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Relationship between geomorphology and quality of the semi-fixed dune landscape

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1 INTRODUCTION

Coastal sand dunes are sedimentary deposits built by the transport of sediment inland from the beach by wind action. They usually characterize sandy beaches in particular in mid and low latitude (Davidson-Arnot, 2010). Occupying transition zones between terrestrial and marine ecosystems, they host a particularly specialized flora and fauna and constitute one of the most dynamic landscapes on earth (Malavasi et al., 2013).

Healthy coastal dune systems provide important ecosystem services (Barbier et al., 2011; Dahm et al., 2005; Everard & Jones, 2010; Van Der Maarel, 2003). First of all, they offer natural protection from coastal erosion and flooding, providing a natural buffer zone which enables communities to withstand natural shoreline movements and preserving the natural and human use values of beaches (Dahm et al., 2005). High and wide dune systems represent a physical barrier against sea action. Dunes play also an important role in the natural cycle of erosion and recovery that occur on sandy beaches as they store sand providing additional material that re-enters the marine transport system and forms a new beach profile after erosion events. Sand dunes may also serve water purification roles, offer landscape of cultural value, supply important recreational benefits and provide maintenance and protection of natural habitats.
Nevertheless, coastal sandy ecosystems are currently identified as one of the most threatened ecosystems prone to biodiversity loss (EEA, 2009). Increasing population pressure, combined with the desirability of shoreline for human investment, settlement and use, generates significant transformations in coastal ecosystems. A key factor in coastal urbanization is the mass-tourism developed after World War II. In Italy, it led to the development of settlements, infrastructure and touristic facilities, resulting in degradation or even disappearance of coastal habitats (Cencini et al., 1988).

Until the 1950s, the eastern coast of the North Adriatic Sea was almost entirely fronted by dune ridges up to 10 m in height (Zunica, 1971), forming the major dune system in Italy (Audisio, 2002). Nowadays, only a few of them still exists (Nordstrom et al., 2009), being in a large part demolished to provide space for housing, resort and beach facilities development (Del Vecchio et al., 2015). At present, this coastal area is also affected by beach erosion mainly due to a decrease of sediment supplies delivered by rivers, subsidence, and reduction in longshore sediment transport owing to the presence of shore-perpendicular structures (Nordstrom et al., 2009). This makes the above-mentioned protection functions of the dune systems even more interesting and highlights the need of a sound management in order to conserve and restore them. Furthermore, North Adriatic coastal landscape is characterized by a remarkable phytocoenotic originality (Sburlino et al., 2013). Besides a small sector of the Ligurian coast, its dune system is the only coastal area of the Mediterranean basin to be included in the temperate region (Sburlino et al., 2013). In particular, the semi-fixed or transition dunes, located between the mobile dunes and the dune scrub and woodland habitats, are characterized by the presence of the habitat type 2130* "Fixed coastal dunes with herbaceous vegetation (grey dunes)", more or less closed perennial grasslands associated with abundant carpets of lichens and mosses, which finds in North Adriatic coasts the only Italian part of its distribution area (Houston, 2008). It is designated as "priority habitat" as it requires conservation actions because of its decline, rarity and importance (92/43/EEC Directive). In fact, transition dune systems are often squeezed between a regrading beach and dune scrub and anthropic areas (Nordstrom et al., 2009) and their vegetation is threatened by tree plantation, invasion of exotic species, impact of recreation pressure (foot traffic, off-road driving), which lead to habitat degradation, fragmentation and loss (Houston, 2008).

The conservation of this priority habitat and of the dune system, with its important functions, results to be undeniably linked. Coastal plant communities are strongly influenced by the sea-inland environmental gradient and by the geomorphological characteristics of the beach and the dune system. Each zone in the coastal vegetation sequence has a different species composition, related to the ability of the plant species to withstand environmental factors, which differ with distance from the sea and topographic sheltering (Prisco et al., 2012).

In particular, the habitat 2130* settles on the semi-fixed dune zone, where wind strength, sand transport and salt spray are reduced by both the increasing distance from the sea and the active dunes reliefs. Moreoversalty groundwater becomes less influent landward, nutrient content in sediments increases, soil is more mature, dunes are stabilized and their forms are smoothed. Mobile aeolian features, in fact, represent the first obstacle to wind and sea actions providing a protection service to the inland habitats (Audisio, 2002). In these contest, the key of this priority habitat's conservation could be a coastal management strategy that considers dune systems in their entirety as a resource and not as an obstacle for coastal economy.

Given that, the aim of this thesis is to investigate the relationship between geomorphology and vegetation features on semi-fixed dunes, to understand if morphological characteristics of the mobile dune system can influence 2130* habitat type vegetation structure and its quality. In particular, the protection function of mobile dunes towards semi-fixed dunes plant communities is analysed.

2 Study area

The investigated littoral faces the Northwest Adriatic Sea (Italy) and extends from Porto Caleri to Eraclea Mare (Fig. 1).

The Northwest coast of the Adriatic Sea consists of an alluvial plain margin and its beach slope is low (Zunica, 1971) with isobaths mostly parallel to it (Fontolan, 2014). Until the 1950s, it was almost entirely fronted by dunes up to 10 m in height (Zunica, 1971). Nowadays, only a few of them still exist (Nordstrom et al., 2009): they were demolished to provide space for housing, resort and beach facilities development (Del Vecchio et al., 2015). At present, surviving dunes are often affected by beach erosion due to natural processes and anthropogenic impacts. As since the 1950s the Venetian coast has been subjected to an intense touristic and urban development, many portions of beach have been fixed by coastal defence, such as groynes, jetties and seawalls, in order to prevent beach erosion (Fontolan, 2014).

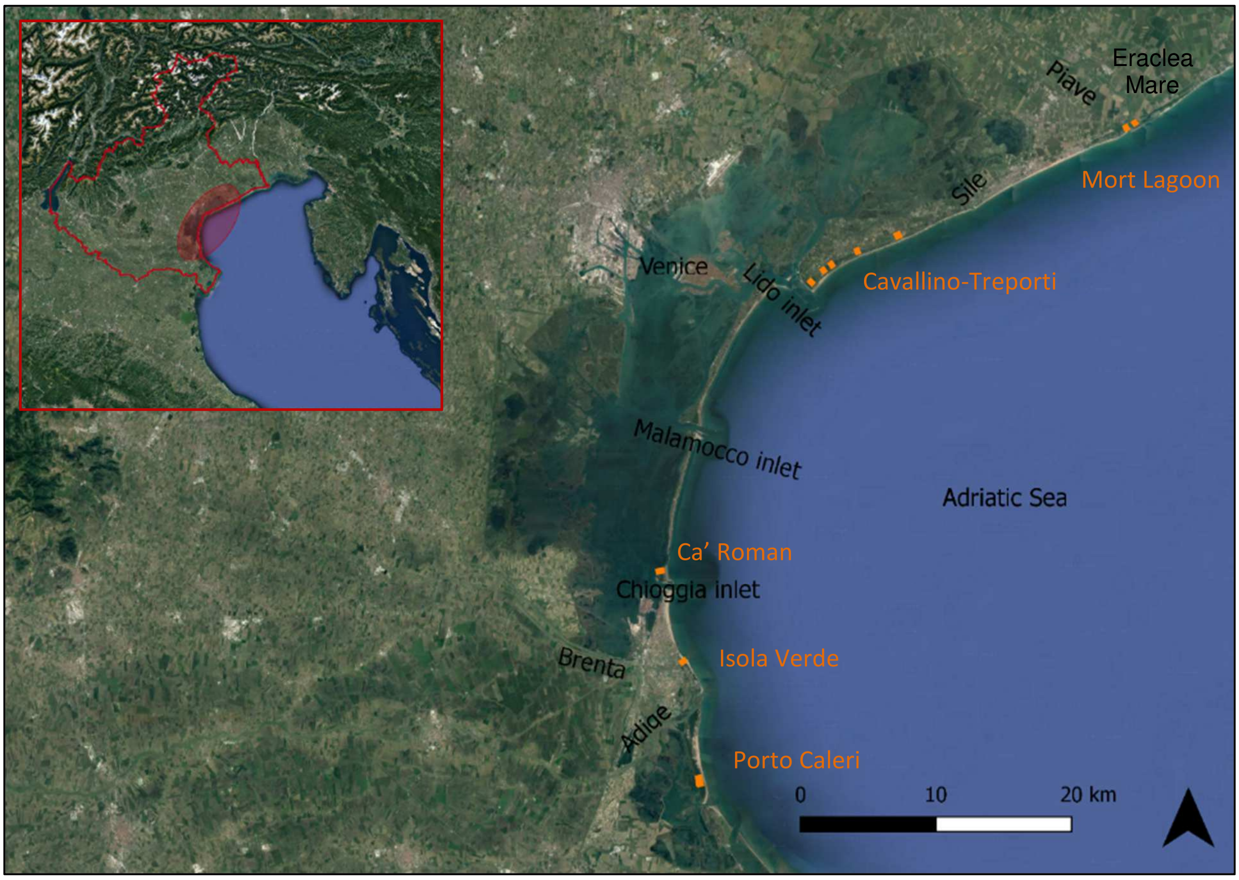


Fig. 1 - The study area extending from Porto Caleri to Eraclea Mare (Veneto region, Northeast Italy). The red squares represent the locations of the twelve shore-perpendicular transects chosen for investigations (Porto Caleri, Isola Verde, Ca' Roman, Cavallino-Treporti, Mort Lagoon).

The investigated stretch of coast is characterized by sandy beaches and is interrupted by river mouths and lagoon inlets; consequently, delta and barrier-island systems are presents (Fontolan, 2014). The southern part, extending from Porto Caleri to the Lido Inlet, has a N-S direction and a curved shape; the northern part, up to the Mort Lagoon, is generally straight and WSW-ENE oriented (Zunica, 1971). The littorals are made of sands transported to the sea by different rivers. Tagliamento river sediments (the Tagliamento River flows into the Adriatic northeast of the study area) extend as far as Jesolo, mixed with those coming from the Piave river mouth. The Piave river sands extend as far as the Pellestrina beach, whereas those transported by the Brenta and Adige rivers are present between Porto di Chioggia and Porto Caleri, mixed with the sediments coming from the Po River, which flows into the Adriatic Sea south of the investigated littoral (Gazzi et al., 1973).

During the study, investigations were carried out along twelve shore-perpendicular transects, located in five different areas: Porto Caleri, Isola Verde, Ca' Roman, Cavallino-Treporti, Mort Lagoon (Fig. 1).

Winds, tides and currents

According to a Massalin and Canestrelli's (2006) study on the North Adriatic Sea wind regime between 1983 and 2004, the prevailing winds are the Bora wind, blowing from NNE, NE and ENE, and the Sirocco wind, blowing from ESE, SE and SSE. The former is more intense, reaching a mean speed of 15 m/s (Orlić et al., 1994), and frequent, but it is characterized by a fetch of about 100 km; on the contrary, the fetch of the Sirocco wind is about 800 km long, being its direction parallel to the Adriatic Sea longer axis, with a speed rarely exceeding 10 m/s. The Sirocco wind is often associated with rain and storm surge, which strongly affect aeolian transport on the beach (Bezzi et al., 2009). The Bora prevailing direction was from NE during the 1980s, from ENE during the 1990s and from NE again after 2002. The Sirocco blew mainly from SSE and SE during the early 1980s, from S until 2000 and later again from SE. The Bora generally prevailed on the Sirocco, but the latter one's frequency became more important during the 1990s.
On an annual scale, the Bora and Sirocco prevail between March and September; during February and October, only the Bora prevails, whereas other winds blow with an equal frequency; in winter, from November to January, prevailing winds are the Bora and winds from SW. Sirocco reaches his maximum frequency in March and April when it can prevail on the Bora; it is less frequent, but

more intense, in winter. In winter intense winds are usually more frequent (Massalin & Canestrelli 2006).
On a daily scale, between February and October a rotation of wind direction can be observed with prevailing winds from NE between 7 and 10 am and from SE after 4 pm.
Observations recorded between 1950 and 1959 in the stations of Chioggia and Porto di Lido generally indicate a wind regime similar to that described above (Zunica, 1971).

In view of the modest tidal amplitudes of the adjacent Ionian Sea, the tides in the Adriatic Sea are remarkable (Franco et al., 1982), in particular in the shallow North Adriatic. The tides are prevalently semidiurnal with a spring range of about 1 m and a neap range of about 0.20 m (Nordstrom et al., 2009). Neaps tides can sometimes occur only twice a day (http://www.venezia.isprambiente.it/la-marea). Semidiurnal tides have a period of about 12 hours and 24 minutes and propagate counterclockwise around an amphidromic point between Ancona and Zara (Franco et al., 1982; Zunica, 1971). Free oscillations, called seiches, are associated with particular atmospheric conditions, such as blowing of intensive SE winds and the passage of frontal system or a cyclonic area over the Adriatic Sea. They can exhibit on one or more nodal lines. Seiches are higher in winter; in the North Adriatic, they can reach an average amplitude of 20-30 cm (Franco et al., 1982, Zunica, 1971). Furthermore, the sea level is influenced by atmospheric factors, such as wind and air pressure. The combination of spring tides, seiches, Sirocco winds and low atmospheric pressure can raise sea levels by 1.60 m (Nordstrom et al., 2009).

Coastal sediments are distributed along the shoreline by advection, i.e. transport of suspended materials away from the input sources, such as rivers. The general circulation in the Northern Adriatic is counterclockwise and along the western side of the basin, where study sites are located, one of the major features of the circulation is the Western Adriatic Coastal Current. It is driven by winds and thermohaline conditions connected to the Po river fresh water run-off and is stronger during winter due to winter wind intensity. Consequently, sediments from the northern rivers are generally transported southward by the coastal current. During this process, suspended sediments are mechanically sorted out by their grain size through the sediment deposition process, so that the grain size decreases as the distance increases from the river sources southward (Wang & Pinardi, 2002).

2.1 BIOCLIMATE

The North Adriatic dune system, besides a small sector of the Ligurian coast, is the only one of the coastal areas of the Mediterranean basin to be included in the temperate region (Sburlino et al., 2013). The mean annual temperature is about 13°C, with low winter (0.3°C) and high summer

(17.7°C) values. Mean annual rainfall is 831.5 mm, with maximum precipitation (89.1 mm) in the spring-autumn season and a minimum (49.3 mm) in summer (Buffa et al., 2012).

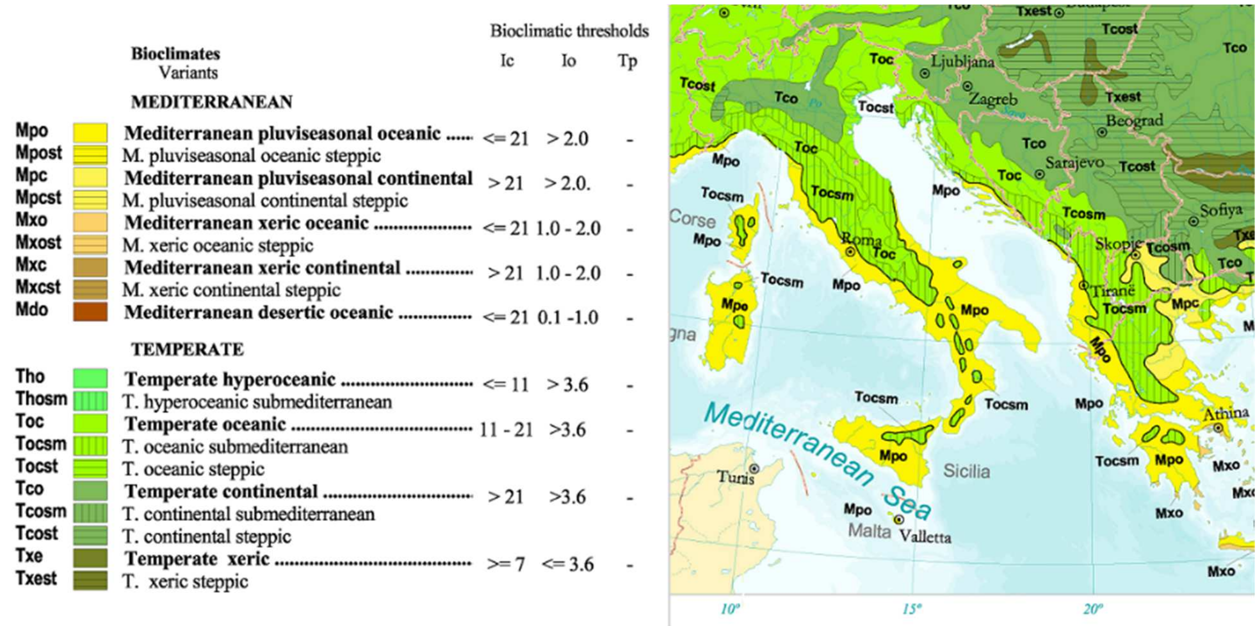


Fig. 2 – Bioclimates in Italy. The North Adriatic coast, besides a small sector of the Ligurian coast, is the only one of the coastal areas of the Mediterranean basin to be characterized by a temperate bioclimate (Rivas-Martínez, 2004).

The bioclimate (Fig. 2) can be classified as Temperate Oceanic with a steppic variant (characterized by attenuated summer aridity and a certain dryness during the winter solstice) in the area around the Venice Lagoon (Rivas-Martínez, 2004) and up to Porto Caleri according to Gamper et al. (2008). In the last decades some changes have been observed in some bioclimatic indices indicating a process of "mediterraneisation" with an increase of summer aridity due to the simultaneous increase in temperature and decrease in precipitation (Buffa et al., 2012).

2.2 Study sites' characteristics

2.2.1 Porto Caleri

Transect 7 and 9 (Fig. 3) are located in the Southern part of the split, which extends over about 8 km in a NNE-SSW direction between Adige River and Porto Caleri. In the northern part of the split, the beach is very narrow and in the central tract, where Rosolina Mare urban settlements develop, is stongly anthropized (Corbau & Simeoni, 2013). In this area, foredunes have almost disappeared or present marked sea scarps as a result of touristic facility development or beach erosion (Simeoni et al., 2010). The most southern zone is a protected area with a coastal botanic garden, included in the Site of Community Importance IT3270017 “Delta del Po: tratto terminale e delta veneto” and in the Regional Park of the Po Delta. Here, beaches are wider, dunes are well developed with a good lateral continuity (Simeoni et al., 2010). These features allow the development of a complete psammophilous vegetation sequence (Caniglia, 2007). Foredunes elevation ranges between 2 and 5.8 m, while internal dune altitude reaches about 6 m (Simeoni et al., 2010).

The local coastline is free from artificial defence and the beach management system of the botanic garden provides for avoiding mechanical raking and organic remains removal. Beach sediments of the area comes from the Adige River and are characterized by high quartz, feldspars and volcanics fragments contents.

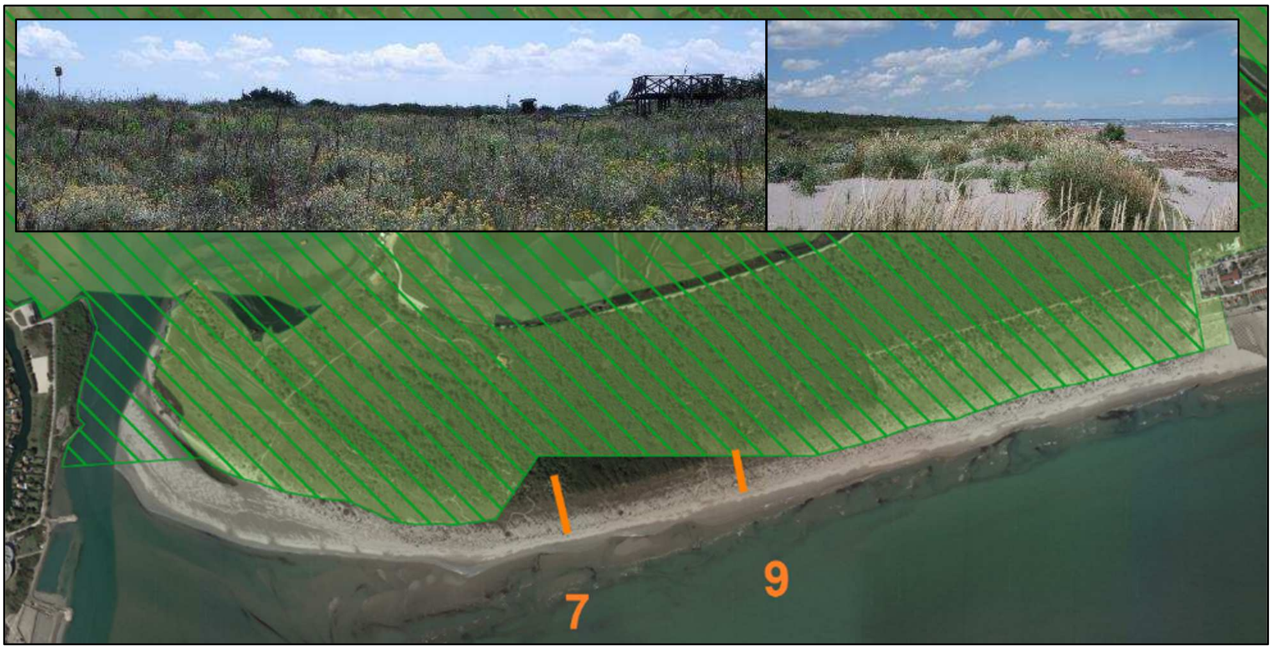


Fig. 3 – Porto Caleri (Green simple fill area: Site of Community Importance; green line pattern fill: Special Protection Area).

2.2.2 Bacucco – Isola Verde

Transect 8 (Fig. 4) is located on the Isola Verde littoral zone, extending for about 2.5 km in a NNW-SSE direction and bordered by the Adige river mouth in the South and by the Brenta river mouth in the North (Fontolan et al., 2005).

