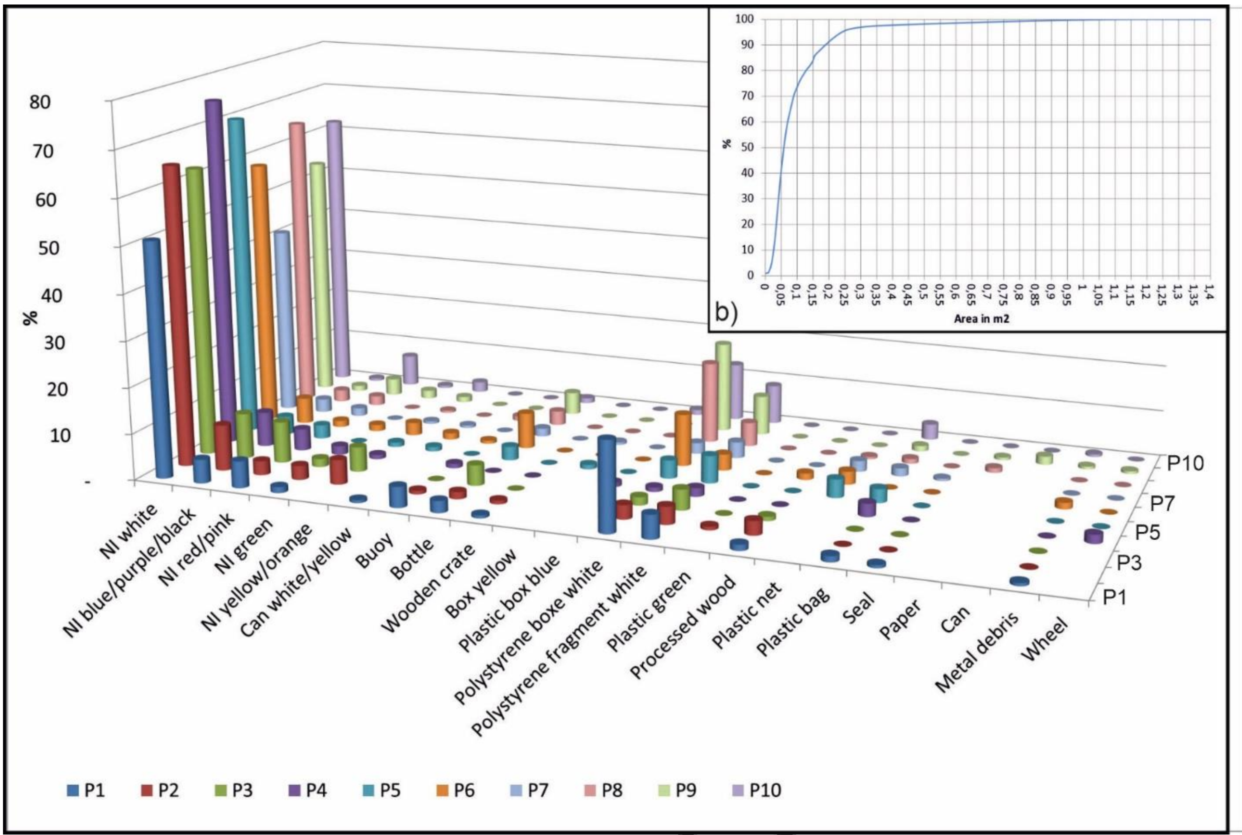

Figure 5: Distribution of the different item's categories in the 10 polygons analysed in this study. (NI: not-identified)

Regarding the position of the items (Figure 6, **Error! Reference source not found.**Table 2), the results indicate:

- Most of the items were observed in the beach wrack, except for P4, P9 and P10 (noting that beach wrack was almost absent in P9-P10);
- ML items were more frequent in the dune system (active and fixed dunes) compared to the beach; except in P4 and P5;
- In P4 marine debris was most frequent in the salt marshes. Debris was also frequent in the saltmarshes of P1, P3, P6, P7 and P10;
- In Polygons 2, 3 and 4, items were found at low elevation, generally than 2 meters. For P1, P9-P5 most items were observed below 2.5 m, while the distribution of the marine litter items in polygons 6, 7, 8 and P10 respecting the elevation was more casual, especially for polygon 10, with about 50% of the items observed below 2 m, and normally the 90% of ML is below 3 m;
- Regarding their position from the shoreline, most of the items were positioned close to the shoreline. Indeed, 68% of the items identified were observed closer to the shoreline compared to the lagoon, in particular for P2, 3, 4, 5. In P3 most of the items were observed within the 30 meters from the shoreline (P3 and P4 are characterized by a well S shaped distribution). Polygons 6, 9 and 10 however present a bimodal distribution with two outbreaks.