This tract of coast has a recent origin. In the early 1800s Brenta and Adige river mouths were not really distinct; they flowed into the sea through only one mouth with many dynamic channels forming small islands, sandbanks and salt marshes (Zunica, 1971). Between 1892 and 1896, when the lower Brenta river course was diverted to the north into an artificial channel, the river mouths were divided. The islands located close to the mouth merged into one, which grew up. The coastline progradation was promoted by the two rivers' sediment convergence and reached the velocity of 36 m per year between 1892 and 1908 (Fontolan et al., 2005). Then, the progradation velocity decreased. At present, this beach segment is subjected to erosion problems, in particular in his southern and central part. Between 1987 and 1998, a marine transgression of about 46 m was registered; only the northern tract showed a slow accretion (Fontolan et al., 2005). At the end of the 1980s, seven rock groynes were realized to protect the coast from erosion. Between 1998 and 2002 the old groynes were substituted with new ones distributed along the whole length of Isola Verde, the river mouths' banks were equipped with longer jetties and a beach nourishment with 300,000 m^3 of sand was realized. Furthermore, to promote the re-building of damaged dunes some windbreaks and a breakwater bank on the backshore were set up (Fontolan et al., 2005). In the northern tract, where the transect is located, there is an older wide dune ridge ranging between 4.4 and 5.7 m and a more recent dune ridge whose formation was promoted by plastic windbreak net. This tract is not as threatened by erosion as the southern part, and the wide beach (about 60 m) ensures a good sediment supply. The northern dune area is also declared a Site of Community Importance (IT 3250034 "Dune residue del bacucco") (Fontolan et al., 2005). Landwards, there are several urban and touristic settlements (Fontolan et al., 2005) and on the central and southern beaches there are several tourist facilities.

Fig. 4 – Isola Verde (Green simple fill area: Site of Community Importance; green line pattern fill: Special Protection Area).

2.2.3 Ca’ Roman

Transect 10 (Fig. 5) is located at Ca’ Roman, which is the most southern part of the Pellestrina littoral (i.e. the barrier island stretching between the Malamocco inlet to the north and the Chioggia inlet to the south). Ca’ Roman represents the only wide beach along the Pellestrina littoral. This barrier island, about 11 km long, has been threatened by erosion for the last centuries; it was protected by a seawall since the XVIII century but in the XIX century the beach disappeared (Fontolan et al., 2005). The erosion was exacerbated by the jetties built along the Malamocco inlet in 1872, which prevented sediment supply from the north. In the 1990s, some groynes linked by submerged breakwaters were built to solve the erosion problem and a beach nourishment was realized using 4,600,000 m^3 of sand; nevertheless, Pellestrina beach is still very narrow, except for Ca’ Roman section. In fact, in the southern part of the island, the coastline progradated fast thanks to sediment trap function of the Chioggia inlet, built between 1911 and 1933. Nowadays, Ca’ Roman strand extends for about 70 ha with the shoreline in a NNW-SSE direction. On the lagoon side, there is a couple of buildings, then, seaward, there are relict dunes ridges ranging between 3 and 7 m and covered by a littoranean forest, a zone of dunes ranging between 2.3 and 3.5 m in height and foredune ridges with a height between 1.7 and 2.4 m (Fontolan et al., 2005). The beach is about 60 m wide. This area is included in the Site of Community Importance IT3250023 “Lidi di Venezia, biotope litoranei”.

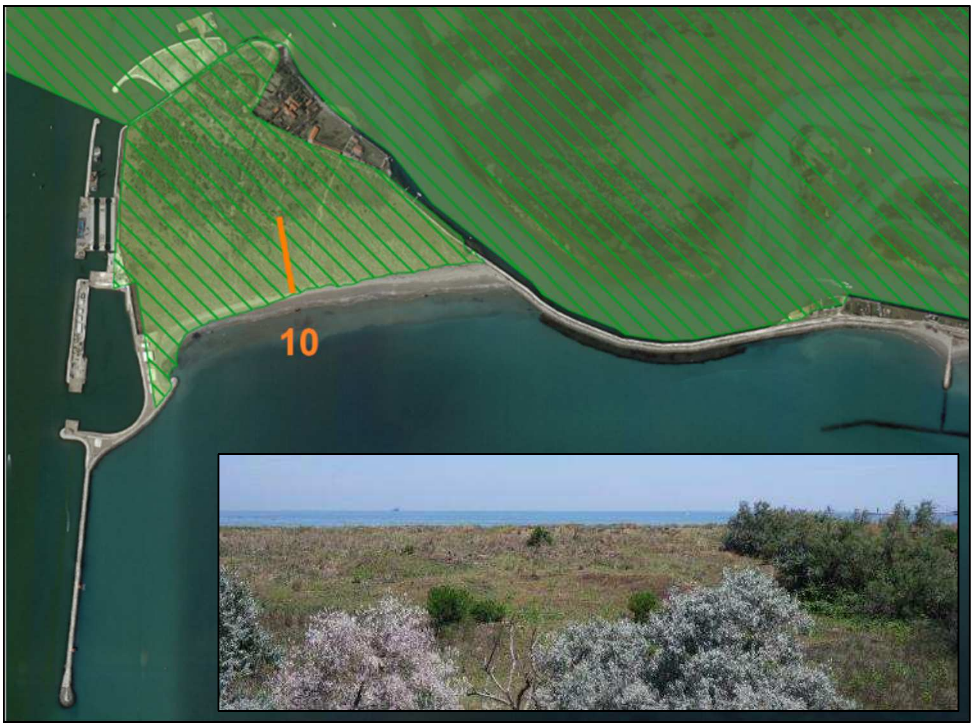


Fig. 5 – Ca’ Roman (Green simple fill area: Site of Community Importance; green line pattern fill: Special Protection Area).

2.2.4 Cavallino-Treporti

Transects from 1 to 6 (Fig. 7) are located on the Cavallino-Treporti littoral area, which extends for about 13.5 km from the Lido inlet to the Sile river mouth in a ENE-WSW direction and turns to NE-SW in the southernmost tract). Nowadays, this coastal area, originated from a split, is affected by an intense touristic and residential development pressure. Landward, there are arable lands and residential settlements, while seaward there is an almost continuous series of campsites. So, the original well-developed dune ridges were almost completely dismantled to leave space for tourist facilities. Today, some dunes remain only in some delimited areas where also an artificial dune ridge was built. For the first time in Italy, between 1994 and 1999, a protective dune (4-m-high, 50 to 90 m wide) was constructed for flood protection along a discontinuous 4.8-km-long tract, covering the old revetment. The protective dune was constructed using bulldozers and then planted with European beach grass (*Ammophila arenaria*) (Fig. 6) (Bezzi et al., 2009).

Fig. 6 – Dune system restoration in two zones of Cavallino-Treporti (Cecconi & Nascimbeni, 1997).

Constructed dunes have an unnatural sweet slope and their height ranges between 3 and 4 m (Fontolan et al., 2005). Elevated dune walkovers were built for access to the beach and sand fences were placed on the seaward side (Bezzi et al., 2009). On the landward side of the protective dunes windbreaks (Cecconi & Nascimbeni, 1997) were placed with a NW-SE direction. The signs of their morphology are still visible from aerial photographs. The 3625 m long northern jetty of the Lido inlet, realized between 1882 and 1925, strongly affected the sediment transport equilibrium of this area. Records indicate that between 1886 and 1951 Cavallino littoral was characterized by accretion from the Lido inlet for 6500 m to the north and by erosion toward the Sile River mouth (Zunica, 1971). The maximum accretion was registered near the inlet jetty (1800 m) and the maximum erosion was registered at the opposite side, near the Sile river mouth (280 m). In the 1940s, in the northern sector, some rock groynes and a concrete parallel defence in the backshore were built to protect the coast from erosion and floods (Zunica, 1971). Recently the accretion trend of the northern section seems to run out (Fontolan et al., 2005). Between 1994 and 1999 the central and northern parts of the section were nourished using 2 million m^3 of sand. Thirty-two stone groynes, spaced 300 m apart, were built in addition to the protective dune reconstruction already mentioned (Bezzi et al., 2009). According to 1998-2004 records, this work seems to produce positive effects with a general positive trend of the nearshore (Fontolan et al., 2005). Between 2012 and 2014 a series of wooden windbreaks was placed next to the foredune ridges, then artificially covered with European beach grass (*Ammophila arenaria*) at Punta Sabbioni, Ca' Savio and Ca' Ballarin (Ministero delle Infrastrutture e dei Trasporti Provveditorato interregionale per le Opere Pubbliche per il Veneto, 2016).

Transect 5 is located near the inlet jetty, in the area called Punta Sabbioni, where there is a wide beach and a natural dune field (Fontolan et al., 2005). Dune field width reaches 100 m (Fontolan et al., 2005). Seawards some embryo dunes are forming, even if part of the beach is mechanically raked, as in the entire Cavallino section. Dunes average height reaches 2.8 m (Fontolan et al., 2005). The dunes area is delimited on the seaward side by a fence, which should encourage tourist to walk on the designated paths and walkovers.

Transects 4 and 6 are located in another dune field and they are spaced about 1 km apart, near Ca' Savio settlement. Here, dunes have an average height of 4.35 m (Fontolan et al., 2005). All these area is delimited seaward by a fence; a series of wooden windbreaks were also installed with an approximately NNW-SSE direction. Transect 4 area was protected by the man-made dunes.

Transect 3 is located to the north, close to Ca' Vio settlement and in front of a campsite. This area was also affected by protection dune construction, but there is not any fence or windbreak.

Transect 1 and 2 are located in Ca' Ballarin zone and partially inside the Union Lido campsite area, about 100 m apart from each other. Here, there is the artificial protection dune and also the recent wooden windbreaks placed in a NNE-SSW direction.

At Punta Sabbioni, Ca' Savio and Ca' Ballarin some portions of littoranean forest still exist. Some tracts of the coast including dunes areas are contained in a Site of Community Importance (IT3250003 "Penisola del Cavallino: biotope litoranei").

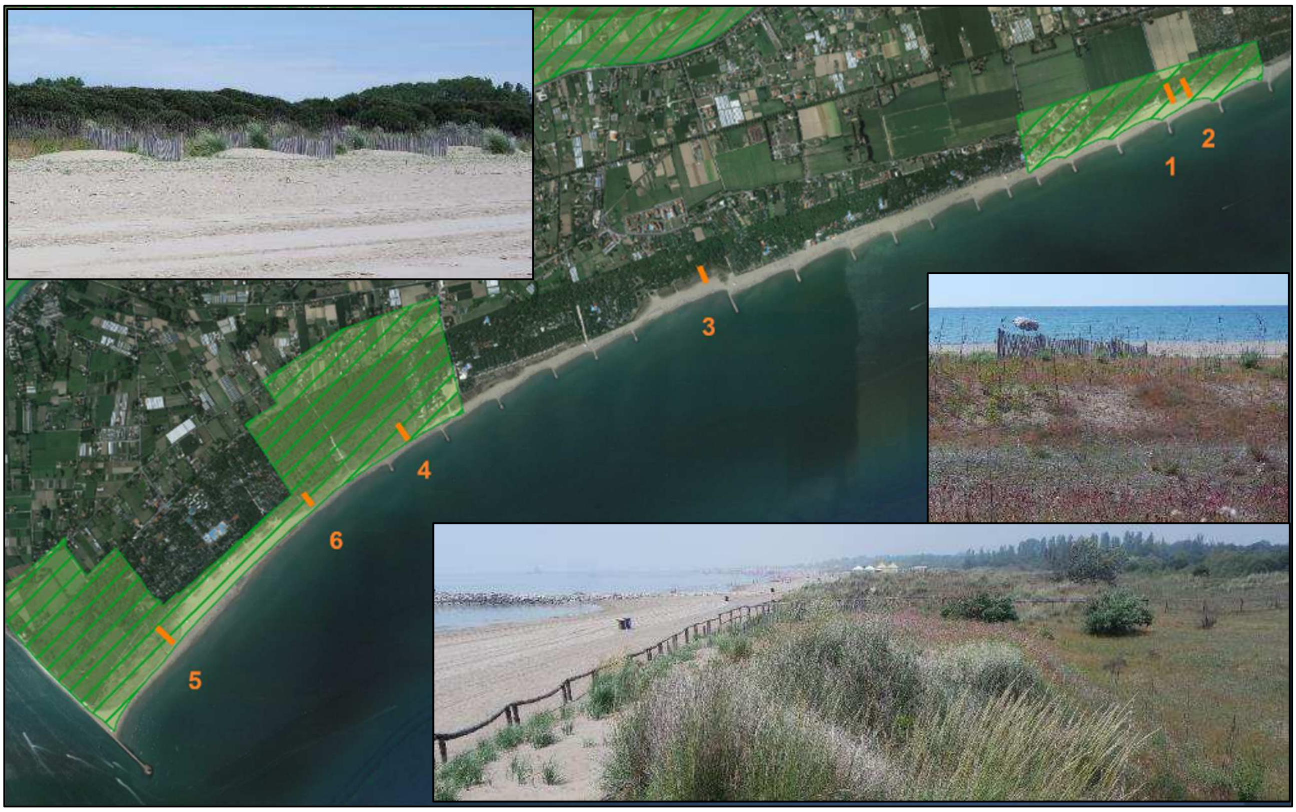


Fig. 7 – Cavallino-Treporti (Green simple fill area: Site of Community Importance; green line pattern fill: Special Protection Area).

2.2.5 Mort Lagoon

Transect 11 and 12 (Fig. 8) are located on the beach in front of the Mort Lagoon. The coastline is in a ENE-WSW direction. This small lagoon originated around 1935, when the Piave River broke his bank. In the past, the lower Piave river course flowed eastward, parallel to the coastline, for a short tract. Between 1892 and 1937, the split representing the right river bank, elongated up to about 130 m thanks to the Piave river sediment supply. In 1935, the strength of the flood broke the right bank where it bent, changing the river mouth location. The abandoned branch of the river was isolated from the new riverbed by debris deposition, but it was still communicating with the sea through the old river mouth, becoming a lagoon (Zunica, 1971). After 1935, the beach section in front of the Mort Lagoon did not received the sediment supply from the river mouth anymore (because of the counterclockwise circulation) and so it was subjected to erosion (110 m between 1937 and 1961) (Zunica, 1971). Between 1954 and 1969, the area located close to the river mouth accreted, while the zone near the inlet eroded, as a result of the works realized to create a small harbour, which diminished the lagoon extension and moved the inlet into an artificial channel. Recently, the coastline has not changed significantly because from 1969 longitudinal and parallel coastal defences were placed. There is a continuous series of rock groynes linked by breakwaters from the river mouth to the inlet. From about 1 km far from the river mouth to the inlet, on the landward side of the breakwaters there is a concrete revetment made of three wide concrete steps ending in a concrete seawall. Nevertheless, this beach section is still subjected to erosion as the excavation at the breakwaters base and seawater infiltrations demonstrate. As the beach is not easily reachable, because it is necessary to turn around the lagoon, it is rarely subjected to any kind of beach management, nevertheless it is subjected to a certain peculiar touristic pressure as it is frequented by many visitors that appreciate its wild aspect. The Mort Lagoon area is included in a Site of Community Importance (IT3250013 "Laguna del Mort e pinete di Eraclea").

Fig. 8 – Mort Lagoon (Green simple fill area: Site of Community Importance).

3 COASTAL SAND DUNES: FORMATION AND MORPHOLOGY

Coastal sand dunes are sedimentary deposits formed by the transport of sediments inland from the beach by wind action. They usually characterize sandy beaches mainly located at mid- and low latitudes (Davidson-Arnot, 2010). The heigth of the aeolian sand deposits ranges from less than 1 m to 100 m and more (Davidson-Arnot, 2010).

Wind can mobilize sediment particles when the forces acting on an individual grain overcome the gravitational and frictional forces holding the grain in place, which depends on grain size. In most cases, sand transport takes place only with wind speeds over 6 m/s (Davidson-Arnot, 2010).

Eolian sediment transport can occur as suspension, saltation and by rolling or sliding along the surface.

The possibility of sand transport by wind is also influenced by the presence of a coating of fine sediments and/or organic material; the effects of binding salts and the presence of moisture in the sand produce cohesion between grains or cover a portion of the surface, preventing sediment movement (Davidson-Arnot, 2010). Silt and clay size particles are generally carried high into the air and can be maintained in suspension and transported over long distances (Fig. 9). Fine to medium sand can be launched into suspension off sand ramps but they can not be maintained in the air for very long periods (Davidson-Arnot, 2010).

Most sand transport (75% as estimated by Bagnold, 1941) occurs in saltation: in high-energy saltation, grains are launched to various heights, from a few centimetres to 0.5 m or more, and travel downwind over distances ranging from a few centimetres to several metres; on the contrary, low-energy saltation (also known as reptation) makes fine-to-coarse sand being ejected a few cm into the air stream and travelling only a few cm, not always downwind (Davidson-Arnot, 2010). Reptation results primarily from the impact of high-energy saltating grains with the bed (Davidson-Arnot, 2010).

Fine sand to granule-sized particles can also be moved through rolling or sliding along the bed, usually after the impact of saltating grains. Particles > 1mm are generally left on the beach but gravel and pebbles can sometimes be found on coastal dunes brought by swash action during storms (Davidson-Arnot, 2010).

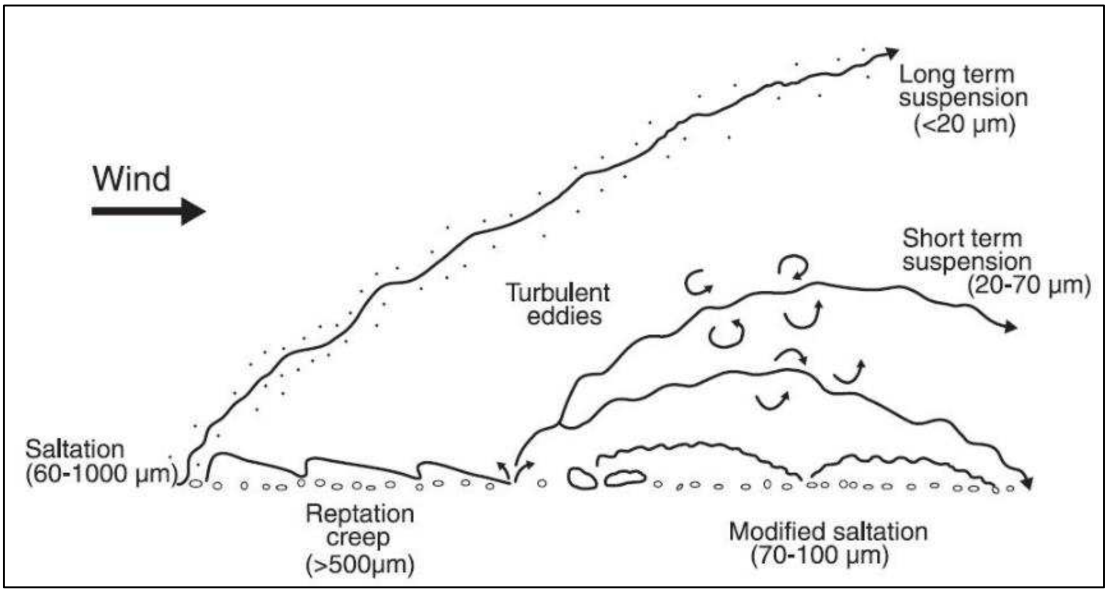


Fig. 9 - Modes of aeolian sediment transport (Davidson-Arnot, 2010).

Sediment particles are deposited when wind speed decreases, either because of changes within the wind flow itself or because of interaction of the wind with the beach and dune topography, obstacles or presence of vegetation affecting the wind flow. On bare surfaces the sand is readily mobilised again, but in the lee of objects the sand may be sheltered, e.g. within vegetation, inducing accretion (Davidson-Arnot, 2010). As a consequence, vegetation has a fundamental role in dunes formation and development. On one hand it promotes sand trapping and accumulation affecting the wind flow and the sand transport, on the other hand it stabilezes the sediment accumulated with its below-ground systems (e.g. roots and rhyzomes) (Audisio, 2002).

The effectiveness of vegetation in reducing transport is primarily controlled by the percent cover but also plant height, form and flexibility, and spatial pattern of bare surfaces affect it. Field studies show that when vegetation cover is 20-25% the sand transport rate is reduced to negligible amounts compared to a bare surface (Davidson-Arnot, 2010).

Dunes size and morphology are also controlled by sediment supply, dominant wind velocity and direction, and geomorphology of the nearshore and beach face (Sloss et al., 2012), such as beach width and beach-surf zone type. All other factors being equal, larger dunes occur on dissipative and wider beaches (Hesp, 2002; Davidson-Arnot, 2010; Sloss et al., 2012). Dissipative beaches, like North Adriatic beaches, have a flat shallow profile, relatively large subacqueous sand storage and a high potential for aeolian sediment transport; on these beaches most wave energy is expended through the process of breaking (Davidson-Arnot, 2010). Reflective steep beaches, where most wave energy is reflected by the nearshore morphology, are characterised by low potential sedimemt transport (Davidson-Arnot, 2010).

Different factors affecting dunes formation lead to the development of a variety of dune morphologies: there are diverse ways to classify sand dunes.

A general classification between primary and secondary dunes can be made. Dune systems with sand supplied directly from the beach and with form and orientation reflecting the beach dynamics (Davidson-Arnot, 2010; Sloss et al., 2012) are defined primary dunes. Secondary dunes develop from the modification of primary dunes (Sloss et al., 2012).
Primary dunes are often identified with the foredune system, consisting of a foredune and the associated embryo dunes (also termed as incipient foredune) that may form at the toe of the seaward slope of the foredune ridge or on the backshore separated from the foredune ridge (Davidson-Arnot, 2010). Foredune can be defined as a generally continuous established, shore-parallel, convex, symmetrical to asymmetrical dune ridge, which originates at the rear of the backshore environments (landward of the active beach) (Sloss et al., 2012).
Shoreline parallel orientation of foredune ridges derives from the role of plants in trapping the sediment and the seaward edge of the vegetation, trimmed - for example - by wave action (Davidson-Arnot, 2010). In fact, the influence of the sea leads to a strong sea-inland environmental gradient which determines a compressed shore-parallel vegetation zonation (Prisco et al., 2012). On the strand, where conditions are too severe, no vascular plants are able to grow; first pioneer plants begin to colonize the ground starting from about 50 m from the shoreline (Audisio, 2002).

Then a distinction can be made between active dunes, where vegetation is limited or absent and the sediment is still mobilized by wind action, and inactive dunes, i.e. impeded dunes fixed in place by vegetation (Davidson-Arnot, 2010; Tsoar, 2001). In practice, there is a continuum of coastal dune forms from completely unstabilised forms, through forms with varying degrees of vegetation cover and stabilisation, to those that are continuously covered by vegetation, both temporally and spatially (Davidson-Arnot, 2010). An increasing degree of stabilizazion can be observed, from incipient or embryo dunes to established dunes and relict dunes (Sloss et al., 2012). The first ones range between a few centimetres and 1 or 2 m in height and 10-20 m in width, while the others usually range between 5 and 20 m (but also less or more) in height and 30-50 m in width (Davidson-Arnot, 2010).

Wind ripples are the smallest aeolian bedforms and the first features that can be found on the bare beach. They are regular, wave-like undulations lying at right-angles to the prevailing wind direction. The size of ripples increases with increasing particle size, but they typically range from about 10 to 300 mm high and are typically spaced a few centimetres to tens of metres apart. Wind ripples, initiated by an irregularity in the bed that perturbs the population of reptating grains, develop in minutes to hours and quickly change if wind direction or wind speed alter (Huggett, 2007).

Incipient foredunes or embryo dunes usually form owing to sand deposition within clumps of vegetation of pioneer plant communities, or driftwood, flotsam, etc. (Hesp, 2002). The reduction in wind flow speed within and in the lee side of individual plants leads to sand deposition and accumulation (Fig. 10) (Davidson-Arnot, 2010). High dense canopies, such as *Ammophila* sp., reduce air flow velocities very rapidly thereby significantly reducing the sand transport from the leading edge. The greater deposition at the leading edge produces asymmetric forms with the short slope seawards. Lower plant canopies reduce airflow and transport more slowly, so that there is a gradual downwind reduction in transport (Hesp, 2002).

Features shaped as isolated mounds of various height are called shrub-coppice dunes or hummocks (Tsoar, 2001). They are considered to be static bedforms that change in shape as the vegetation changes with time (Tsoar, 2001).

Shrub-coppice dunes are irregular or approximately elliptical in shape and streamlined in the downwind direction; this structure results from the accumulation of sand around a clump of vegetation and downwind of it (Allaby, 2008).

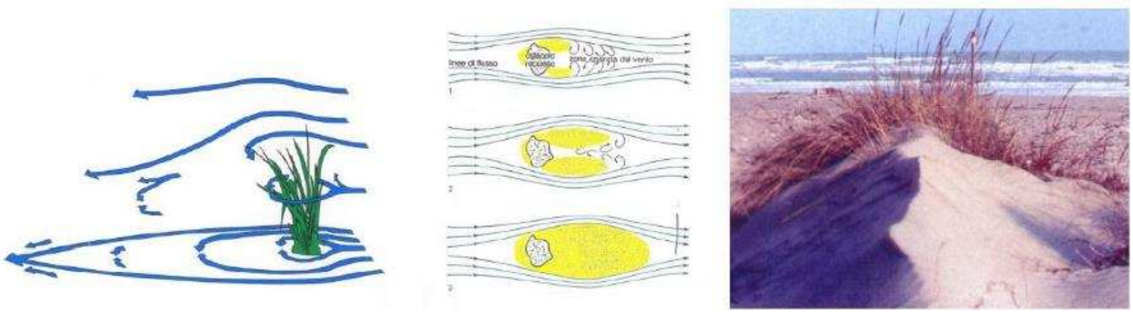


Fig. 10 - Air flow modification and sand accumulition within clumps of vegetation (Brunelli, 2010).

Pyramidal-shaped forms are called shadow dunes. They typically display a triangular ground plan with the short side parallel to the wind direction. In the vertical plane, a ridge tapers from high point at the rear of the plant (upwind) to a zero height downwind of the plant along the triangular base (Hesp, 1981). Shadow dune height and length are mainly determined by roughness element width (Hesp, 1981).

In prograding beaches, the embryo dunes grow over time and can form a ridge developing in a new foredune. During its development, the morphology of the foredune changes from sparsely vegetated hummocky foredunes, which are discontinuous alongshore and display concave vegetated stoss faces adjacent to hollows or depressions, to uniform and continuous alongshore foredunes (Fig. 11) (Hesp, 1988).

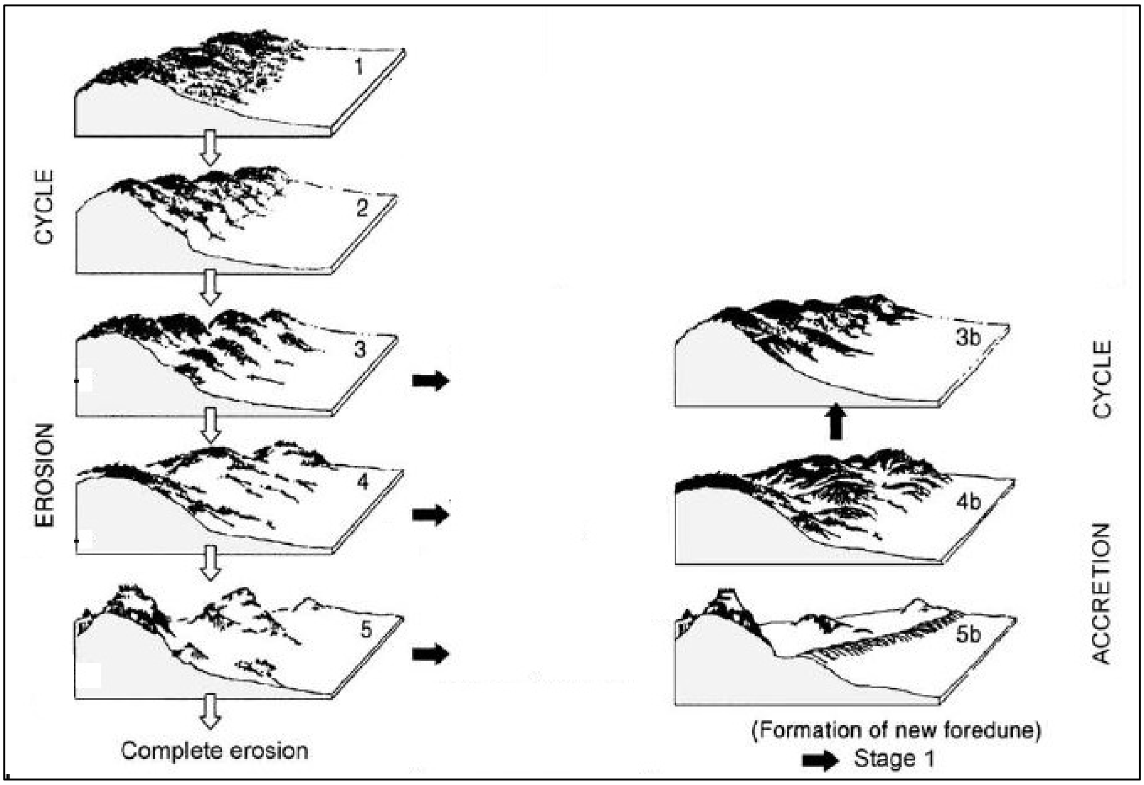


Fig. 11 - A model of foredune morphology, dynamics and evolutionary trends. A foredune may develop towards and remain in a particular morpho-ecological stage or it may evolve to another stage over time through erosion or accretion cycles (from Hesp, 2002).

The formation of a new ridge cuts off the sediment supply to the older dune landward (Davidson-Arnot, 2010). Consequently, better conditions for plants occur and vegetation cover can progressively increase, stabilizing the dune ridge. So, vegetation play a foundamental role in maintaining dune system integrity.

The seaward accretion of a foredune generally create swales, i.e. lee dune depressions, which develop as low to limited aeolian deposition zone (Hesp, 2002).

On stable or eroding shoreline the embryo dunes are usually ephemeral features developing and disappearing alternatively (Davidson-Arnot, 2010).

Particularly important in determining foredune height is the length of time a foredune remains adiacent to the beach, which represents its sediment supplier (Sloss et al., 2012). Rapid progradating beaches have usually lower foredunes.

From a morphological point of view, many other forms can be distinguished. Main groups (Fig. 12) are barchans, i.e. crescent-shaped dunes with wings pointing downwind (Sloss et al., 2012) formed by unidirectional winds, linear elongated dunes formed under bidirectional wind regimes (Tsoar, 2001), star dunes, features with sinous arms radiating from a central, pyramed-shaped peak, formed by a wind regime with high directional variability, and parabolic dunes (Hesp, 2002), a U-shaped dune with the arms pointing upwind (Tsoar, 2001).

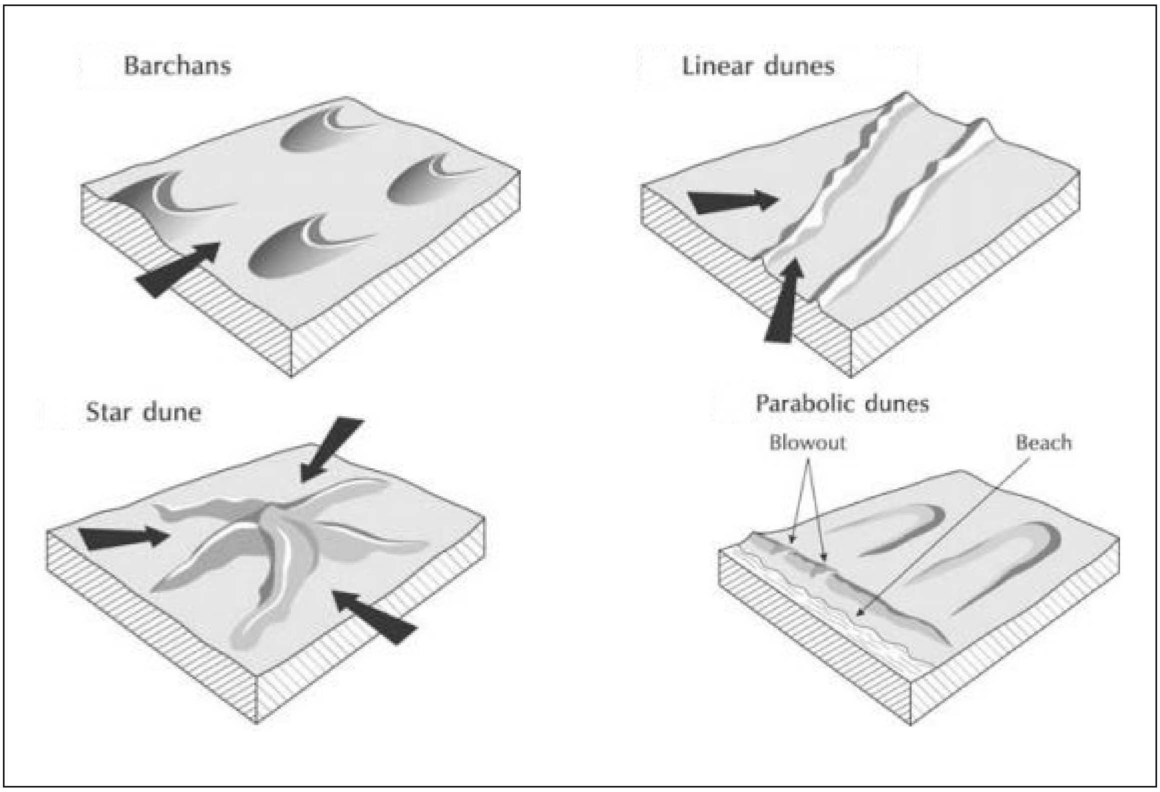


Fig. 12 – Main types of dune morphologies (from Huggett, 2007).

Two or more dunes of the same type can coalesce forming compound dunes, while coalesced dunes of different types form complex dunes (Tsoar, 2001).

Changes can also occur to primary features. For example, disturbance of the vegetation can result in the development of secondary forms, such as blowouts, parabolic dunes and transgressive dunefields (Davidson-Arnot, 2010).

Vegetation disturbance may be initiated by natural processes, such as storm wave erosion, topographic acceleration of airflow over the dune crest, burial of plants by excessive sand deposition, drought, trampling or overgrazing by animals, but often also by human activities, such as pedestrian trampling and track creation, housing and resort development, sand extraction and offroad vehicle activity (Hesp, 2002). Disturbance on stabilized dunes is often responsible for the formation of bare sand patches, where wind can blow the sediments away, giving origin to depressions called blowouts (Fig. 13).

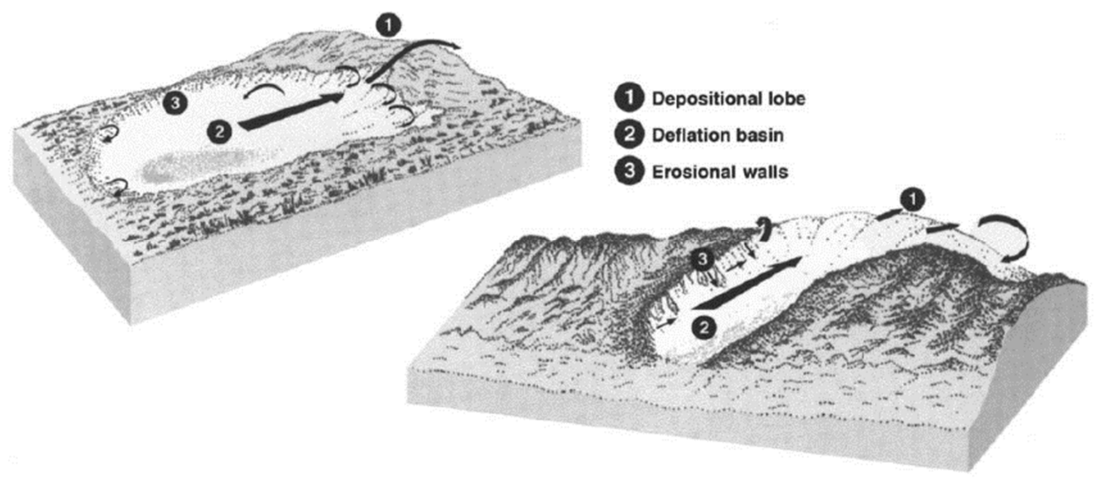


Fig- 13 – Schematic diagrams of a saucer and a trough blowout with typical wind flow patterns indicated (Hesp, 2002).

Once developed, blowouts affect the air flow. The so formed new topographic setting accelerates the wind flow enlarging the depression (deflation basin). Consequently, the sides slump and the sand from the deflation basin is blown out over the depositional lobe (Davidson-Arnot, 2010). This process enhances the deeping and the elongation of the blowout (Davidson-Arnot, 2010).

Blowout morphology may be variable and three main types can be distinguished. Saucer blowouts are semicircular or saucer-shaped and often appear as shallow dishes (Hesp, 2002). Cup-shaped blowouts are deeper, while trough blowout are generally more elongated, with deeper deflation floors and basins and steeper longer erosional lateral walls or slopes (Hesp, 2002).

Blowouts in vegetated dunes may stabilise over time when conditions change, erosion decreases and vegetation becomes established. This can occur when the deflation basin intersects a moist sand layer or the groundwater table (Davidson-Arnot, 2010).

Blowouts can also evolve into a parabolic dune (Fig. 12) (Hesp, 2002). Parabolic dunes may be initiated in the foredune system and migrate landward into older deposits or may be initiated in the dunefield itself (Davidson-Arnot, 2010). As blowouts, they may be stabilized by vegetation (Tsoar, 2001).

If high rates of erosion or strong onshore winds occur, a very active inland transfer of sand may take place leading to dunfields, i.e. successions of overlapping aeolian deposits with sediments from the older episodes being buried beneath younger deposits (Davidson-Arnot, 2010).

Coastal dunes play an important role in the mitigation of coastal hazards. They provide natural protection from coastal erosion and flooding and have a central role in preservation of natural character, coastal biodiversity and habitat, and in landscape protection (Dahm et al., 2005). Coastal dunes also play a critical role in beach dynamics: they erode during beach erosional phases and repair or form during accretionary periods. However, in the recent decades, human activities strongly affected costal dunes. Increasing population pressure, combined with the desirability of shoreline for human investment, habitation and use, generate consistent transformations in coastal ecosystems. A large part of the dune systems were demolished to provide space for development of settlements, infrastructure and touristic facilities for urbanization and mass-tourism (Cencini et al., 1988; Del Vecchio et al., 2015).
Together with beach management and touristic activities (e.g. mechanical ranking, trampling), this leads to changes in dune morphology, vegetation and natural coastal processes, resulting in dune system degradation and desappearance, increases the exposure to coastal hazards.

4 COASTAL DUNES VEGETATION AND NORTH ADRIATIC LITTORAL HABITATS

Beach and coastal dune ecosystems are characterized by peculiar environmental conditions and microclimate (Audisio, 2002) which lead to a peculiar vegetation with plants reflecting the environmental features (Chapman, 1976). The influence of the sea leads to a strong sea-inland environmental gradient which determines a compressed sea-inland vegetation zonation defined by the sequence of different plant communities occurring with increasing distance landward (Prisco et al., 2012). The environmental gradient generally consists in a decrease of the stress and disturbance which characterize the coastal dune ecosystem moving inland: salt spray, sand burial, swash inundation, dryness, high light intensity, wind exposure, soil salinity and nutrient deficiency (Hesp, 1991). Many plants respond to these environmental features with different adaptation such as salt resistance or salt preferring, node, root, shoot and rhizome development, flooding resistance, leaves adaptation such as leaf hairiness, succulence, epicuticular wax layer, sclerophylly, root adaptations, variation of life cycle and flowering time etc. (Hesp, 1991). Consequently, each zone in the vegetation sequence has a different species composition that is related to the ability of the plant species to withstand environmental factors prevailing in that zone. Therefore, plant species richness typically increases following the sea-inland gradient (Buffa et al., 2012).

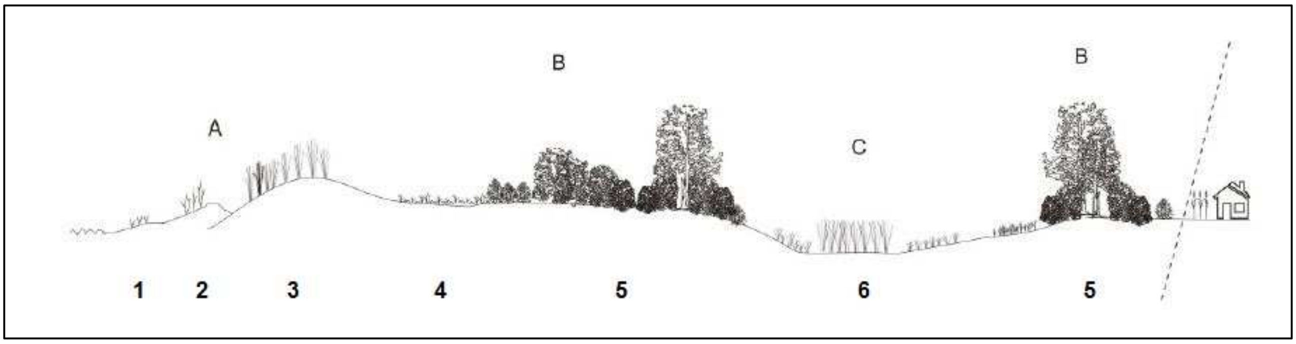


Fig. 14 – Example of vegetation zonation along the N-Adriatic coast. A = beach and mobile dunes; B= edapho-xerophilous series; C = edapho-higrophilous series. 1= habitat 1210; 2= habitat 2110; 3= habitat 2120; 4= habitats 2230 and 2130; 5= shrubs and forest; 6= hygrophilous species of dune slacks (from Buffa et al., 2012).

In order to describe the vegetation types which can be found on the North Adriatic coast, the European Union habitats classification of the Annex I of the Habitat Directive was used (European Commission, 1992). The Directive defines natural habitat types as terrestrial or aquatic areas distinguished by geographic, abiotic and biotic features, whether entirely natural or semi-natural;

their description is often mainly linked to the vegetation which characterizes their structure (Angelini et al., 2016). On the strand where conditions are too severe because of flooding, salinity, wind, heat and dryness, no vascular plants are able to grow: this is called the aphytic zone. Starting from about 50 m from the shoreline, first pioneer plants begin to colonise the ground. Due to the stressing condition, only a few species survive in these zone. They have usually brief life cycles with a growing period of one or two months between autumn and the end of winter, while during summer, the most stressing period, their quiescent seeds stay in the sand. Vegetation cover is still low and discontinuous (usually < 5 %) (Audisio, 2002). The 1210 habitat type "Annual vegetation of drift lines" is usually the first plant community found on the beach. It is characterized by annual alo-nitrophilous terophitic and specialised plants such as *Cakile maritima, Salsola kali, Xanthium italicum* (AA.VV., 2006). Moving landward, perennial grasses such as *Elymus farctus* subsp. *farctus (=Elytrigia juncea=Agropyron junceum)* and *Ammophila arenaria* settle (Audisio, 2002). They benefit from the first small and often ephemeral dune features distancing their roots from the brackish watertable (Audisio, 2002). *Elymus farctus* dominates the habitat type 2110 "Embryonic shifting dunes", characterized by psammophilous perennial plants (geophytes and hemicryptophytes) that give rise to the formation of the first sandy drift, called "embryo dune" (Biondi & Blasi, 2009). The embryo dunes are then colonized by *Ammophila arenaria* which characterize the habitat type 2120 "Shifting dunes along the shoreline with *Ammophila arenaria* (white dunes)". These grasses are very competitive on the active dunes because they react positively to sand burial and may lose their strength when lacking it (Hesp, 1991). Thanks to their dense clumps, fibrous rhizome system and the perennial life cycle, they are considered responsible for building and stabilising the foredune by capturing and binding sand (Audisio, 2002). This habitat represents a semi-permanent stage and the vegetation cover could reach 50-70% of the total. Beach and dune erosion may promote the introduction in the mobile dune habitats of exotic species such as *Oenothera* sp., *Cenchrus incertus*, *Ambrosia* sp., and *Spartina juncea.* The latter competes with *Ammophila* where sand supply and consequently dune height don't provide enough distance from the brackish watertable (AA.VV., 2006). Mobile dune features establish the first obstacle to wind and sea influences providing a protection service to the inland habitats. On the landward side of the active dunes stress diminishes: wind strength, sand transport and salt spray are reduced by the increasing distance from the sea and by the active dunes reliefs; salty groundwater becomes less influent, sand nutrients content increases (also thanks to mobile dune plants decay), soil is developing, dune features are stabilized and their forms are smoothed. In this zone other plants can settle and survive (Audisio, 2002).