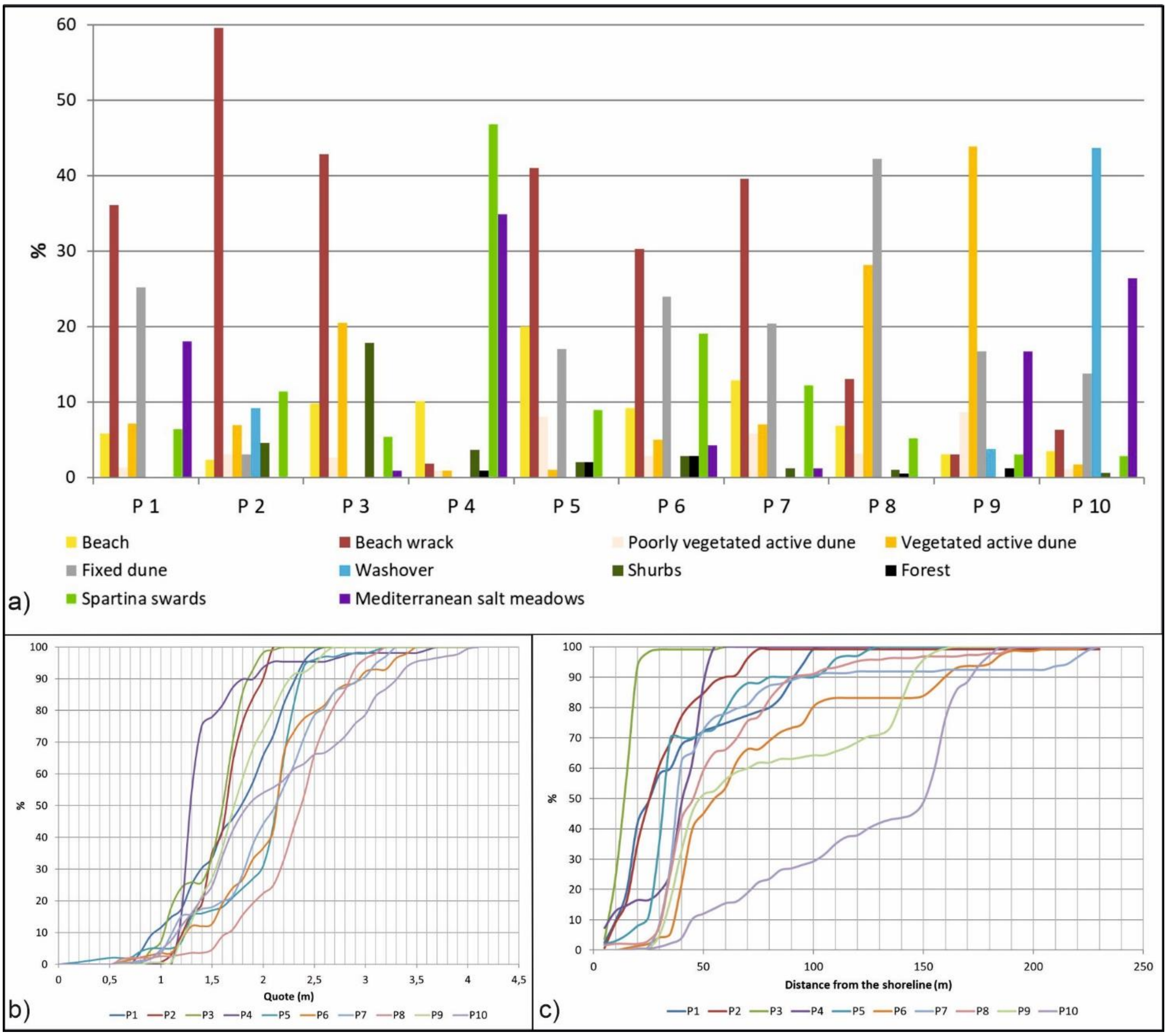

Figure 6: a) Distribution in % of the marine litter items according to the eco-geomorphological classes and polygons; b) Quote of the items; c) Distance from the shoreline.

	P1	**P2**	**P3**	**P4**	**P5**	**P6**	**P7**	**P8**	**P9**	**P10**
Beach	0,016 9	0,0089 3	0,0221 11	0,0310 11	0,0133 20	0,0071 13	0,0121 20	0,0053 14	0,0032 5	0,0032 6
Beach wrack	**0,1324 56**	**0,0873 78**	0.1897 **47**	0,0642 2	**0,1875 41**	**0,135 43**	**0,2774 67**	**0,206** 26	**0,0772** 5	**0,0375** 11
Poorly vegetated active dune	0,0528 10	0,0136 4	0,107 3	0,0169 1	0,0387 8	0,0222 4	0,0585 14	0,0414 6	0,0498 19	0,0143 2
Vegetated active dune	0,026 11	0,0758 9	**0,22** 23	0,0183 1	0,0029 1	0,0216 7	0,0458 12	0,1179 54	0,0342 **71**	0,0128 3
Fixed dune	0,0272 39	0,0208 4	0	0	0,0194 17	0,0107 34	0,0127 34	0,0265 **80**	0,0099 22	0,0151 24
Washover	0	0,0106 11	0	0	0	0	0	0	0,0338 6	0,0224 **76**
Shrubs	0	0,0478 6	0,017 20	0,0058 4	0,0025 2	0,0037 4	0,0108 2	0,0104 2	0	0,0023 1
Forest	0	0	0	0,0022 1	0,0015 2	0,0029 3	0	0,0022 1	0,0119 2	0
Spartina swards	0,0103	0,021	0.02	**0,0691**	0,008	0,01272	0,0058	0,0025	0,0126	0,0212

	10	15	7	**51**	9	27	21	9	5	5
Mediterranean salt meadows	0,019420	0,0151	0.00051	0,055038	0	0,024047	0,00252	0	0,017127	0,024946

Table 2: Items/m^2 and number of identified marine litter items for each eco-geomorphological class.

IV- Discussion

In this study, we focus on remote sensing applications for monitoring the macro litter in lagoon environmental, and especially on items with a length greater than 12 cm. The average litter densities for the different polygons and habitats ranged from 0.017–0.5 items/m^2, which are comparable to the values reported by other surveys using UAV images (Gonçalves et al., 2020), but lower than results obtained in Adriatic seas using the traditional approach (Vlachogianni et al., 2018). However, our paper does not focus on the possibility to use UAV imageries for detecting marine litter, but we assume, given that as reported by several authors (Yang et al., 2022), UAV imageries can be used to map the distribution of marine litter on coastal systems. Andriolo et al. (2020) report that the Unmanned Aerial System-based approach allows a non-intrusive survey of marine litter on a coastal dune system on the Atlantic coast, while Gonçalves et al. (2020) developed a procedure for an automated Unmanned Aerial System-based marine litter mapping on a beach-dune system. Similarly, Deidun et al. (2018) proposed a protocol to monitor marine litter along coastal stretches of the Maltese Islands using aerial drones and generate density maps for the beached litter. We used UAV imageries to map marine litter items present in the different habitats/systems along the spit. In addition, like Andriolo et al. (2020), the different coastal habitats (beach, dune, back dune, saltmarsh) and coastal features (washover, beach wrack) have been identified through visual analysis of the orthophotos and DSM, highlighting the benefit in terms of human effort due to the difficulty to access to such areas like salt marshes, as reported by Green et al. (2017) or Doughty and Cavanaugh (2019).

The manual UAV image screening can have a variable accuracy in litter identification rate depending on several factors like operator abilities (from 62% in Martin et al., 2018; to 98% in Fallati et al., 2019), size and colour of the items (Taddia et al., 2021; Escobar-Sanchez et al., 2021; Martin et al., 2018; Lo et al., 2020). In addition, compared to a standard monitoring approach (i.e. walking on the beach), the UAV approach reduces the time of analysis and can be used in areas with difficult access (Martin et al., 2018). Consequently, UAV imageries may be used to monitor marine litter, but more appropriate techniques should be developed to avoid misclassification, since most of the items detected were non-identified items (75%), while polystyrene white boxes and fragments and bottles were the most frequent recognized. Our results attest that a specific UAV imagery classification should be developed considering at least three easy observable parameters, which are dimension, shape, and colour. Indeed, classification using marine litter category such as plastic, paper, metal, is currently not appropriate considering that the characteristics of the material type (buoyancy and weight) influence the wind and wave driven transport processes, and may result in similar accumulation patterns as noted by Di Febbraro et al. (2021). Consequently, such an UAV classification should be used to provide information to local authorities regarding eventual necessary cleaning operation activities, and successively after the cleaning operations identification of the marine litter can be done to provide additional useful information.