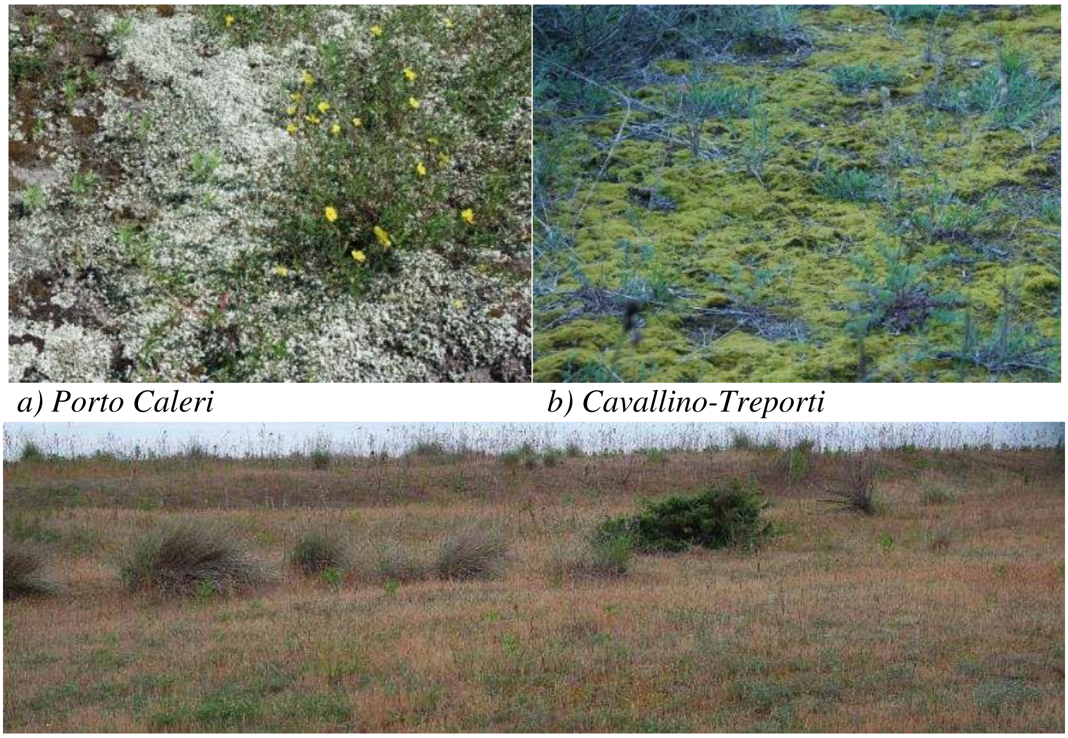
Between the leeslope of active dunes and the fixed dune zone, on the transition or semi-fixed dune area, different herbaceous communities settle. On the leeslope of active dunes is commonly situated the 2230 habitat type "*Malcolmietalia* dune grasslands" characterized by therofitic vegetation with many small annuals and often abundant ephemeral spring bloom (Houston, 2008). On North Adriatic coasts the transition zone is characterized by the 2130* habitat type "Fixed coastal dunes with herbaceous vegetation (grey dunes)" constituted by perennial xerophylous herbs, dwarf shrubs, and moss and lichens ground cover (Houston, 2008). Geophites and hygrophilous species are often found in dune slacks where their roots reach the watertable. Where the groundwater is still salty, salt-tolerant or salt-preferring species are found. Landward, on the inner, more stable and protected dunes, more mature soils evolve and consequently more structured forms of vegetation develop, from medium and high shrubs to the forest (Audisio, 2002). Shrub vegetation is often constituted principally by *Juniperus communis* (habitat type 2150*) which can be found alternatively in dense scrubs and clearing with 2130 communities. The coastal zonation final stage in North Adriatic dune systems is represented by the *Quercus ilex* wood (*9340* "*Quercus ilex* and *Quercus rotundifolia* forests"), often substituted by or mixed with pine forests of anthropogenic origin (2270* "Wooded dunes with *Pinus pinea* and/or *Pinus pinaster)*. The changes between different vegetation zones can be gradual, but the significant variations in exposure and shelter associated with dune landforms can cause even abrupt changes.

4.1 2130* HABITAT TYPE

Habitat type 2130* "Fixed coastal dunes with herbaceous vegetation (grey dunes)" is characterized by inland stable dune formations sheltered from physical stresses. Fixed and semi-fixed dunes occupy the zone between the mobile dunes and the dune scrub and woodland habitats. They are colonised by more or less closed perennial grasslands (dominated by hemicryptophytes and chamaephytes) associated with abundant carpets of lichens and mosses (*Syntrichia ruralis, Cladonia convoluta, Cladonia rangiformis*) (Prisco et al 2012).

The habitat is principally found along the Atlantic coasts from the Straits of Gibraltar to the North Sea coasts and the Baltic Sea. In Italy this habitat has been detected only along the North Adriatic coast (Prisco et al. 2012), which is included in the temperate region (Sburlino et al., 2013). This plant community is peculiar due to the presence of species of different origins such as montane species, eastern species and Mediterranean species (Sburlino et al., 2013). In this particular area, in fact, climatic changes, occurred especially between the third and the first millennium BC, led to important floristic migrations. Furthermore, 2130* habitat type was designated as "priority habitat" by the Habitat Directive (92/43/EEC Directive), according to which priority habitats are those habitats which require conservation actions because of their decline, rarity and importance. Its conservation status, evaluated, according to the Habitats Directive, by combining assessments of range, area, structure & function and future prospects, is unfavourable bad (U2, in the Italian continental biogeographic region) (Angelini et al., 2015).

On the North Adriatic coast, the habitat type 2130* is mainly determined by a thick carpet of moss (most likely *Syntrichia ruralis)* and, sometimes, of lichens (*Cladonia* sp.pl.) among which hemicryptophytes, therophytes and chamaephytes occur (Sburlino et al., 2013) (Fig. 15). The biological spectrum, calculated on 39 relevés in Sburlino et al. (2013) leaving out mosses, includes 47% of chamaephytes, 26.5% of hemicryptophytes, 14.8% of therophytes, 11.3% of geophytes and 0.4% of phanerophytes. *Lagurus ovatus*, *Cerastium semidecandrum, Phleum arenarium, Vulpia fasciculata, Silene conica* and *Medicago minima* are indicated as frequent therophytes, *Poa bulbosa, Sanguisorba minor, Silene vulgaris, Oenothera stucchii* and *Petrorhagia saxifrage* as frequent hemicryptophytes. *Carex liparocarpos* was found to be the most frequent between geophytes (Sburlino et al., 2013). Camaephytes such as *Fumana procumbens, Teucrium polium* ssp. *capitatum, Helianthemum nummularium* ssp. *obscurum*, are particularly frequent in the most evolved aspect of the community, often associated to more developed and richer in organic matter soils. Nevertheless, also a chamaephytes-poor aspect of the community was observed (Sburlino et al., 2013).



a) Porto Caleri *b) Cavallino-Treporti*

c) Cavallino-Treporti

Fig. 15 – Three examples of 2130 community found during the sampling.

Cerastium semidecandrum, Silene conica, Cladonia spp.*, Phleum arenarium, Silene otites, Syntrichia* spp. are considered diagnostic species. *Avellinia michelii, Medicago minima, Phleum arenarium, Plantago indica, Vulpia fasciculata, Carex liparocarpos, Fumana procumbens, Scabiosa argentea, Pleurochaete squarrosa, Petrorhagia saxifraga, Poa bulbosa, Sanguisorba minor, Stachys recta, Teucrium polium, Trachomitum venetum* are considered characteristic species. (Acosta & Ercole, 2015)

A 2130 destructuration may lead to the development of the 2230 habitat type, characterized by annual short herbs and grasses, such as *Avellinia michelii, Vulpia fasciculata, Cerastium semidecandrum, Phleum arenarium, Silene conica*, together with some perennial species, such as *Carex liparocarpos, Poa bulbosa, Sanguisorba minor* ssp. *muricata, Cynodon dactylon*. The biological spectrum indicated (mosses excluded) for 2230 is the following: therophytes 75.9%; hemicryptophytes 16.9%; geophytes 5.8%; chamaephytes 1.4% (Sburlino et al., 2013).

Together with the rest of the dune system, semi-fixed and fixed dunes provide important ecological services, such as coastal protection from storm surges, salt-water intrusion prevention, recreational resources (Houston, 2008). Nevertheless, European fixed dunes have been and still are the most threatened and exploited part of the dune system (Houston, 2008). As European coasts, also the Venetian coast suffers from heavy human use; residential and touristic development destroyed many parts of the fixed and semi-fixed dune systems and increasing coastal erosion squeezes transition dune systems between advancing mobile dunes and dune scrub or anthropic areas (Nordstrom et al., 2009). Other threats deriving directly and indirectly from human activities have been and are tree plantation, invasion of exotic species, impact of recreation pressure (foot traffic, off-road driving), which lead to habitat degradation, fragmentation and loss (Houston, 2008). In particular moss and chamaephytic components are extremely vulnerable to trampling leading to a reduction in vegetation cover and consequently to habitat fragmentation. Alien species introduction leads to structural and functional modification. Furthermore, it is important to consider the effects of geomorphological alteration, since mobile dunes degradation exposes semi-fixed and fixed dune habitats to the stress factors coming from the sea, such as salt spray, sand burial, inundation (Angelini et al., 2016).

5 MATERIAL AND METHODS

To acquire information about plant communities' composition and location on dune systems and about their relationship with geomorphology, we conducted a field survey using the transect approach (Paddy & Kent, 1992). The transect is an imaginary line along which samples are taken. This method is usually employed in areas where there are marked spatial environmental gradients and rapid changes in vegetation, with the aim of covering the full variability of vegetation and its relationships with environmental changes.

5.1 GEOMORPHOLOGICAL DATA

5.1.1 Data collection

Geomorphological data were in part collected during the field surveys and in part acquired through aerial photograph interpretation.

The geomorphological characteristics of the study sites were observed in detail on the field. Some morphometric measurements were also taken in order to reconstruct the beach profiles in close proximity to the transects location and to estimate the dune heights. Measurements were made by means of a measuring tape, a folding ruler and a GPS unit (*Garmin GPSmap 62s*).

Through the interpretation of the most recent available aerial photographs (Google, year 2015), performed using the ArcGIS software 10.2.2, some geomorphological maps were created. The aerial photographs were georeferenced using the digital regional technical maps available in vector format and produced in the Monte Mario/Italy zone 1 (EPSG:3003) coordinate system. Then, the areas that had to be investigated were defined: each map represents a zone more than 100 m wide that includes one transect and the most significant features necessary to define the local geomorphological context. Within each map, areas characterized by different landforms and by other elements useful to better define the local geomorphological setting and modifications were distinguished and highlighted. The features were drawn using polygons and lines. Dunes morphology was often identifiable from aerial photographs. In fact, on the photos active dunes generally appeared as very light-toned patches often arranged in elongate, lobate, or curvilinear patterns (Marrs & Kolm, 1982) and their shape was readily identifiable from the shade produced. Stabilized dunes were more difficult to identify and interpret from aerial imagery; in this case, the vegetation pattern was mainly useful to recognize their morphological arrangement. The results obtained from the aerial photograph interpretations were often validated by field survey observations.

First, a general distinction between active and inactive dune areas was done using three different polygons:

- inactive dune area, including impeded dunes fixed in place by vegetation;
- active dune area, including free dunes characterized by moving wind–blown sand where vegetation is limited or absent;
- ripple area, on the aphytic zone, characterized by ephemeral ripples' presence.

The degree of stabilization was mostly deduced from the vegetation cover observed on the aerial photographs, since sand stabilization increases with vegetation density.

Other polygons were used for a more in-depth description.

Subareas within the inactive dune area:

- Woodland area, including zones covered by coastal forest or patches of brush of notable dimensions.
- Cleared forest.
- Inactive hummock dune area, characterized by various stabilized hummock dunes, which can be more or less pronounced, denser or sparser, smaller or larger.
- Inactive hummock foredune area, including stabilized dune ridges displaying a hummock morphology on the top.
- Inactive foredune area, including stabilized continuous shore-parallel dune ridges, lacking the hummock morphology on the top.
- Ridge of anthropogenic origin, originated from to the accumulation of sediments close to anthropogenic structures and man-made ridges, which often show an unnatural orientation.

Subareas within the active dune area:

- Active hummock dune area, mainly characterized by small active hummock dunes with clumps of vegetation on their top.
- Active foredune.
- Active hummock foredune area, including active shore-parallel dune ridges displaying a hummock morphology on the top.
- Active large shrub coppice dune area, characterized by 6-7 m long and wide shrub coppice dunes.

- Active medium shrub coppice dune, characterized by 3-4 m wide and 2-3 m long shrub coppice dunes.
- Active scattered small shrub coppice dune area, characterized by 1-1.5 m wide and 1-2 m long sparse shrub coppice dunes.
- Embryo dune area, characterized by the presence of embryo dunes often not higher of some tens of centimetres and colonized by some clumps of pioneer plants.

Orientation and direction of features, if distinguishable, were marked using lines:

- Dune direction
- Dune alignment
- Artificial ridge direction
- Ephemeral ripple crests

Other natural and anthropogenic elements were indicated using lines:

- Shoreline
- Trails
- Roads
- Fencing
- Windbreak
- Groynes
- Breakwater
- Old revetment

Also, anthropized areas were indicated with different polygons:

- Campsite area
- Anthropogenic sediment removal, including bare areas interested by anthropogenic sand removal.

5.1.2 Data analysis

Geomorphological data were then used for a descriptive purpose and in order to calculate some geomorphological variables to be related to the vegetation data (see paragraph 5.3).

5.2 VEGETATION DATA

5.2.1 Data collection

Samples of vegetation were collected along twelve transects which were located in different sites, chosen in a preliminary plan. Transects were all laid down perpendicularly to the coastline in order to highlight the sea-inland gradient. The exact location of the transects within each site was established on the field according to a preferential method so as to represent the main features of the area in terms of both vegetation and morphology. Each transect started on semi-fixed dunes, where 2130 habitat type was found, and ended on the limit of the aphytic area. Consequently, their length was variable and dependent on the beach profile. Sample plots were then laid down whenever a new plant community was found along the transect, at variable distances depending on changes in vegetation. Plot sites in the field were positioned in vegetation stands that were homogeneous in terms of structure, species composition, and environment, so as to minimize variation within the plot and maximize that between plots. Thus, the plots sequence represented the series of communities or different vegetation aspects found along the transect.

Data on plant communities were collected by using the relevé approach. This procedure, developed in the early 1900s by the Swiss biologist J. Braun-Blanquet, involves describing or characterizing recognizable units in the vegetation of a region by the description or characterization of the vegetation in a representative standard plot- the so called relevé. It is a statistical approach that aims at characterizing vegetation types by the combined information from many different plots. It has become the standard in vegetation science and is increasingly used as a practical, relatively fast mean of collecting information on vegetation (Almendinger, 1988).

Plots were uniform in shape (square) and size (2x2 m). Plot sizes smaller than 5 - 10 m^2 are often used in low vegetation stands or in vegetation types frequently developed in small patches of a few m^2 (Otypková & Chytry, 2006).

On each plot, on a standard relevé data form, several general assessments were made on abiotic features and on vegetation: relevé name, date, location, plot area, slope (%) and aspect (noting the cardinal point which the slope faced), geographic coordinates (registered using a GPS unit (*Garmin GPSmap 62s*), distance between each plot and the following and between the last seaward plot and the shoreline, total percentage vegetation cover and percentage cover of moss layer, average height of the herbs (cm), the supposed plant community. Then a list of all species present on each plot was noted and completed with visually estimated cover of each species using the Braun-Blanquet cover-abundance scale (Braun-Blanquet, 1928, 1964), where the range 0-100% is portioned into five classes. Cover is defined as the area of ground within the plot that is occupied by the above-ground parts of each species when viewed from above (Paddy & Kent, 1992).

Plants not readily identified to species level were collected for following identification.

The sampling was conducted between the end of May and the beginning of July in 2016 as it was the period of maximum expression for the semi-fixed and mobile dunes' plant communities.

Vegetation data were then organized in a matrix in which the columns are relevés and the rows are species (species x relevés matrix). The cells of the matrix contained the cover value for each species listed and for each relevé. A floristic matrix with 71 species x 63 relevés was obtained.

5.2.2 Data analysis

5.2.2.1 Plant communities' identification and description

A classification of the vegetation sampled was made based on the similarity in species composition and cover using the cluster analysis conducted on the floristic matrix. Cluster analysis is a method of classifying objects into groups; similar relevés were grouped in the same cluster and dissimilar relevés were grouped in different clusters. The result of the cluster analysis was plotted as a dendrogram. The distance measures represent the degree of similarity between relevés (Podani, 2005).

Then Raunkiaer's system was used to classify each species sampled in life forms. It is a classification of plants based on the position and degree of protection of renewing buds, which are responsible for the renewal of the plant's aerial body when the favorable season comes and represents plants adaptation to ecological condition (Batalha & Martins, 2004). The system was proposed by Raunkiaer (1934) at the beginning of 1900 as a tool to study the correlation between vegetation and climate (Smith, 2013). However nowadays life form study is an important part of vegetation description (Batalha & Martins, 2004) as it is the basis upon which the community structure is analysed (Gimingham, 1951), including spatial and temporal structure. The structure is regarded as the primary "morphological" features of a community (Gimingham, 1951). Life form distribution in a vegetation sample can be expressed by the "biological spectrum", calculated as the percent representation of the number of species belonging to each life-form (Smith, 2013). According to the life form system defined by Raunkiaer (1934), the dune system plants can be categorized into five major classes, arranged according to increased protection of the renewing buds and decreased stability in spatial and temporal occupation of the space: phanerophytes (large terrestrial plants, form stems, often with naked buds, projecting high into the air), chamaephytes (woody or herbaceous low-growing plants whose buds are on aerial branches not more than 25 cm above the soil), geophytes (which have perennating buds buried beneath the soil on rootstocks, corms, bulbs, tubers or rhizomes), hemicryptophytes (whose buds are at the surface of the soil) and therophytes (tipical of open community, they are often annual plants and survive the unfavourable season as seeds) (Packham & Willis, 1997).

In order to describe the peculiarity of each group of relevés determined by the cluster analysis on the dendrogram, the diagnostic species were also identified. Diagnostic species are the species whose relative constancy or abundance differentiate one vegetation type from another. For the groups pertaining to semi-fixed dune, the diagnostic species were obtained by means of a statistical analysis conducted using the software *JUICE (*Tichý, 2002*)* to identify constant and dominant species. As "constant species" of a group were considered those species which were present with a frequency higher than 30% in the group, while species with a cover percent higher than 30% in more than 30% of the relevés of the group were considered as "dominant species". Alien species were not included in the calculation as they were considered not typical of a habitat by definition.

The above-mentioned elements were useful also in determining the conservation status of the community. The conservation status can be evaluated on the base of the adherence to the community type described in literature in terms of species composition and on the base of the vegetation structure (i.e. life form composition and life cycle). In general, perennial species provide stable spatial and temporal occupation of the space, while stability decrease as a result of increasing annual species component. Exotic species abundance can also indicate community degradation. In fact, aliens and ruderal species are predicted to increase as a result of increasing human disturbance (Buffa et al., 2012), as they fill the gaps left by resident species becoming less adapted to new conditions generated by the alteration of natural disturbance or the introduction of new disturbances (Del Vecchio et al., 2015).

Exotic species were identified according to Celesti-Grapow et al. (2010) in order to evaluate their frequency and percentage cover in relevés as they are connected to habitat disturbance.

5.2.2.2 Active dunes' quality determination

Since one of the main purpose was to analyse the correlation between the active dune system's protection capacity and semi-fixed dune habitat quality, the state of active dune systems sampled was evaluated by considering the total percent vegetation cover measured on the habitat type 2120 (Shifting dunes along the shoreline with *Ammophila arenaria*), and calculating the percent cover of mobile dune diagnostic species and exotic species with respect to the total vegetation cover in the habitat type 2120. Furthermore, the height of the active foredune or of the seaward pronounced alignment of active dunes was estimated. Where pronounced active elevations were absent (Ca' Vio, Mort Lagoon), the height of the immediately following stabilized dune ridges was noted.

For groups of active dunes, diagnostic species were acquired from ISPRA (Istituto Superiore per la Protezione e la Ricerca Ambientale, the Italian National Institute for Environmental Protection and Research) manual on sandy coast environment (Acosta & Ercole, 2015) as they can be considered as reference values to evaluate the degree of adherence of the groups and the relevés to mobile dune habitats.

5.3 SEDIMENT DATA

5.3.1 Data collection

Grain size is the most fundamental property of sediment particles, affecting their entrainment, transport and deposition and therefore providing important clues to the sediment provenance, transport history and depositional conditions (Blott & Pye, 2001). In fact, grain size distribution is affected by several factors such as distance from the shoreline, distance from the source (river), source material, topography and transport mechanisms and it can in turn influence vegetation composition (Abuodha, 2003).

In order to define the granulometric characteristics of the present coastal deposits characterizing the study areas, sediment samples were collected along selected transects using a small shovel. Before sampling, the surface was cleared; then, the shovel was pushed into the soil down to a depth of 10-15 cm and lifted to get the sediments, which were stored in plastic bags. The weight of each sample was about 200 g. In the laboratory, sediments were dried and a sieve analysis was performed in order to assess the particle size distribution of each sample.

A nested column of sieves with decreasing openings from the top to the bottom, including pan and cover, was used. The stack of sieves was made of six sieves having the following opening sizes: 1 mm, 500 µm, 300 µm, 150 µm, 106 µm, 63 µm. The pan collected grains smaller than 63 µm, corresponding to the last sieving class (silt and clay).

A 60 g portion of each sample were weighted and poured into the top sieve. Then, the stack of sieves was put on the mechanical sieve shaker for 15 minutes. Later, the contents of all sieves and pan were separately weighted and recorded.