Furthermore, our results indicate that the distribution and abundance of marine litter along coastal spit are related to the interactions between eco-geomorphological factors and hydrodynamic conditions as synthesized in Figure 7. Their interactions also determine the retention time of the marine litter in the coastal system, which in turn will impact the litter degradation, fragmentation and further dispersion. Regarding the eco-geomorphological factors, and in particular the role of the vegetation, our results reveal a strong effect of habitat and vegetation on litter distribution and deposition. As a matter of fact, we observed a vegetation differentiation along the spit from North to South with the progressive reduction of the beach wrack and an increasing trend of the dune system (with a progressive dune elevation). In addition, salt marshes and shrubs/forests are more developed in the central part of the spit. Regarding the marine debris distribution, commonly, less than 10% of the items were observed on the beach (no items in P7), indicating that beaches represent temporary sinks for marine litter deposition, with a low retention time. As a consequence, the data on beach macro marine litter reported in the literature represents only a small part of the marine litter deposited in the coastal system.

Moreover, marine litter items were generally more abundant on the coastal side and in particular in beach wracks (when present) and in vegetated dune systems, suggesting the important role of the eco/geo-morphological elements in trapping litter, as observed by Battisti et al., 2020; Gonçalves et al., 2020; Chubarenko et al., 2021; Cesarini et al., 2021; Sanchez-Vidal et al., 2021; Menicagli et al., 2022). For instance, Di Febbraro et al. (2021) and de Francesco et al. (2018) found that marine litter accumulation follows a sea-inland gradient, while Cesarini et al. (2021) reported a positive correlation between vegetal wrack and plastics, and consequently a greater weight of beached vegetation suggests a greater weight of plastic in the same area. Menicagli et al. (2022) found that items, consisting of fragmented plastics, microplastic particles and polystyrene, collected along Mediterranean beaches were trapped in the natural wrack, while Gonçalves et al. (2020) observed that marine litter was deposited chiefly around dune plants. However, the abundance of marine litter in beach wrack may also be a result of human activities, like beach cleaning operations. Indeed, during the winter season, mechanical beach cleaning removes both human-generated debris and biotic material from the beach and deposit them close to the dune foot for management purpose.

Therefore, beach vegetal wracks and dune plants may represent indicators for marine litter accumulation, but the items permanence and retention in these ecosystems are different. Indeed, most accumulations of natural wrack are short-lived, often being removed from the beach by natural processes within a relatively short period of time or mechanically removed before the summer season for touristic purposes as reported by Pal and Hogland (2022). Consequently, the retention time of the marine litter in these accumulations is generally short (months). On the other hand, marine litter items in coastal dunes are exposed to burial processes and, consequently, their retention time is probably longer. Marine debris may be also removed during most intense events or exhumed during erosion processes (Andriolo and Gonçalves, 2022).

The role of the vegetation in capturing and accumulating marine litter is also highlighted by the abundance of marine litter observed in low and high salt marshes in agreement with other studies (Viehman et al. 2011; Uhrin and Schellinger, 2011; Mazarrasa et al., 2019; Harris et al., 2021). Viehman et al. (2011) noted that large debris, mainly anthropogenic wood and derelict fishing gear, were found in all marsh habitat types of North Carolina (USA), but were most highly concentrated in natural wrack lines. Similarly, Mazarrasa et al. (2019) studied the distribution of marine litter in three estuaries of the Gulf of Biscay and found that the variability of the differences in litter accumulation responds to the variability in hydrodynamic conditions within estuaries. They further observed the role of estuarine vegetated communities as marine litter traps, especially the high marsh strata formed by large, dense and perennial vegetated communities only inundated during extreme tidal events. In our study, marine litter accumulated in both low and high saltmarshes. Most probably low salt marshes first capture litter items during normal hydrodynamic conditions, which are successively transported deepest into the high salt marshes during high water events, as suggested by Viehman et al. (2011). Once deposited in the salt marshes, the retention of the items time is governed by the density and composition of the vegetation and by the sediment: the saltmarsh environment with muddy sediments and roots acting as marine litter traps and causing their entanglement. Therefore, marine litter retention time is most probably longer in the high salt marshes compared to low salt marshes. The persistence/retention of the items will be related to degradation processes allowing their remobilization and fragmentation into smaller pieces and microplastics in the coastal lagoon, which is likely to retain microplastics due to low flushing time.

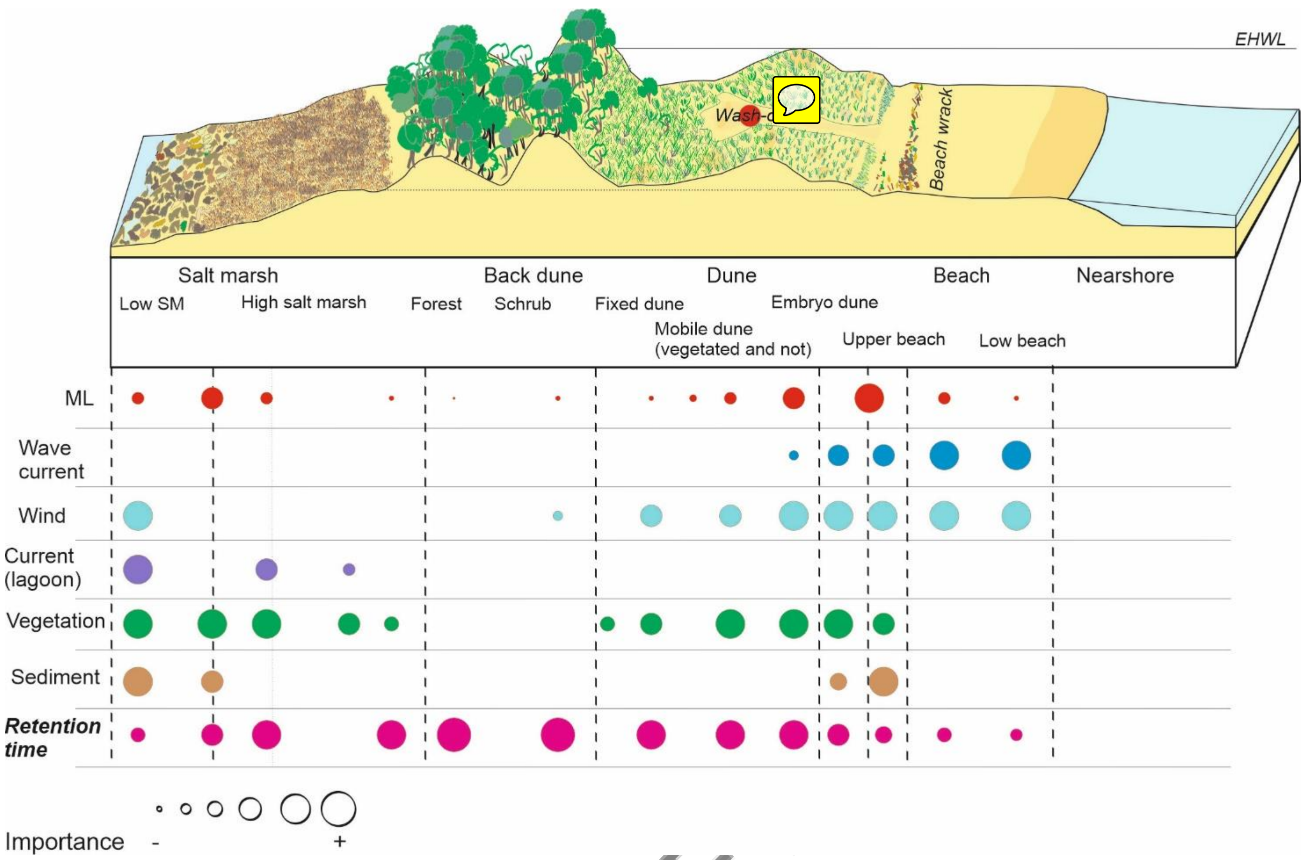

Figure 7: Pattern of marine litter distribution considering different factors and the retention time. Note that the dimensions of the dot indicate the relative importance of the factors as indicated in the figure.