Sieves were then cleaned to avoid any contamination during the following sieve analysis.

5.3.2 Data analysis

The main parameters generally used to describe grain size distribution are the average size, the standard deviation (sorting) of the sizes around the average, the symmetry or preferential spread (skewness) to one side of the average, and the degree of concentration of the grains relative to the average (kurtosis). These parameters can be easily calculated by mathematical or graphic methods (Blott & Pye, 2001).

The data obtained by sieve analysis were processed using the free software GRADISTAT (Blott & Pye, 2001). It provided calculation of the above-mentioned parameters by the Folk & Ward (1957) method and by the method of moments (Krumbein & Pettijohn, 1938; Friedman and Johnson, 1982), using both the metric unit and the log-based Krumbein & Pettijohn (1938) phi (φ) scale ($\phi = -log_2 d$, where d is the diameter of the particle in mm) (Fig. 16).

(a) Arithmetic method of moments

Mean	Standard deviation	Skewness	Kurtosis
$\bar{x}_a = \frac{\Sigma f m_m}{100}$	$\sigma_a = \sqrt{\frac{\Sigma f (m_m - \bar{x}_a)^2}{100}}$	$Sk_a = \frac{\Sigma f (m_m - \bar{x}_a)^3}{100 \sigma_a{}^3}$	$K_a = \frac{\Sigma f (m_m - \bar{x}_a)^4}{100 \sigma_a{}^4}$

(b) Geometric method of moments

Mean	Standard deviation	Skewness	Kurtosis
$\bar{x}_g = \exp \frac{\Sigma f \ln m_m}{100}$	$\sigma_g = \exp \sqrt{\frac{\Sigma f (\ln m_m - \ln \bar{x}_g)^2}{100}}$	$Sk_g = \frac{\Sigma f (\ln m_m - \ln \bar{x}_g)^3}{100 \ln \sigma_g{}^3}$	$K_g = \frac{\Sigma f (\ln m_m - \ln \bar{x}_g)^4}{100 \ln \sigma_g{}^4}$

Sorting (σ_g)		Skewness (Sk_g)		Kurtosis (K_g)	
Very well sorted	<1·27	Very fine skewed	<⁻1·30	Very platykurtic	<1·70
Well sorted	1·27–1·41	Fine skewed	⁻1·30 to ⁻0·43	Platykurtic	1·70–2·55
Moderately well sorted	1·41–1·62	Symmetrical	⁻0·43 to ⁺0·43	Mesokurtic	2·55–3·70
Moderately sorted	1·62–2·00	Coarse skewed	⁺0·43 to ⁺1·30	Leptokurtic	3·70–7·40
Poorly sorted	2·00–4·00	Very coarse skewed	>⁺1·30	Very leptokurtic	>7·40
Very poorly sorted	4·00–16·00				
Extremely poorly sorted	>16·00				

(c) Logarithmic method of moments

Mean	Standard deviation	Skewness	Kurtosis
$\bar{x}_\phi = \frac{\Sigma f m_\phi}{100}$	$\sigma_\phi = \sqrt{\frac{\Sigma f (m_\phi - \bar{x}_\phi)^2}{100}}$	$Sk_\phi = \frac{\Sigma f (m_\phi - \bar{x}_\phi)^3}{100 {\sigma_\phi}^3}$	$K_\phi = \frac{\Sigma f (m_\phi - \bar{x}_\phi)^4}{100 \sigma_\phi^4}$

Sorting (σ_ϕ)		Skewness (Sk_ϕ)		Kurtosis (K_ϕ)	
Very well sorted	<0·35	Very fine skewed	>+1·30	Very platykurtic	<1·70
Well sorted	0·35–0·50	Fine skewed	+0·43 to +1·30	Platykurtic	1·70–2·55
Moderately well sorted	0·50–0·70	Symmetrical	−0·43 to +0·43	Mesokurtic	2·55–3·70
Moderately sorted	0·70–1·00	Coarse skewed	−0·43 to −1·30	Leptokurtic	3·70–7·40
Poorly sorted	1·00–2·00	Very coarse skewed	<−1·30	Very leptokurtic	>7·40
Very poorly sorted	2·00–4·00				
Extremely poorly sorted	>4·00				

(d) Logarithmic (original) Folk and Ward (1957) graphical measures

Mean	Standard deviation	Skewness	Kurtosis
$M_Z = \frac{\phi_{16} + \phi_{50} + \phi_{84}}{3}$	$\sigma_I = \frac{\phi_{84} - \phi_{16}}{4} + \frac{\phi_{95} - \phi_5}{6{\cdot}6}$	$Sk_I = \frac{\phi_{16} + \phi_{84} - 2\phi_{50}}{2(\phi_{84} - \phi_{16})} + \frac{\phi_5 + \phi_{95} - 2\phi_{50}}{2(\phi_{95} - \phi_5)}$	$K_G = \frac{\phi_{95} - \phi_5}{2{\cdot}44(\phi_{75} - \phi_{25})}$

Sorting (σ_1)		Skewness (Sk_1)		Kurtosis (K_G)	
Very well sorted	<0·35	Very fine skewed	+0·3 to +1·0	Very platykurtic	<0·67
Well sorted	0·35–0·50	Fine skewed	+0·1 to +0·3	Platykurtic	0·67–0·90
Moderately well sorted	0·50–0·70	Symmetrical	+0·1 to −0·1	Mesokurtic	0·90–1·11
Moderately sorted	0·70–1·00	Coarse skewed	−0·1 to −0·3	Leptokurtic	1·11–1·50
Poorly sorted	1·00–2·00	Very coarse skewed	−0·3 to −1·0	Very leptokurtic	1·50–3·00
Very poorly sorted	2·00–4·00			Extremely leptokurtic	>3·00
Extremely poorly sorted	>4·00				

(e) Geometric (modified) Folk and Ward (1957) graphical measures

Mean	Standard deviation
$M_G = \exp \frac{\ln P_{16} + \ln P_{50} + \ln P_{84}}{3}$	$\sigma_G = \exp\left(\frac{\ln P_{16} - \ln P_{84}}{4} + \frac{\ln P_5 - \ln P_{95}}{6{\cdot}6}\right)$
Skewness	**Kurtosis**
$Sk_G = \frac{\ln P_{16} + \ln P_{84} - 2(\ln P_{50})}{2(\ln P_{84} - \ln P_{16})} + \frac{\ln P_5 + \ln P_{95} - 2(\ln P_{50})}{2(\ln P_{25} - \ln P_5)}$	$K_G = \frac{\ln P_5 - \ln P_{95}}{2{\cdot}44(\ln P_{25} - \ln P_{75})}$

Sorting (σ_G)		Skewness (Sk_G)		Kurtosis (K_G)	
Very well sorted	<1·27	Very fine skewed	−0·3 to −1·0	Very platykurtic	<0·67
Well sorted	1·27–1·41	Fine skewed	−0·1 to −0·3	Platykurtic	0·67–0·90
Moderately well sorted	1·41–1·62	Symmetrical	−0·1 to +0·1	Mesokurtic	0·90–1·11
Moderately sorted	1·62–2·00	Coarse skewed	+0·1 to +0·3	Leptokurtic	1·11–1·50
Poorly sorted	2·00–4·00	Very coarse skewed	+0·3 to +1·0	Very leptokurtic	1·50–3·00
Very poorly sorted	4·00–16·00			Extremely leptokurtic	>3·00
Extremely poorly sorted	>16·00				

Fig. 16 – Formulae used in calculations of the granulometric parameters by the software GRADISTAT (Blott & Pye, 2001).

The statistical parameters were also related to descriptive terms (Fig. 17). Moreover, mode or modes and cumulative percentile values were calculated. The program also allowed displaying the samples grain size on gravel–sand–mud and sand–silt–clay triangular diagrams.

Grain size		GRADISTAT program	
phi	mm/µm		
−11	2048 mm		
		Very large	Boulders
−10	1024		
		Large	Boulders
−9	512		
		Medium	Boulders
−8	256		
		Small	Boulders
−7	128		
		Very small	Boulders
−6	64		
		Very coarse	Gravel
−5	32		
		Coarse	Gravel
−4	16		
		Medium	Gravel
−3	8		
		Fine	Gravel
−2	4		
		Very fine	Gravel
−1	2		
		Very coarse	Sand
0	1		
		Coarse	Sand
1	500 µm		
		Medium	Sand
2	250		
		Fine	Sand
3	125		
		Very fine	Sand
4	63		
		Very coarse	Silt
5	31		
		Coarse	Silt
6	16		
		Medium	Silt
7	8		
		Fine	Silt
8	4		
		Very fine	Silt
9	2		
		Clay	

Fig. 17 – Grain size scale adopted in the GRADISTAT program (from Blott & Pye, 2001).

In order to compare the results obtained from the analysis of each sample, a graph of all the grain size distributions was plotted.

5.4 ANALYSIS ON THE CORRELATION BETWEEN VEGETATION ASPECTS AND GEOMORPHOLOGICAL CHARACTERISTICS

To examine the relationships between the vegetation features found on the semi-fixed dunes and geomorphological characteristics of the beach system and of active dunes, a permutational multivariate analysis of variance (PERMANOVA) was used. The analysis was performed using the group number which the relevé belonged to, according to the cluster analysis, as grouping (independent) variable. Dependent variables were chosen among sedimentological, geomorphological and vegetation variables: mean particle size and sorting (phi) (Logarithmic (original) Folk and Ward (1957) graphical measures), height of the active fordune (m), distance from the shoreline (m), distance from the active foredune (m), number of dune ridges between the plot and the shoreline, width of the aphytic zone (m), width of the active dune area and of the inactive dune area, total percentage vegetation cover measured on the habitat type 2120 (Shifting dunes along the shoreline with *Ammophila arenaria*), and percentage cover of diagnostic species on the total vegetation cover in the habitat type 2120.

As post hoc test a Least Significant Difference (LSD) Fisher's test was chosen. Its aim is to identify whether there are significant differences among groups for the variables considered through the use of a pair-wise comparison of means.

6 RESULTS

6.1 GEOMORPHOLOGICAL DATA

Transect 1 and 2 – Ca' Ballarin (Cavallino-Treporti) (Appendix A)

Image date: 12th July 2015

General distinction:

- Inactive dune area (Woodland area, Inactive hummock dune area, Sediment removal area, Campsite area, Ridges of anthropogenic origin)
- Active dune area (Active hummock dune area, Embryo dune area)
- Ripple area (Ephemeral ripple crests)

The vegetation cover was generally low in the active dune area (about 30-40%), high in the inactive dune area (70-90%) and reached the 100% in the woodland area.

Main dune morphology: features of artificial origin.

Seven areas were distinguished:

- Woodland area: in the landward portion of the map there was a pine forest. The geomorphological features were not distinguishable under the dense vegetation of the forest; anyway, it was conceivable, on the base of the field observations, that this area was characterized by relict hummock dunes.
- Inactive hummock dune area: beside the forest there was an area characterized by small hummock dunes and inter dune zones. The vegetation, composed by herbs and bushes, was generally dense; however, some areas with sparse vegetation were present. This zone was crossed by several trails.
- Sediment removal area: located within the above-mentioned fixed dune area, characterized by a bare sand surface with excavation evidences observed during the field survey.
- Campsite area: it was enclosed by a fence (Fencing) and included the above-mentioned areas.
- Ridges of anthropogenic origin: this area was now characterized by various anthropogenic ridges. Some linear features (Artificial ridge direction), from 5 to 30 m long in a NW-SE direction, could be distinguished on the aerial photographs; they had gentle slope and were possibly formed in the past due to the accumulation of sediments close to anthropogenic structures (i.e. windbreaks). There were also two more pronounced ridges mainly parallel to the coastline, probably the remain of old man-made ridges. The landward ridge partially

covered (north-east part) a concrete revetment. These elements were clearly recognizable on older aerial pictures (Fig. 18). The vegetation was characterized by herbs and some sparse bushes; it is denser landward and sparser seaward.

- Active hummock dune area: small hummock dunes (mound shape), aligned parallel to the shore, mainly developed among the windbreaks (Windbreak). They were around 50-60 cm high, 4-6 m long and 3-4 m wide. The windbreaks were in a NNE-SSW direction. The vegetation cover was scarce (30-40%).
- Embryo dune area: embryo dunes originated on a narrow area on the active beach where the vegetation was commonly very scarce. They were mostly small features reaching a few centimetres in height and some tens of centimetres in width and length.

On the active beach there were some ripples (Ephemeral ripple crests) with crests perpendicular to the shore. Two or three alignment can be recognized. Crests were up to 10 m long. Ripples were ephemeral features, probably forming during the short time the beach is not raked.

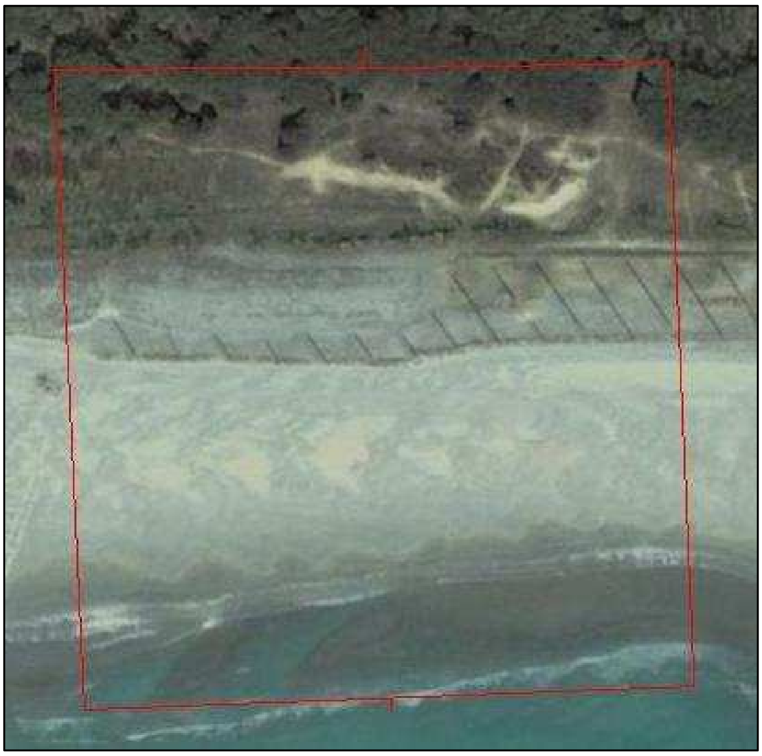


Fig. 18 - Cavallino-Treporti littoral: dune restoration intervention visible on an aerial picture taken in 2001 (see paragraph 3.3.4).

Transect 3 – Ca' Vio (Cavallino Treporti) (Appendix B)

Image date: 12th July 2015

General distinction:

- Inactive dune area (Campsite area, Ridges of anthropogenic origin, Inactive foredune area)
- Active dune area (Embryo dune area)

The vegetation cover was generally low in the active dune area (about 30-40%) and increased in the inactive dune area.

Main dune morphology: dunes of artificial origin and embryo dune.

Four areas were distinguished:

- Campsite area: the landward portion of the map corresponded to a campsite area completely reshaped by human intervention.
- Ridges of anthropogenic origin: it was characterized by an almost flat surface with some ridges of anthropogenic origin (Artificial ridge direction), distinguishable on the aerial picture; some of them were elongated in a NW-SE direction and probably formed in the past due to the accumulation of sediment in close proximity to anthropogenic structures (e.g. windbreaks); there was also the remnant of an artificially built ridge, whose western part was parallel to the shoreline, whereas the eastern tract curved landward. These elements were clearly recognizable on older aerial pictures (Fig. 19). The herbaceous vegetation, which characterizes this area, was denser landward and sparser seaward.
- Inactive foredune area: it was characterized by a continuous ridge (observed on the field) parallel to the shoreline, not very pronounced with a high vegetation cover.
- Embryo dune area: embryo dunes formed on a wide area on the active beach where the vegetation was commonly very scarce. They were mostly very small features reaching a few tens of centimetres in height and some tens of centimetres in width and length. A few of them, more developed, appeared as small shadow dunes with 1-2 m long lees elongated roughly in a NNW-SSE direction.

In this area the shoreline was interrupted by some groynes (Groynes).

Fig. 19 – Cavallino-Treporti littoral: dune restoration intervention visible on an aerial picture taken in 2001 (see paragraph 3.3.4).

Transect 4 – Ca' Savio (Cavallino-Treporti) (Appendix C)

Image date: 12th July 2015
General distinction:

- Inactive dune area (Woodland area, Inactive hummock dune area, Ridges of anthropogenic origin)
- Active dune area (Active foredune)

The vegetation cover was generally lower on the foredune (about 50%) and increased landward, reaching the 100% in the woodland area.
Main dune morphology: hummock dunes.

Four areas were distinguished:

- Woodland area: it was not a part of a coastal forest, but it was formed by a patch of brush.
- Inactive hummock dune area: it was a wide area characterized by some scattered large hummock dunes with a gentle slope, more pronounced seaward, separated by flat areas. The herbaceous vegetation was denser landward and sparser seaward on the top of the hummock dunes. Some ridges showed a NW-SE or NNW-SSE direction.
- Ridges of anthropogenic origin: within the inactive hummock dune area there were three linear ridges probably formed in the past due to the accumulation of sediment in close proximity to anthropogenic structures (e.g. windbreaks). They were elongated perpendicularly to the shoreline.
- Active foredune: it was represented by an active ridge 10-15 m wide and 2-3 m high. The foredune crest was quite continuous, except for a couple of interruption that occured where

two trails cross the ridge. The vegetation was organized into sparse clumps. This foredune probably developed from a ridge of anthropogenic origin (Fig. 20).

The dune area was enclosed by a fence (Fencing).

Fig. 20 – Cavallino-Treporti littoral: dune restoration intervention visible on an aerial picture taken in 2004 (see paragraph 3.3.4).

Transect 5 – Punta Sabbioni (Cavallino-Treporti) (Appendix D)

Image date: 12th July 2015

General distinction:

- Inactive dune area (Inactive hummock dune area)
- Active dune area (Active hummock foredune area)
- Ripple area (Ephemeral ripple crests)

The vegetation cover was generally lower on the foredune (about 50%) and increased landward reaching the 90-100%.

Main dune morphology: hummock dunes.

Two areas were distinguished:

- Inactive hummock dune area: this was a wide inactive hummock dune area covered by herbaceous vegetation. Dunes were not very pronounced; they had gentle slopes and are separated by flat areas. In this hummock dune area some shore-parallel dune alignments could be distinguished.
- Active hummock foredune area: it was formed by an active foredune 20-30 m wide and 2-3 m high, composed by small hummock dunes merged together; clumps of vegetation were

present on their top. The foredune crest was quite continuous and parallel to the shoreline. Some dunes forming the foredune were elongated in a WNW-ESE direction.

On the active beach there were some ripples having crests perpendicular to the shore. Ripple crests were up to about 30 m long (Ephemeral ripple crests).
The dune area is enclosed by a fence (Fencing).

Transect 6 – Ca' Savio (Cavallino-Treporti) (Appendix E)

Image date: 12th July 2015
General distinction:

- Inactive dune area (Inactive hummock dune area, Inactive hummock foredune area)
- Active dune area (Active hummock foredune area, Embryo dune area)
- Ripple area (Ephemeral ripple crests)

The vegetation cover was generally lower on the foredune (about 50%) and increased landward, reaching the 100% in the woodland area.
Main dune morphology: hummock dunes.

Five areas were distinguished:

- Inactive hummock dune area: it was an area with a complex morphology of hummock dunes with gentle slope separated by some flat areas. It was covered principally by a dense herbaceous vegetation landward and by a discontinuous herbaceous vegetation seaward. It was cut by some trails.
- Inactive hummock foredune area: it was represented by two inactive foredunes about 10 m wide and 1-1.5 m high, displaying a hummock morphology on their top. The vegetation, herbaceous and with clumps, was sparse. The foredune crests were quite continuous and parallel to the shoreline.
- Active hummock foredune area: a shore parallel alignment of small hummock dunes (mound shape) formed among the windbreaks (Windbreaks), mainly on their downwind side. Their morphology was not regular and not always clearly distinguishable. They were between 50 cm and 1 m high. The windbreaks were in a NNW-SSE direction. The vegetation cover was around 50%.
- Embryo dune area: it was characterized by embryo dunes formed close to the fencing delimiting the dune area, which was partially buried. They were mostly small features and they gradually merged with the gentle slope of the rear dunes. Some alignments in a NNE-SSW direction could be identified.

On the active beach there were some ripples with shore parallel crests. They were aligned parallel to the coast (Ephemeral ripple crests).

The dune area was enclosed by a fence (Fencing).

Transect 7 - Porto Caleri (Appendix F)

Image date: 28th March 2015

General distinction:

- Inactive dune area (Woodland area, Inactive hummock dune area, Inactive hummock foredune area, Inactive hummock dune area, Inactive hummock dune area)
- Active dune area (Active hummock foredune, Active scattered small shrub coppice dune area, Active medium shrub coppice dunes)

The vegetation cover was generally low in the active dune area (about 40%) and high in the inactive dune area (about 90%).

Main dune morphology: shadow dunes/shrub coppice dunes in the active dune area; hummock dunes and inactive dune ridges in the inactive dunes area.

Eight areas were distinguished:

- Woodland area: the geomorphological features were not distinguishable under the dense vegetation of the coastal forest; anyway it is conceivable, on the base of field observations, that this area was characterized by large relict hummock dunes alternated with dune slacks and wetlands.
- Inactive hummock dune area: at the border of the forest there was an area characterized by very large relict hummock dunes partially covered by shrubs. Seaward, there was another area characterized by hummock dunes having very gentle slopes covered by herbaceous vegetation and clumps. The reliefs were generally lower than those located in the surrounding zones.
- Inactive hummock foredune area: a stabilized dune ridge composed of stabilized large hummock dunes covered by shrub vegetation.
- Active hummock foredune: it was an active dune ridge between 20 and 30 m wide composed by medium hummock dunes having a vegetation cover less dense than the previous ones, arranged in scattered clumps.
- Active scattered small shrub coppice dune area: in the zone between the active hummock foredune and the external dune alignment, there were some scattered small shrub coppice dunes, as described in paragraph 5.1.1.

- Active medium shrub coppice dunes (see the description of the dimension classes in paragraph 5.1.1): shrub coppice dunes, formed close to vegetation clumps, covered a zone about 30 m wide. They were arranged in discontinuous alignments parallel to the shore; most of them were 5 to 10 m long, 2 to 5 m wide and 2 or 3 m high, with evident shadow dunes leeward.

  The shadow dune arms were generally elongated in a WSW-ENE direction.

Embryo dunes on the active beach were not clearly distinguishable maybe due to recent storm surges; in fact, during the field surveys some landward zones of the beach were still wet and some active dunes displayed clear evidences of wave erosion.
Some trails were observed, particularly within inter-dune zones, despite the presence of a protected area.

Transect 8 – Isola Verde (Appendix G)

Image date: 28th March 2015
General distinction:

- Inactive dune area (Inactive hummock foredune area, Anthropogenic sediment removal, Inactive hummock dune area)
- Active dune area (Active large shrub coppice dunes, Active scattered small shrub coppice dune area, Embryo dune area)

The vegetation cover was generally low in the active dune area (about 40%) and high in the inactive dune area (about 80%) except for some portion strongly affected by human activities, such as trails and a sediment removal area.
Main dune morphology: shadow dunes/shrub coppice dunes in the active dune area; hummock dunes in the inactive dunes area.

Six areas were distinguished:

- Inactive hummock foredune area: a stabilized dune ridge composed of stabilized large hummock dunes. It was not continuous as some features were affected by anthropogenic sediment removals (Anthropogenic sediment removal), which appeared as bare sand areas.
- Inactive hummock dune area: an area characterized by scattered hummock dunes with gentle slopes covered by herbaceous vegetation. They were more pronounced southward and less pronounced northward, where they were separated by flat areas and bare sand zones beside the trails.

- Active large shrub coppice dunes (see the description of the dimension classes in paragraph 5.1.1): they were shrub coppice dunes formed within vegetation clumps, organized into shore parallel alignments covering a zone that is about 70 m wide. Seaward they had greater dimensions (up to about 10 m in length, 15 m in width and 3 or 4 m in height) with evident shadow dunes leeward.
- Active scattered small shrub coppice dune area: landward and southward there were smaller shrub coppice dunes, as described in paragraph 5.1.1.
  The shadow dunes developed leeward were generally elongated in a E-W direction.
- Embryo dune area: embryo dunes formed on the active beach where the vegetation was absent or very scarce. Sand accumulation was possibly enhanced by flotsam and driftwood deposited on the strand. They were mainly small shadow dunes elongated in a E-W direction. Their width ranged from a few cm to about a couple of m, whereas they are 3 or 4 m long. Most of the embryo dune were organized into shore parallel alignments.

Between the anthropogenic features a groyne (Groynes) and a portion of fence (Fencing) were pointed out northward.

Transect 9 – Porto Caleri (Appendix H)

Image date: 28^{th} March 2015

General distinction:

- Inactive dune area (Woodland area, Cleared forest, Inactive hummock foredune area, Inactive hummock dune area)
- Active dune area (Active hummock foredune area, Active scattered small shrub coppice dune area, Active medium shrub coppice dunes, Embryo dunes area)

The vegetation cover was generally low in the active dune area (about 40%) and high in the inactive dune area (about 90%).

Main dune morphology: shadow dunes/shrub coppice dunes in the active dune area; hummock dunes and inactive foredunes in the inactive dunes area.

Eight areas were distinguished:

- Woodland area: landward, the zone was characterized by a pine forest. The geomorphological features were not distinguishable under the dense vegetation, anyway it is conceivable, on the base of field observations, that this area was characterized by large relict hummock dunes alternated with dune slacks.

- Cleared forest: southward, there was an area characterized by recent deforestation as the logs still lie on the ground.
- Inactive hummock foredune area: it was represented by a stabilized dune ridge composed of stabilised large hummock dunes covered by shrub vegetation.
- Inactive hummock dune area: it was an area characterized by hummock dunes with very gentle slope covered by herbaceous vegetation and clumps. The reliefs were generally lower than those located in the surrounding zones.
- Active hummock foredune area: it was represented by an active dune ridge (locally discontinuous) composed by small hummock dunes 15 to 20 m wide. The vegetation cover was higher than in the shadow dunes area, especially on the landward side.
- Active scattered small shrub coppice dune area: southward, in the zone between the active hummock foredune and the external dune alignment, there were some scattered small shrub coppice dunes, as described in paragraph 5.1.1.

  Active medium shrub coppice dunes (see the description of the dimension classes in paragraph 5.1.1): shrub coppice dunes, formed within vegetation clumps, covered a zone about 30 m wide. They were about 3 m wide and 2 m high and are organized into very discontinuous shore parallel alignments. Evident shadow dunes were elongated in a WSW-ENE direction from the lee side of the shrub coppice dunes. They were up to 6 m long.

  The shadow dune arms were generally elongated in a WSW-ENE direction.
- Embryo dunes area: embryo dunes formed on the active beach where the vegetation was absent or very scarce. Sand accumulation was possibly enhanced by flotsam and driftwood deposited on the strand. They were mainly small shadow dunes elongated roughly in a WSW-ENE direction. Their dimensions ranged from a few cm to about a couple of m in width and 5 or 6 m in length. Most of the embryo dunes were organized into shore parallel alignments.

Some trails were observed, particularly within inter-dune zones, despite the presence of the protected area.

Transect 10 – Ca' Roman (Appendix I)

Image date: 28th March 2015

General distinction:

- Inactive dune area (Inactive hummock foredune area, Inactive hummock dune area)
- Active dune area (Active hummock dune area, Embryo dune area)

The vegetation cover gradually increased from the active dune area (about 50%-60%) to the inactive dune area (about 90%-100%).
Main dune morphology: hummock dunes.

Four areas were distinguished:

- Inactive hummock foredune area: it was represented by an old inactive dune ridge, formed by very large hummock dunes (more than 5 m high) covered by dense herbaceous vegetation, shrubs and small trees.
- Inactive hummock dune area: an area characterized by small and pronounced hummock dunes. Landward, they were larger, scattered and divided by flat zones; the vegetation cover was denser and mostly herbaceous. Seaward, hummock dunes were smaller and closer together; vegetation became gradually sparser and characterized by clumps. In this area, some alignments or inactive foredune remains were distinguishable roughly in a NNW-SSE direction. Some features were elongated in NNE-SSW and ENE-WSW directions.
- Active hummock dune area: characterized by small, but pronounced, active hummock dunes on an area about 50 m wide. The vegetation spread out in clumps on the dune top. They were close together and form alignments, which were continuous and parallel to the shore (or slightly oblique) seaward, discontinuous, hardly distinguishable and elongated in NW-SE direction landward.
- Embryo dune area: it was characterized by embryo dunes formed within flotsam and driftwood deposited on the strand. Vegetation was very scarce.

The different morphologies and the limit between active and inactive dunes were not easily identifiable; the vegetation cover (type and density) gradually changes seaward.

Transect 11 – Mort Lagoon (Appendix J)

Image date: 12th July 2015
General distinction:

- Inactive dune area (Woodland area, Inactive hummock dune area, Inactive hummock foredune area)
- Active dune area (Active hummock dunes area)

The vegetation cover was locally high between the foredune and the woodland area but its distribution was very patchy due to a dense network of trails.
Main dune morphology: hummock dunes.

Four areas were distinguished:

- Inactive hummock dune area: this area was strongly affected by a dense network of trails. It was covered landward by a patchy woodland (Woodland area). It was really difficult to recognize the morphology of these features as the trails fragmented and modified them.
- Inactive hummock foredune area: it was represented by an inactive dune ridge about 10 m wide, stabilized by dense shrubs and displaying a hummock morphology on the top.
- Active hummock dunes area: on the seaward side of the dune ridge some small active hummock dunes couldn be identified within *Ammophila* clumps but their development was limited by rudimentary fence built with driftwood.

The shoreline of this coastal area was characterized by many coastal defences: a shore-parallel concrete breakwater (Breakwater) divided the beach from the sea and a series of groynes (Groynes) was present.

Transect 12 – Mort Lagoon (Appendix K)

Image date: 12th july 2015
General distinction:

- Inactive dune area (Woodland area, Inactive hummock dune area, Inactive hummock foredune area)
- Active dune area (Active hummock dunes area, Embryo dune area)

The vegetation cover was locally high between the foredune and the woodland area but it was very patchy due to a dense network of trails.
Main dune morphology: hummock dunes.

Five areas were distinguished:

- Inactive hummock dune area: it was strongly affected by a dense network of trails. This area was covered landward by a patchy woodland (Woodland area). It was really difficult to recognize the morphology of this features as the trails fragmented and modified them.
- Inactive hummock foredune area: it was represented by an inactive dune ridge about 10 m wide, stabilized by dense shrubs and displaying a hummock morphology on the top.
- Active hummock dunes area: on the seaward side of the dune ridge some small active hummock dunes ccouldn be identified within *Ammophila* clumps but their development was limited by rudimentary fence built with driftwood.

- Embryo dune area: embryo dunes formed within flotsam and driftwood deposited on the shore. Vegetation was very scarce.

The shoreline of this coastal area was characterized by many coastal defences: a shore-parallel concrete breakwater (Breakwater) divided the beach from the sea and a series of groynes (Groynes) was present.

6.1.1 Main characteristics of the transects

The transects could be grouped on the basis of their geomorphological characteristics, in order to identify dune system types.

Porto Caleri transects (7 and 9) were characterized by a sequence of different environments, the most complete in the sampled areas. They generally crossed large (around 50 m) active dune zones, formed by several discontinuous alignment of shrub coppice dunes instead of a continuous foredune. Semi-fixed and fixed dune areas were characterized by some pronounced stabilized hummock dune ridges, and associated interdune zones, with different vegetation types. Landward, there were relict hummock dunes covered by shrub vegetation; a coastal forest was present in the inner zone.

The Isola Verde transect (8) had the same characteristics of the previous ones as it crossed a large (around 50 m) active dune area formed by several discontinuous alignment of shrub coppice dunes. Moreover, the inactive dune area appeared to have been modified by anthropogenic activities. The transect was characterized by sparse hummock dunes with herbaceous vegetation; inland,a discontinuous stabilized dune ridge, partially altered by anthropogenic sediment removals, was present. Landward, the coastal forest was substituted by anthropized areas.
In these transects (7, 8 and 9), the active shrub coppice dunes located seaward were from about 1 to 3 m high.

The six transects located in **the Cavallino-Treporti area** appeared to be strongly modified by human intervention. In fact, Ca’ Savio, Ca’ Vio and Ca’ Ballarin transects were affected by the dune reconstruction and restoration interventions already mentioned (see paragraph 3.3.4).
Punta Sabbioni and Ca’ Savio transects were characterised by a rather continuous active foredune (as regards Ca’ Savio transects, it developed beside a series of windbreaks), which represented an active dune area less wide then the active Porto Caleri zone, whose width ranged from a minimum

of about 10 to a maximum of about 30 m. The foredune was about 3 m high at Ca’ Savio and about 0.50 m high at Punta Sabbioni. Along the Ca’ Ballarin and Ca’ Vio transects, the foredune area was less developed. The Ca’ Ballarin active dune zone was composed by a shore parallel alignment of small hummock dunes, not higher than 0.50 m, formed on the downwind side of the windbreaks. In the Ca’ Vio active dune area, foredunes or dune alignments were absent and a large embryo dune zone was present.
Along the Cavallino-Treporti transects, the inactive dune area was characterized by various geomorphological features (i.e., sparse hummock dunes with gentle slopes and, with the exception of the Punta Sabbioni area, shore-parallel and oblique ridges of anthropogenic origin developed from sand accumulation close to artificial features, such as windbreaks or man-made structures).
With the exception of Punta Sabbioni, this transects were bordered by campsite areas.

The Mort Lagoon transects constitute another dune system type. It was characterized by the almost total absence of the active dune area. There were just some active features on the seaward side of a pronounced, and rather continuous, inactive dune ridge covered by shrubs. Landward, the inactive dune area’s morphology was really difficult to recognize as the trails fragmented and modified its characteristics. In the inner zone crossed by the transect, a patchy coastal forest was present. It bordered the Mort Lagoon.

Ca’ Roman morphology was quite different from the others. It was characterized by a quite continuous succession of scarcely aligned small hummock dunes with an increasing degree of stabilization landward. Inland, in the coastal forest, there was a wide area of high relict dune ridges, relict dunes and inter-dune areas.

6.2 VEGETATION DATA

6.2.1 Cluster analysis

The dendrogram (Fig. 21) based on cover percentage data allowed to distinguish mobile dune habitat types (1210, 2110, 2120) from semi-fixed or fixed dunes habitat types considered (2230, 2130). The dendrogram substantially confirmed the first classification done on the field.

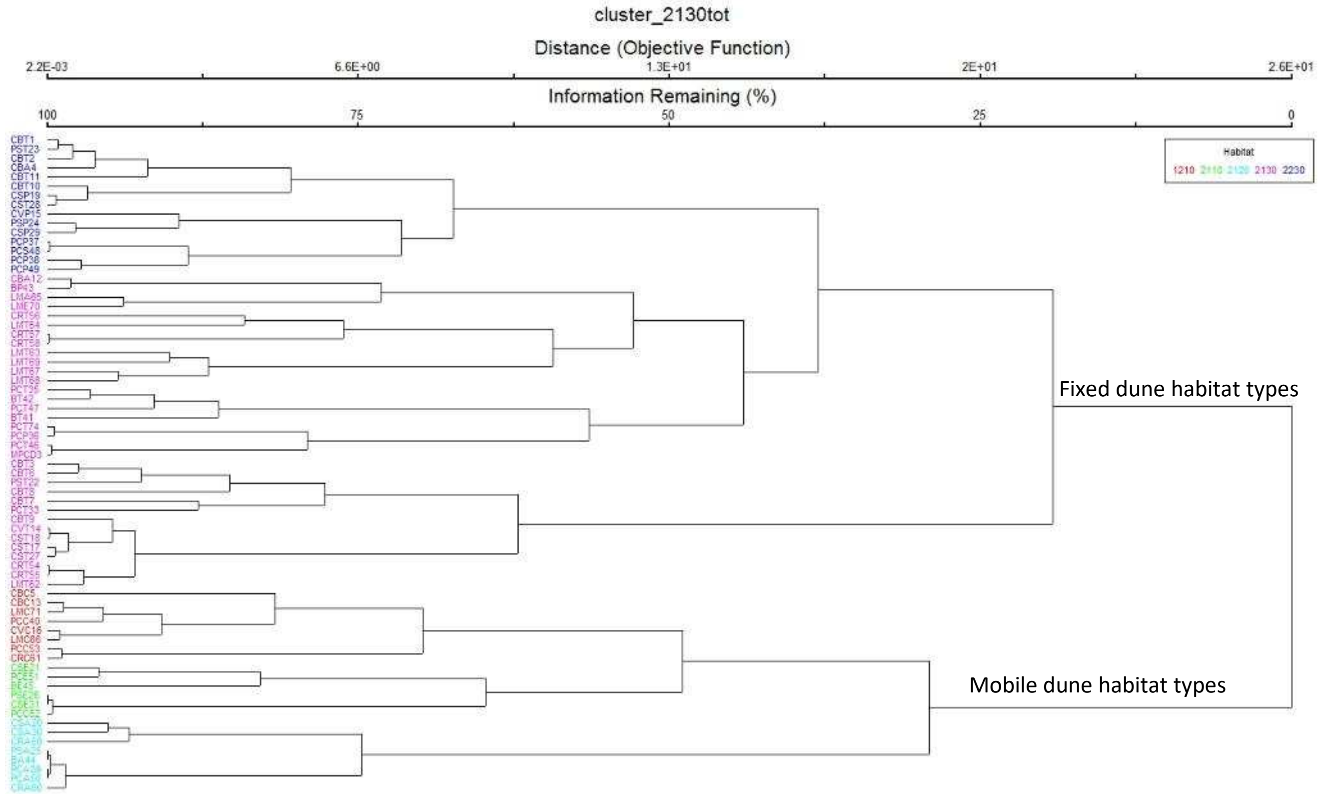


Fig. 21 – Dendrogram of the 63 relevés resulted from the cluster analysis.

Focusing the attention on semi-fixed dune vegetation (Fig. 22), four groups were distinguished. These groups represented different plant communities or different features of the same vegetation type. Groups 1, 2 and 3 have a higher degree of similarity while group 4 resulted to be well distinguished.

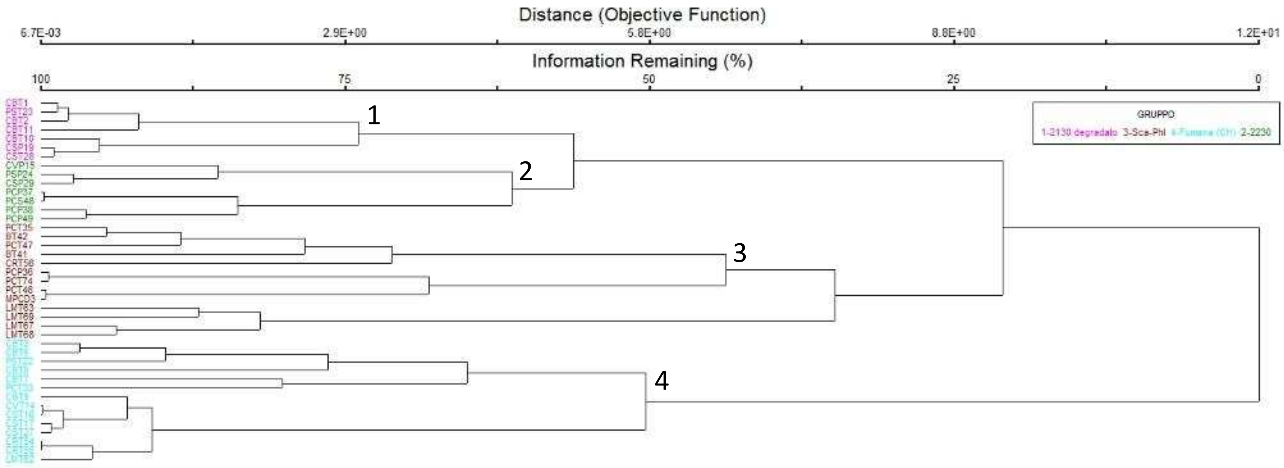


Fig. 22 – Dendrogram of the fixed and semi-fixed dune relevés resulted from the cluster analysis showing the four groups.

The four groups evidenced several differences, regarding both compositional and structural features.

Tab. 1 illustrates some general descriptive attributes. Overall, total vegetation cover was high, and always higher than 50%. The percentage cover of the moss layer was quite high and similar in groups 1, 3 and 4, while it was null in group 2.

Group	Total % vegetation cover	% cover of moss layer	Average number of species per plot
1	76.4	60.7	11.9 (sd 0.9)
2	57.1	0.0	8.8 (sd 2.41)
3	84.6	67.9	14.6 (sd 4.12)
4	80.0	67.1	12.4 (sd 2.64)

Tab 1 - Total percentage vegetation cover, percentage cover of moss layer, average number of species per plot (standard deviation in brackets).

The four groups differed in the average species richness per plot. The average species richness of group 3 was the highest (14.6), groups 4 and 1 displayed lightly smaller values (respectively 12.4 and 11.9), while group 2 had the smallest average species richness (8.8).

6.2.2 Species composition and diagnostic species

The diagnostic species (constant and dominant species) obtained for each group of semi-fixed dune vegetation are listed in Tab. 2. Constant species (CS) represented those species which had a frequency higher than 30% in a given group. Conversely, Dominant species (DS) were those species with a percent cover higher than 30% in more than 30% of the relevés of a given group. Having a high cover, Dominant species define the structure of a community and rule its dynamics.

		Group 1		Group 2		Group 3		Group 4	
		CS	DS	CS	DS	CS	DS	CS	DS
ah	*Catapodium rigidum*	71				62		57	
ah	*Cerastium semidecandrum*	100				85		79	
ah	*Hypochoeris radicata*					38	8	36	
ah	*Lagurus ovatus*					38			
ah	*Medicago littoralis*			57	14	46			
ah	*Medicago minima*		14	57	14			64	
ah	*Phleum arenarium*	100				92		71	
ah	*Silene colorata*	43		43	43				
ah	*Vicia pseudocracca*						15		
ah	*Vulpia fasciculata*	100	86	100	14	69		100	7
ph	*Calystegia soldanella*			43					
ph	*Chrysopogon gryllus*								7
ph	*Cyperus kalli*						8		
ph	*Sanguisorba minor*	71	14			38		64	14
ph	*Scabiosa argentea*						31		
ph	*Scabiosa columbaria*					31			
ph	*Silene otites*							36	
ph	*Silene vulgaris*	57				54		36	
ph	*Spartina juncea*				29		15		
ds	*Fumana procumbens*								79
ds	*Helianthemum nummularium*								14
ds	*Helichrysum italicum*						23		
ds	*Teucrium polium*								7
ds	*Thymus pulegioides*								7

Tab. 2 - Diagnostic species obtained for each group by mean of the software JUICE (Tichý, 2002) consisting of constant and dominant species. Constant species (CS) had a frequency higher than 30% in the group, dominant species (DS) had a percent cover higher than 30% in more than 30% of the relevés of the group (alien species were not included in the calculation). Numbers in the table cells indicates the relevés percentage fulfilling these constraints. Species are distinguished as annual herbaceous (ah), perennial herbaceous (ph) and dwarf shrubs (ds).

The analysis evidenced a group of species in common among groups. This set of species was mostly represented by short annual herbs, such as *Catapodium rigidum, Cerastium semidecandrum, Phleum arenarium* and *Vulpia fasciculata,* and secondarily by perennial herbs such as *Sanguisorba* *minor* and *Silene vulgaris*. However, only in few cases they were also among the dominant species. It is the case, for example, of *Vulpia fasciculata* in Group 1.