Our results do not suggest a strong control of the topography on the distribution of the marine litter items along and across the spit. Instead, we believe that it is the result of the marine and weather conditions as illustrated in Figure 7. Indeed, our results indicate that "beach site" and "lagoon site" were significantly different in terms of marine litter abundance, which could be related to the hydrodynamic conditions "controlling" the deposition, retention and turnover of the items. Indeed, litter items were observed along the beach/dune profile, highlighting the role of the waves, currents and winds in transporting marine litter as suggested by various authors (Van Sebille et al., 2020; Prevenios et al., 2018, Kako et al.,2010). Waves most probably carry and wash marine litter items up to the maximum sea level (including setting up and run-up) reached during storm events. The role of the storm surge in transporting marine litter is clearly observed in the "washover area" where litter is normally associated with the vegetal debris. Winds, and in particular offshore winds, also participate in the transport of light items (buoyant objects like foamed plastic pieces) across the beach profile (further inland and higher), explaining the presence of items in the dune system above the maximum sea level. Indeed, the wave-driven transport of marine litter generally occurs up to the maximum sea level including run-up and set-up (about 2.3 m in our study case) and cannot explain the presence of marine litter at the higher level (fixed foredune). Consequently, the presence of marine items at a higher level generally found further onshore is most probably related to the onshore winds, once the items have been transported by the sea. In addition, the presence of litter items over all the profiles (Polygons 1, 8 and 10 for instance) suggests that the wind action in transporting and distributing litter items should be considered an important factor for the coastal system. Such wind evidence has been clearly observed by Kako et al. (2010) who concluded that wind-driven supply of litter was an important factor in the distribution of beach litter in Japan. Similarly, Schernewski et al. (2018) observed along the German coastline that litters with very low densities were subject to wind-driven transport and especially the prevailing winds. Arcangeli et al. (2018) also reported the action of winds in transporting and depositing marine litter in the coastal zones. Therefore, we believe that further studies to better understand the role of the waves and winds in transporting marine litter and their interaction are necessary to improve our understanding of the dynamics and distribution of beach litter and consequently assess its local, regional, or global impact, and its temporal and spatial variability as well.

The presence of marine litter in the lagoon side of the spit (in particular in salt marshes as discussed previously) suggests the role of the hydrodynamic circulation in transporting and depositing marine items. Indeed, marine litter was observed near the inlet mouth (P1-P9 and P10) and on the internal boundary of the lagoon (P4). The presence of marine litter in coastal lagoons have been described by different authors (David et al., 2019; Oztekin et al., 2019; Lorenzi et al., 2020; Ertas, 2021) who mentioned the role of the tides and the water in time of residence and distributing marine litter. The higher water resident time and weaker hydrodynamics on the internal part of the lagoon might explain the abundance of litter observed at polygon 4. In addition, the transport and presence of marine litter in the deepest part of the saltmarsh could be associated with high water level events eventually connected with storms as suggested by Viehman et al (2011) or Uhrin and Schellinger (2011).

Moreover, our results do not highlight a clear relation between erosion or accumulation processes and the presence of marine litter, as suggested for instance by Andriolo and Gonçalves (2022) who reported that coastal erosion processes may exhume litter buried in dune volumes and on other coastal environments over short- and long-term. However, wash-over seems to influence the accumulation and distribution of marine litter as suggested by Turner et al. (2021), who reported that the fate of plastic may be similar to that of eroded sediment in being redistributed amongst the dune system with wash-over, dune slumps and blowouts.

Finally, our results regarding the presence of marine litter on a coastal spit provide useful information for beach cleaning operations. As suggested by different authors, remediations actions and cleaning operations must be better designed in order to enhance their efficiency in particular by prioritizing specific areas over others, paying attention to not damaging specific target habitats like a salt marsh (Barbier et al., 2021) or a beach wrack (Cesarini et al., 2021). In the dune systems, mechanical cleaning operations should be avoided to preserve the plants promoting manual cleaning operations Additionally, we agree with Viehman et al. (2011) who suggested that for minimal habitat trampling and maximum efficiency, marsh clean-ups strategies should prioritize the wrack lines for removal of small debris, and target large debris items individually based on size and accessibility, which can be assessed through the analysis of UAV images. Due to the difficulty to access to salt marsh, organized volunteer-based marine debris clean-up operations are almost impossible. Therefore, we suggest that management should focus on this habitat and sensibilization to marine debris in salt marsh should be improved.