Indeed, if considering the life cycle of the species, it appeared that annual species, such as *Cerastium semidecandrum*, *Medicago littoralis*, *M. minima*, *Phleum arenarium*, *Silene colorata* and *Vulpia fasciculata* prevailed only in groups 1 and 2, both among constant and dominant species. Conversely, group 3 was characterized by a high number of annual species (i.e. the constant species), but its structure, i.e. the dominant species, was determined by perennial herbaceous species, like *Cyperus kalli*, *Scabiosa argentea* and *Spartina juncea*. In group 4, annual species also prevailed among constant species, but the community structure was defined by both perennial herbaceous (*Sanguisorba minor*, *Silene otites*, *S. vulgaris*) and dwarf shrubs, like *Fumana procumbens,* the most widespread*, Helianthemum nummularium* and *Teucrium polium*.

Exotic species cover (Tab. 3) was more abundant in group 2, followed by group 1, while group 4 distinguished itself for a lower exotic component, both in terms of frequency and percentage cover.

Group	Exotic frequency	Exotic % cover
1	18.0	25.2
2	25.5	31.7
3	19.9	18.7
4	12.0	8.8

Tab. 3 - Exotic species frequencies and percentage cover average data in the four groups.

6.2.3 Biological spectrum

The analysis of life forms (Tab. 4) confirmed the trends observed in diagnostic species and allowed to further distinguish the four groups on the basis of the plant community structure.

		Chamaephytes (%)	Geophytes (%)	Hemicryptophytes (%)	Phanerophytes (%)	Therophytes (%)
Groups	**1**	0.31746	19.59672	19.8172	0	**60.26861**
	2	0.21978	**47.19308**	7.274134	0	**45.31301**
	3	12.33126	27.44544	**33.27917**	8.480094	18.46403
	4	**58.5268**	8.93705	12.96985	0.170068	19.39623

Tab. 4 - Biological spectra showing for each group the average percent representation of the number of species belonging to each life-form.

The biological spectra (Tab. 4) showed that:

- group 1 was characterized mostly by therophytes, i.e. species which complete their life cycle typically in one or two months, followed by herbaceous perennial species (geophytes and hemicriptophytes). Only a very low percentage of species was represented by woody perennials such as chamaephytes;
- group 2 was defined by a similar percentage of therophytes and geophytes (45% and 47% respectively), i.e. species with aboveground perennant organs, like bulbs or rhizomes;
- life forms percentages were more heterogeneous in group 3; contrary to what evidenced by the other groups no life form resulted to be dominant and characteristic (therophytes percentage was similar to group 4, hemycriptophytes and geophytes were present in moderate abundance and chamaephytes percentage was not as high as in group 4 but markedly higher than in groups 1 and 2)
- group 4 was definitely characterized by chamaephytes dominance (58% of the species) while all other life forms were underrepresented.

6.2.4 Active dunes' quality

The sampled dune systems displayed various mobile dunes morphologies. Six types of mobile dune systems could be identified on the basis of their morphological features (Tab. 5).

1. transects 7, 8 and 9 (Porto Caleri and Isola Verde): the mobile dune area was characterized by a large active dune area formed by several discontinuous alignment of shrub coppice dunes.
2. transect 10 (Ca' Roman): the active dune area was also wide but composed by dense small hummock dunes.
3. transects 4, 5 and 6 (Punta Sabbioni and Ca' Savio): transects were characterised by a rather continuous active foredune
4. transects 1 and 2 (Ca' Ballarin) transects' active dune area was composed by a shore parallel alignment of small hummock dunes not higher than 0.5 m.
5. transect 3 (Ca' Vio) active dune area was constituted only by some embryo dunes.
6. transects 11 and 12 (Mort Lagoon): transects were characterized by almost total absence of active dune area; there were just some active features on the seaward side of a pronounced rather continuous inactive dune ridge covered by shrubs.

These geomorphological types of mobile dune systems could then be grouped on the basis of their vegetation characteristics.

First three types (transects 7, 8, 9, 10, 5, 4 and 6, located in Porto Caleri, Isola Verde, Punta Sabbioni and Ca' Savio) were characterized by an average height of the active foredune of 2 m and an average width of ca. 43 m. The vegetation was high, on average more than 50cm, and quite dense (total percent cover was on average 66%). Although the frequency of mobile dune diagnostic species was low, their percent cover was high, ranging from 91% to 96%, with the only exception of transect 4. The frequency of exotic species was high (40%), but their relative cover was always very low (on average 7%).

Last three foredune types (transects 1, 2, 3, 11, and 12, located in Ca' Ballarin, Ca' Vio and Mort Lagoon) were characterized by an average height of the active foredune of only 0,5 m and an average width of ca. 25 m. The vegetation was on average lower than 50cm, and sparse (total percent cover was on average 36%). Although the frequency of mobile dune diagnostic species was comparable to that of former type, their percent cover was much lower, approximately 36%. Species composition was contaminated by alien species which reached a more than doubled frequency and a much higher average cover (40%) when compared with former type.

Transect	**Total % vegetation cover**	**% cover of mobile dune diagnostic species**	**Frequency of mobile dune diagnostic species**	**2120 vegetation heigth (m)**	**Active foredune heigth (m)**	**Active dune width (m)**	**Beach width (m)**	**Exotic % cover**	**Exotic frequency**	**Mobile dune habitat types observed**
7	70	93.1	12.5	60.0	1.5	47.5	30.0	5.0	8.3	2120, 1210
8	70	91.4	12.5	100.0	3	88.0	53.6	6.2	8.3	2120, 2110
9	70	94.4	12.5	50.0	1	58.5	47.5	3.4	4.2	2120, 1210, 2110
10	90	94.5	12.5	60	-	58	23	1.8	4.2	2120, 1210
4	50	36.7	12.5	50.0	3	16.7	33.0	26.5	12.5	2120, 2110
5	60	95.8	4.2	80.0	3	23.1	70.0	4.2	4.2	2120, 2110
6	50	93.1	12.5	80.0	0.5	10.7	38.0	6.9	8.3	2120, 2110
1	40	27.4	12.5	40.0	0.5	25.0	71.3	24.5	8.3	2120, 1210
2	40	17.3	4.2	60.0	0.5	26.6	65.3	42.7	16.7	2120, 1210
3	15	43.6	37.5	10.0	-	34.4	67.8	38.5	25.0	1210
11	50	45.3	12.5	60.0	-	6.0	19.0	50.0	16.7	2120, 2110
12	100	48.1	8.3	50.0	-	2.0	42.0	48.1	8.3	2120, 2110

Tab 5 – Data on mobile dune characteristics for each transect: vegetation cover percent, percent cover and frequency of mobile dune diagnostic species, vegetation height, active foredune height, active dune width, beach width, exotic species percent cover and frequency, mobile dune habitat types observed on the transect.

From the analysis of active dune characteristics interdependences, it emerged that the percent cover of mobile dune diagnostic species was lightly correlated to active foredune height (Pearson correlation; r = 0.55) and the exotic percent cover was negatively correlated to active dune area width (Pearson correlation; r = - 0.62).

6.2.5 Grain-size

Sediment samples resulted to be quite uniform.

The mean grain-size (Folk & Ward, 1957) varied from a minimum of 172.8 μm to a maximum of 315.6 μm. The sorting classes (Folk & Ward, 1957) varied from very well sorted to moderately sorted.

As it can be seen in Fig. 23, all samples were unimodal. The majority (sixty-five samples out of sixty-nine) had the same mode (225 μm) and were defined as fine sand (125 μm < *d* < 250 μm).

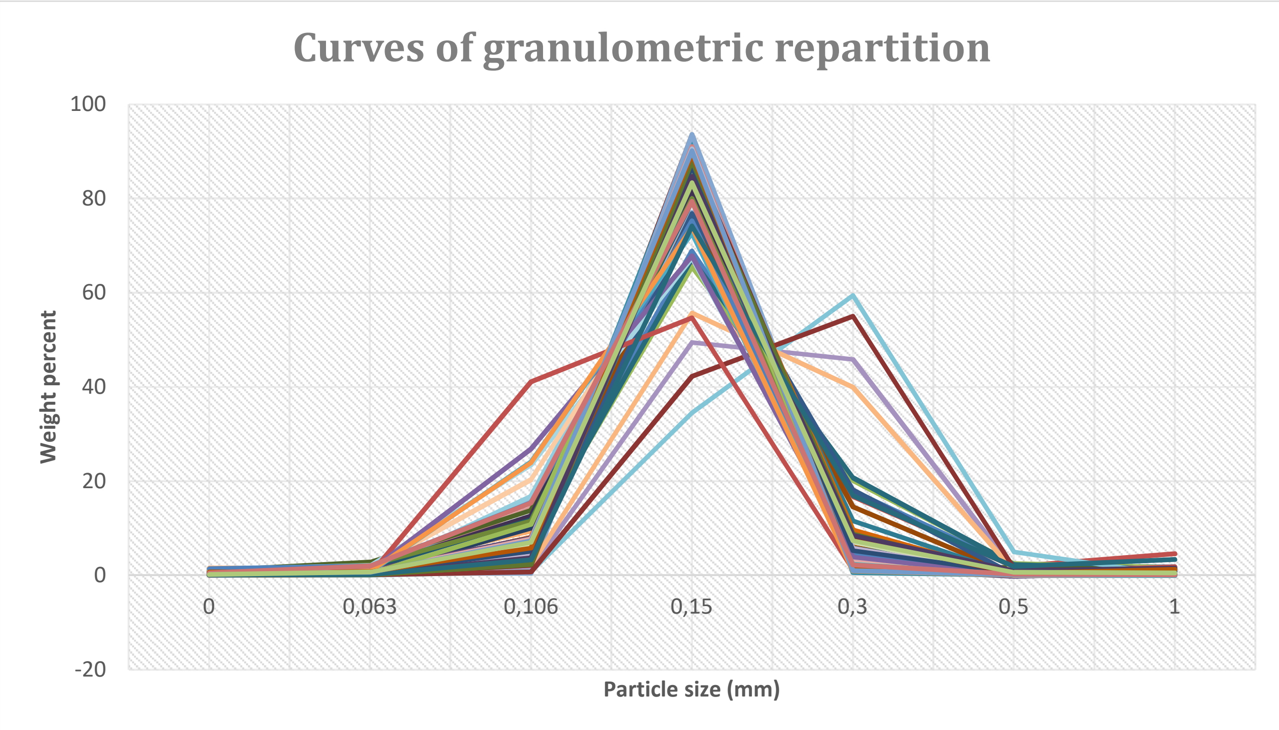


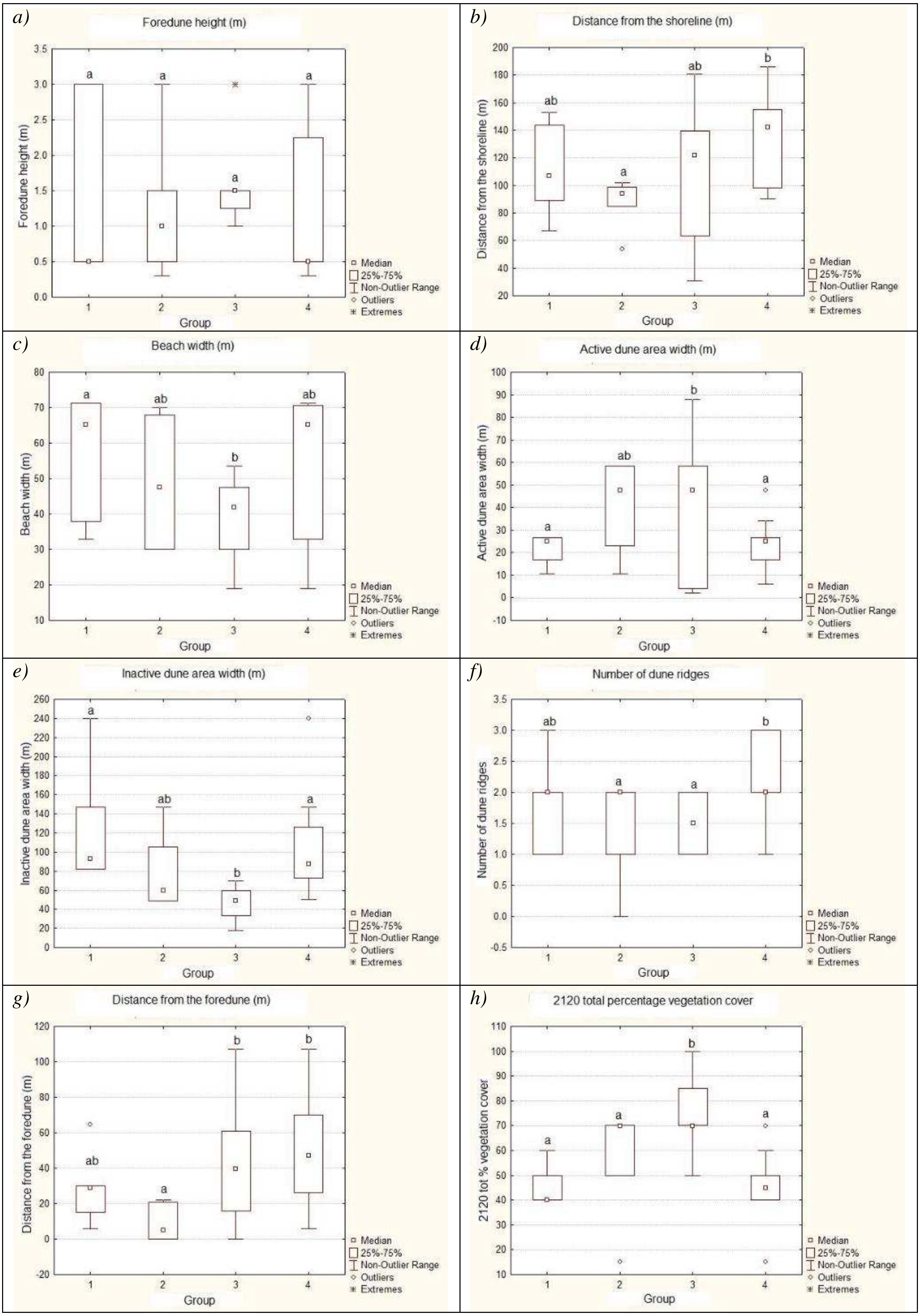
Fig. 23 – *Curves of granulometric repartition, from the result of the sieving analysis on sediment sampled on the plots.*

Only five samples resulted to be evidently different. They were mostly represented by samples collected in Isola Verde (BT41, BT42 and BE45, with a mode = 400 μm; BP43 with a mode = 225 μm). Accordingly, they were classified as medium sand, in general resulting coarser than the others. The fifth sample was collected in Ca' Roman (CRT57) and was included in the fine sand class, as the majority of the samples, but evidenced a finer mode (128 μm).

A correlation between finer granulometric classes and two other variables was observed: the percent of the sediment samples found on the last sieve (63 μm) and on the pan after sieving resulted to be correlated (Pearson correlation; r = respectively 0.52 and 0.55) to the distance from the shoreline, and the percent of the sediment samples found on the pan after sieving resulted correlated (Pearson correlation; r = 0.58) to the percentage cover of moss layer.

6.2.6 Permanova analysis

PERMANOVA analysis (F = 4.223, p = 0.0001) (Fig. 24 and Tab. 6) evidenced some significant relationships between the vegetation features found on the semi-fixed dunes and geomorphological characteristics of the beach system and of active dunes. Tab. 6 summarizes average value per group. In fact, some variables, such as distance from the active foredune and from the shoreline, number of dune ridges between the plot and the shoreline, active and inactive dune area and beach width, sediment sorting, mobile dune vegetation cover, percent cover of mobile dune diagnostic species, resulted significantly different at least in some of the four groups.


a)
Foredune height (m)
b)
Distance from the shoreline (m)
c)
Beach width (m)
d)
Active dune area width (m)
e)
Inactive dune area width (m)
f)
Number of dune ridges
g)
Distance from the foredune (m)
h)
2120 total percentage vegetation cover
2120 tot % vegetation cover
Group
Median
25%-75%
Non-Outlier Range
Outliers
Extremes

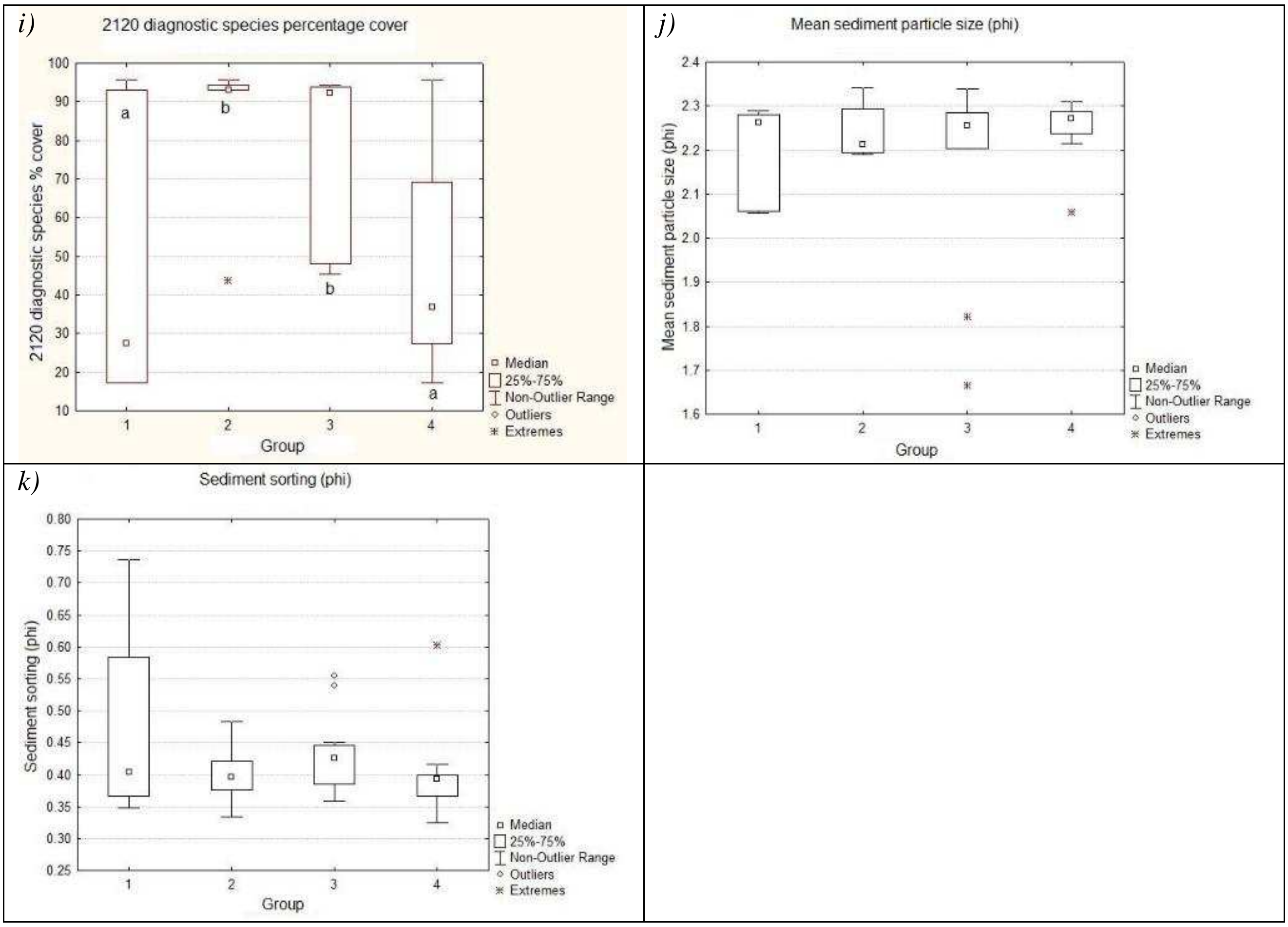


Fig. 24 - Box-plots showing the results of PERMANOVA analysis and post hoc Least Significant Difference (LSD) Fisher's test. Each plot shows the grouping variables (groups 1,2,3,4) and a dependent variable. Different letters above the boxes indicates a significant difference. a) - Active foredune height (m) (where absent the height of the dune ridge immediately behind was used). b) - distance from the shoreline (m). c) - width of the aphytic zone (m). d) - width of the active dune area (m). e) - width of the inactive dune area (m). f) - number of dune ridges between the plot and the shoreline. g) - distance from the active foredune (m). h) - total percentage vegetation cover measured on the habitat type 2120 (Shifting dunes along the shoreline with Ammophila arenaria). i) - percentage cover of diagnostic species on the total vegetation cover in the habitat type 2120. j) - mean particle size (phi). k) – sediment sorting (phi).

	Group 1			Group 2			Group 3			Group 4		
	Mean	*SD*	*Median*	*Mean*	*SD*	*Median*	*Mean*	*SD*	*Median*	*Mean*	*SD*	*Median*
Foredune height	1.21	1.22	0.50	1.26	0.89	1.00	1.63	0.68	1.50	1.28	1.11	0.50
Shoreline distance	111.43	30.25	107.00	88.29	16.44	94.00	106.83	48.44	122.00	132.58	34.74	142.00
Beach width	59.15	16.41	65.25	47.27	16.44	47.50	40.39	10.82	42.00	52.93	20.27	65.25
Active dune area width	21.95	6.03	25.00	40.02	18.14	47.50	42.17	31.96	47.50	23.60	10.80	25.00
Inactive dune area width	120.28	57.28	92.60	75.96	36.72	59.53	47.34	19.23	49.25	111.46	64.92	87.49
Number of dune ridge	1.86	0.69	2.00	1.43	0.79	2.00	1.50	0.52	1.50	2.25	0.75	2.00
Distance from the foredune	27.82	18.59	29.00	9.14	9.23	5.00	40.83	31.24	39.50	50.80	31.56	47.00
2120 vegetation cover	45.71	7.87	40.00	57.86	20.38	70.00	75.83	15.64	70.00	45.42	13.39	45.00
% cover of mobile dune diagnostic species	45.00	34.43	27.36	86.77	19.07	93.10	77.89	22.55	92.21	46.76	29.80	36.73
Mean size (phi)	2.19	0.11	2.26	2.24	0.06	2.21	2.18	0.21	2.25	2.25	0.07	2.27
Sediment sorting (phi)	0.49	0.15	0.40	0.40	0.05	0.40	0.43	0.06	0.43	0.40	0.07	0.39

Tab. 6 - Mean, Standard Deviation and Median values for each group of the dependent variables used in PERMANOVA analysis.