V- Conclusions

Our study confirmed the usefulness of the employment on the use of UAV images to monitor marine litter items on a spit. Our results confirm that UAV techniques are useful for monitoring beach litter and in particular UAV images represent high-resolution data over inaccessible areas like salt marshes or protected areas. Moreover, our study complements to the rich literature showing that anthropogenic litter is abundant throughout the marine environment, but importantly highlights the strong trapping effect of habitat on litter material and source. In particular, the results indicate that:

- The marine litter distribution suggests that the coastal system should be considered in its integrity considering the entire coastal process. Marine litter items were generally more observed on the coastal side of the spit (beach and dune) than on the lagoon side (salt marsh), but cleaning operations are more easily performed on the beach compared to the lagoon.

- In addition to the negative impacts related to the presence of macro-litter, our results highlight another potential issue related to the fragmentation of the macroplastics in microplastics, especially in the saltmarsh where microplastics can be trapped by the silt, and as a consequence altering the chemical, physical and ecological characteristics of this environment. Further research should focus on the relation between the trapping of macroplastics by the vegetation and the fragmentation and deposition of microplastic in salt marsh environment;
- Vegetation is an important factor in trapping marine litter, and as a consequence, the retention of marine litter in the salt marsh is most probably higher than on the beach wrack or vegetated dunes. Consequently, new cleaning strategies should be implemented in order to avoid damaging of coastal habitats;
- In order to further assess the role of the vegetation and morphology in trapping and accumulating marine litter, the monitoring program should be changed. The use of UAV monitoring system can help to faster the monitoring operations providing useful information to assess the efficiency of mitigation measures.

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Submitted supplementary

SM1 - Main results

Polygon	1	2	3	4	5	6	7	8	9	10
Area	5473	4051	5041	3576	8125	12814	12437	11118	10063	10463
Length	110	82	102	72	160	234	246	221	190	213
Mapped area	5148	3779	4294	3079	7275	10338	11852	10796	8819	10041
Number of Identified items	155	131	112	109	100	142	172	192	162	174
Identified litter class I	57 (37%)	17 (13%)	9 (8%)	11 (9%)	21 (21%)	41 (29%)	50 (29%)	51 (27%)	62 (38%)	40 (23%)
Items/m2	**0,030**	**0,035**	**0,026**	**0,035**	0,014	0,014	0,015	0,018	0,018	0,017
Items/m² excluding shrubs and forests	0,03	0,036	0,036	**0,057**	0,02	0,017	0,018	0,019	0,019	0,018
Beach %	10,96	8,91	11,57	11,51	20,61	17,75	13,93	24,22	17,70	18,61
Beach wrack %	8,21	**23,63**	**5,89**	1,01	3,01	3,08	2,07	1,17	0,73	2,92
Poorly-vegetated active dune %	3,68	7,80	0,65	1,92	2,84	1,74	2,02	1,34	4,23	1,39
Vegetative active dune %	8,20	**3,14**	**2,44**	**1,77**	4,75	3,13	2,21	4,24	23,55	2,34
Fixed dune) %	27,84	**5,08**			12,06	30,61	23,18	27,93	25,20	15,81
Shrubs %			27,51	22,42	11,04	10,42	1,56	1,78	2,20	4,3
Forest %	1,54	3,32		14,97	18,85	9,92	17,92	4,12	1,91	
Washover %	0,86	27,51						1,27	2,01	33,86
Spartina swards %	18,79	18,84	8,10	23,97	15,27	20,54	30,41	33,93	4,50	2,35
Mediterranean salt meadows %	20,00	1,77	43,84	22,44	11,57	2,82	6,70		17,87	18,42
Physical characteristics	Groin W Pond	Wash-over Groin W pond	Between 2 groins pond	Close to Boccassette beach		Dune breach 5 m wide - 40 m long	Well-developed dune	Well-developed dune	Well-developed dune	Old Wash-over
Shoreline evolution 2009-2018 2018-2019	Bar -30 +32	-30 +27	-16 +6	-20 -3	Stable stable	+25 stable	+16 +4	-23 +8	-40 +9	-80 +40
Foot dune evolution 2009-2018 2018-2019	Stable (-2) -9	Wash-over	-8 -5	-6 -8	-5 -9	Stable -8	Stable -3	Stable -6	-33 -8	-9 stable