The four groups evidenced a certain variability in the considered variables, with standard deviations sometimes very high. For this reason, in Tab. 6, besides mean values we also showed median values which provide further information about the sample distribution.

Generally speaking, group 2 was the least variable and group 4 the most, but groups variability changed a lot from one variable to another.

As on the base of the vegetation features, group 4 distinguished itself also on the base of some characteristics of the dune system where it was located. In particular, group 4 relevés were generally located further from the shoreline (median=142 m) (Fig. 24 *b* and Tab. 6) and they were always landward compared to the other groups' plots on the same transect. Furthermore, the dune ridges placed between group 4's plots and the shoreline were often more numerous (Fig. 24 *f*). As regards the others geomorphological aspects, a certain variability was observed. Group 4 is also characterized by better sorted sediments.

Group 2 relevés were located at a distance from the shoreline which had a low variability and was frequently shorter compared with the other groups (median=94 m) (Fig. 24 *b* and Tab. 6). Furthermore, it resulted to be located just before the foredune on its landward side, as its relevés distance from the active foredune was very low (median=5 m) (Figure x). It was found to be characterized by a wide active dune area with quite high total percent vegetation cover of habitat type 2120 and high percent cover of diagnostic species.

Group 1 was characterized by generally narrow active dune zones and wide inactive dune areas (Fig. 24 *d, e* and Tab. 6). As for the distance from the foredune, plots of group 1 were normally located in an intermediate position between group 2 and group 3. Foredune height, as well as its total vegetation cover and the cover of 2120 habitat type were low when compared to other groups. Furthermore, it was characterized by extremely variable grain size of the sediment compared with other groups.

Group 3 relevés were generally found behind quite high and wide active dune zones and in narrow inactive dune areas (Fig. 24 *a, d, e* and Tab. 6). Furthermore, on the active dunes of the transects where group 3 relevés were found, the percent cover of diagnostic species and the total percent vegetation cover of habitat type 2120 were quite high.

Observing these variables, some trends could be distinguished.

Foredune height and active dune area width grew from group 1, through group 2, to group 3 and assumed a lower value again for group 4. As regard the active dune vegetation quality, the total vegetation cover and, partially, the percent cover of diagnostic species had the same trend. Beach width and inactive dune area width had instead an opposite trend.

As regards the granulometric parameters, the mean grain size was not significantly different between the four groups, due to its uniformity, but it appeared to be more variable in group 1 than in the others. Sediment sorting was instead significantly better in group 4 compared to group 1, whose sorting appeared also more variable than the others. Considering that group 1 relevés are all located at Cavallino-Treporti, it would be interesting to understand if this characteristic is connected to the activities of dune restoration realized in this area and the artificial sand supply which probably altered the natural sediment composition.

7 DISCUSSION AND CONCLUSIONS

The results of the study indicated a notable relationship between 2130 community composition and structure, and geomorphology. Moreover, I also found a relationship between the characteristics and quality of the mobile dune system and 2130 characteristics.

The 2130 habitat type occupies the transition dune system, i.e. semi-fixed or fixed dunes. According to literature (Prisco et al., 2012; Sburlino et al., 2013; Del Vecchio et al., 2015), the habitat is characterized by more or less closed perennial grasslands, often dominated by hemicryptophytes and chamaephytes, associated with abundant carpets of lichens and mosses.

Our results showed that plant communities of the transition dunes are characterized by some common features as regards species composition. The common set of species is mainly composed of short annual herbs, such as *Catapodium rigidum, Cerastium semidecandrum, Phleum arenarium* and *Vulpia fasciculata,* and secondarily by perennial herbs such as *Sanguisorba minor* and *Silene vulgaris*. However, a comparison of diagnostic species, total percentage vegetation cover and geomorphological and sedimentological characteristics allowed to clearly distinguish group 2 from others and to identify it as a different habitat. Compared to the other communities found in the transition dune sector, relevés of group 2 had a lower total vegetation cover and were characterized by the absence of the moss and lichen layer and of the set of diagnostic species which the other groups had in common. In particular, the dominance of species with an annual cycle (therophytes) are coherent with 2230 community's description from literature: "*Malcolmietalia* dune grasslands" characterized by therofitic communities with many small annuals and often abundant ephemeral spring bloom (Houston, 2008). The geophyte high percentage was unexpected, but it was mostly due to the abundance of two exotic species, *Ambrosia psylostachia* and *Spartina juncea*.

Plots belonging to Groups 2 also showed a peculiar location along the transect. They were often found on the active foredune lee slope, at a distance from the shoreline which had a low variability and was frequently shorter compared with that of the other plots. This location probably exposes them to natural disturbance, e.g. wind, sand burial, which induces annual species dominance, as a short life cycle allows them to better withstand stress conditions. Also their lower species richness is coherent with the seaward position, since plant species richness typically increases following the sea-inland gradient (Buffa et al., 2012).

Moving inland, environmental conditions progressively become less harsh and plant communities tend to be permanent with both higher species richness and total cover (Del Vecchio et al., 2015).

Indeed, all other plots evidenced a higher total vegetation cover, the dominance of perennial species and the presence of a carpet of mosses and lichens, thereby allowing us to make reference to the habitat 2130, although with different degree of conservation.

Our analysis revealed a progressive decrease in perennial and chamaephytes dominance, an increase of annual and therophytes abundance and a rise in exotic species percentage cover respectively in groups 4, 3 and 1. This suggests that they represent decreasing degrees of conservation of the community. Group 4 represented a well-defined aspect of 2130 habitat type as it was mostly composed of 2130 typical species and it was characterized by perennial dwarf shrubs dominance. Chamaephytes such as *Fumana procumbens, Teucrium polium, Helianthemum nummularium*, are considered to be particularly frequent in the most evolved aspect of the community, often associated to more developed soils, rich in organic matter (Sburlino et al., 2013). These characteristics indicate coherence with literature descriptions, high degree of stability of the plant community due to the dominance of perennial species, and consequently a good quality 2130 habitat type. Group 3 structure was mostly determined by perennial herbaceous species, but it was characterized by a high number of annual species, and group 1 was instead dominated by therophytic species.

The results concerning geomorphological characteristics suggest that the structure and consequently the conservation status of the community might depend on the dune system integrity. Group 4 relevés, found at all the tested localities, except for Isola Verde, were located further from the shoreline and were found to be quite independent of the active dune characteristics. Consequently, the good conservation status of the 2130 community is probably linked to the natural disturbance mitigation produced by the landward position. Furthermore, the correlation found between sediment finer components and the distance from the shoreline, and the cover of moss layer supported the evidence of a relationship between position within the environmental gradient, soil development and 2130 vegetation structure. A relationship between mobile dunes' quality and 2130 habitat quality instead emerged from group 1 and 3 comparisons. Their relevés were never located in the same transects. Group 3, characterized by an intermediate degree of stability, was found behind better-developed mobile dune systems, compared to group 1, which revealed the higher degree of destructuration.

In particular, foredune height and active dune area width appeared to be correlated to 2130 habitat quality. As regard the active dune vegetation, also the total vegetation cover and the percent cover of diagnostic species were found to be correlated to 2130 community stability. This suggests that higher foredunes or wider active dune areas better fulfil their protection function towards semi-fixed and fixed dune habitats.

Furthermore, mobile dune high-quality morphological characteristics appeared to be correlated to vegetation quality, indicating that higher or wider active dune areas are probably in a better overall status (considering diagnostic species dominance and low abundance of exotic species as a quality characteristic), which guarantees their functionality.

In fact, under natural disturbance regime, the mobile dune zone is dominated by *Ammophila arenaria*, a perennial plant with robust erect leaves and stems and an extensive rhizome system, which, being a dune-building plant, is the key species of the community both in terms of geomorphology and biomass (Chapman 1976; Lemauviel & Rozé, 2003). Also *Ammophila* suffers from excessive visitor pressure and trampling as they cause the breakage of the marram tufts and lead to a reduction of the plant cover, producing gaps which are then occupied by other species, either native or alien (Del Vecchio et al., 2015).

When the active dune system is damaged or underdeveloped, environmental conditions of the transition dune area change and the protection from natural disturbance fails, resulting in the degradation of 2130 community. On the same time, mature aspects of the community need sufficient dune system integrity also landward.

However, 2130 habitat type quality appears to be undermined both by natural and anthropic disturbance. Indeed, the occurrence of many alien species has been found to be indicative of land-use change (Maskell et al., 2006). From the second half of the 20th century coastal urbanization and mass-tourism progress led to the development of settlements, infrastructure and touristic facilities, producing direct and indirect impacts on sandy beaches and on their vegetation (Cencini et al., 1988). Specifically, excessive visitor pressure has been proven to damage dunes morphology and to lead to the degradation of the vegetation (Del Vecchio et al., 2015). In particular, trampling causes a significant drop in the plant cover, plant height and species richness, but herbaceous plants, and especially annuals, are more resistant than perennial plants (Cole, 1995; Sun & Liddle, 1993). As regards 2130 community, mosses, lichens and chamaephytes have a low tolerance to trampling (Del Vecchio et al., 2015; Florgård, 2000; Hamberg et al., 2008). Moreover, since plants of the semi-fixed dune are not fitted to unstable substrata, soil movements, generated by trampling, have further adverse effects. Therefore, due to trampling, tolerant herbaceous species and exotics can replace sensitive dwarf shrubs, mosses and lichens (Del Vecchio et al., 2015), leading to an increase of the annual component in the community structure. In general, it can be said that with the alteration of natural disturbance or the introduction of new disturbances, resident species become less adapted to the local environment and leave gaps for species fitted and more competitive under the new conditions (Del Vecchio et al., 2015).

The results obtained by this study could contribute to improve management and conservation strategies, which need as much information as possible on habitats dynamics, to be efficient. In order to conserve the 2130 priority habitat, representing a peculiar element of the North Adriatic coast, dune system integrity and mobile dunes quality should be pursued, avoiding direct dune destruction and other actions preventing dune development (e.g. beach mechanical ranking). In addition to this, the access to the dune system should be managed in order to protect the sensitive dune vegetation from trampling impacts.

These actions need to be conceived within an integrated management strategy, combining economic, social and ecological interests, supported by stakeholders' awareness of dune ecosystems' value. The integrated approach offers the opportunity to reach a win-win situation creating sustainable coastal communities, as ecosystem functionality maintenance would ensure social and economic advantages. In fact, together with the rest of the dune system, semi-fixed and fixed dunes provide important ecological services. As an example, they can furnish recreational resources and they offer natural protection from coastal erosion and flooding, providing a natural buffer zone which enables communities to withstand natural shoreline movements.

Nevertheless, the management strategies observed in the sampled areas, which represent some of the most integer dune systems on the North Adriatic western coast, appeared to be still inadequate or insufficient, and lacking coordination. And this appears even more serious if we consider that most of the sites were included in Natura 2000 sites, which are still lacking of official management plans.

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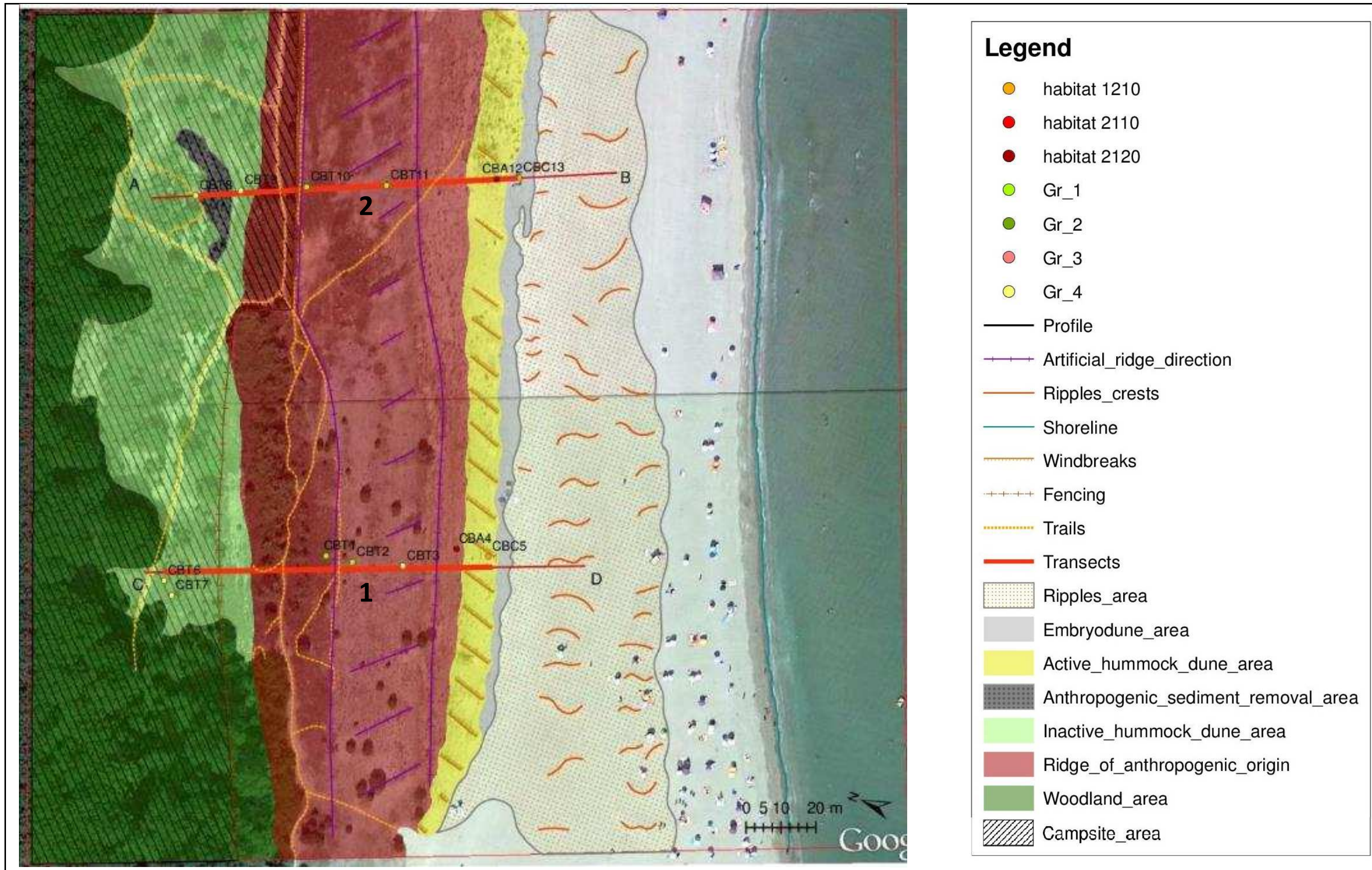
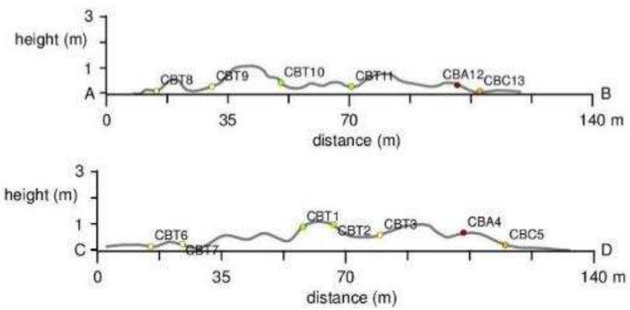
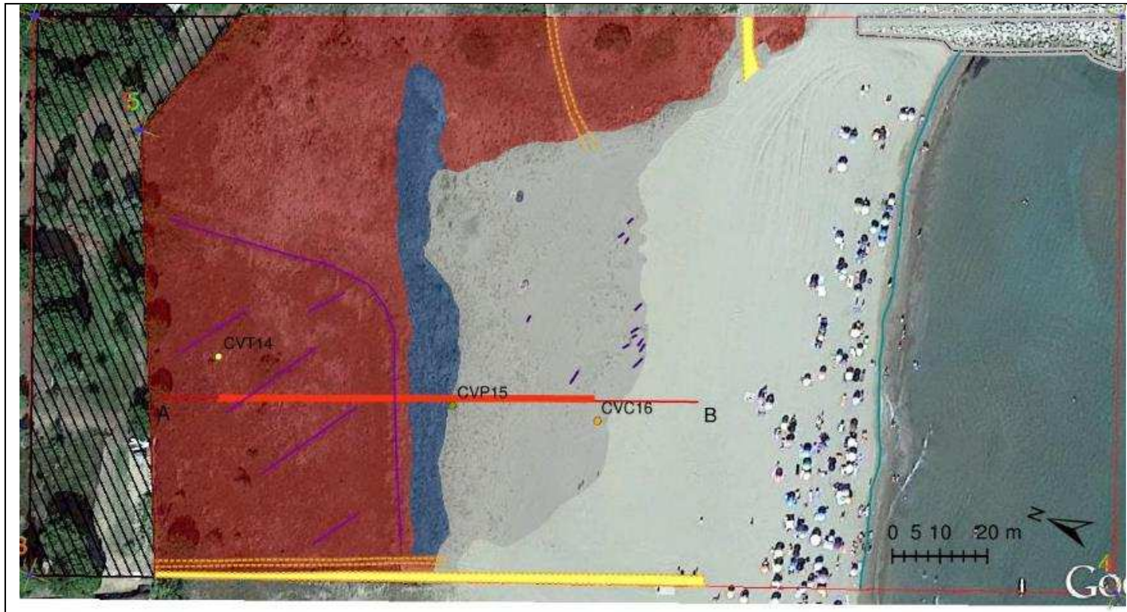
APPENDIX A – Geomorphological maps – Transects 1 and 2 – Ca’ Ballarin

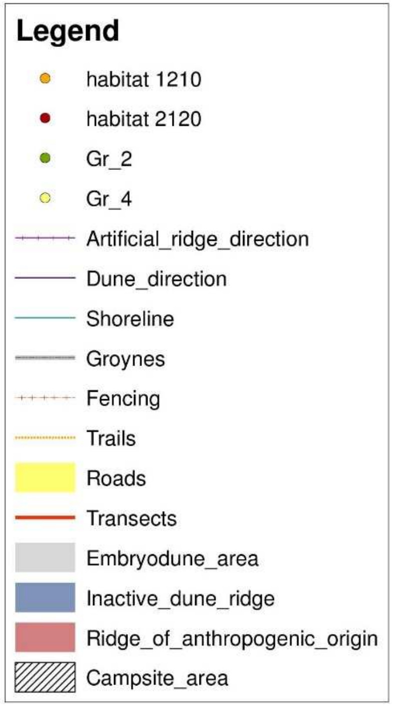


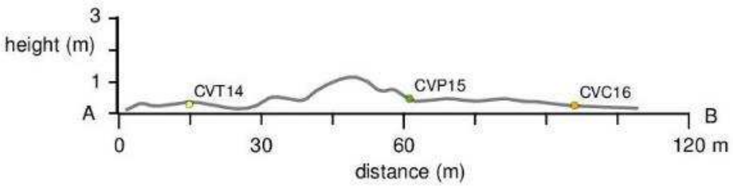


a – Woodland and inactive hummock dune area within the campsite area.
b – Ridges of anthropogenic origin.
c – Ridges of anthropogenic origin and windbreaks.
d – Active hummock dunes aligned parallel to the shore, mainly developed among the windbreaks.

APPENDIX B - Geomorphological maps - Transect 3 – Ca’ Vio

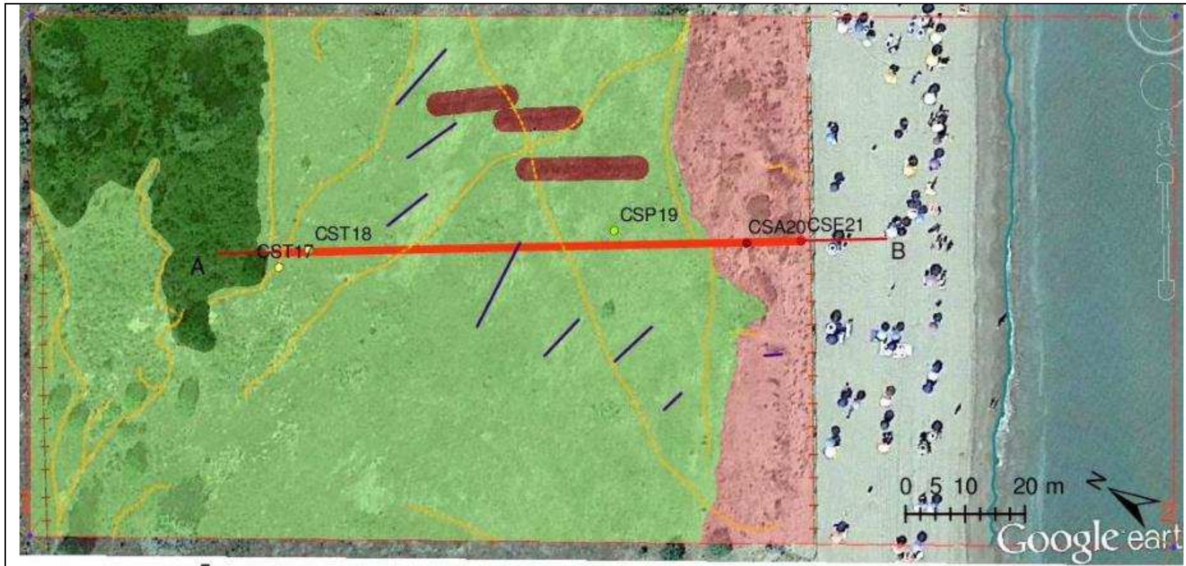


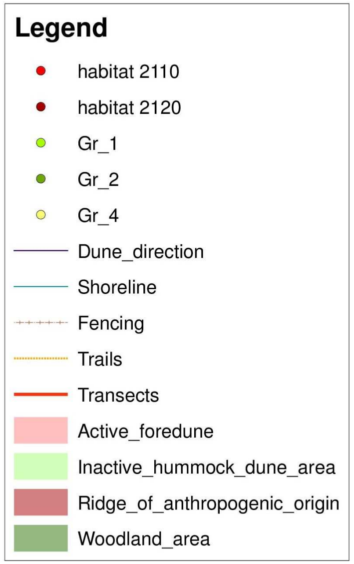


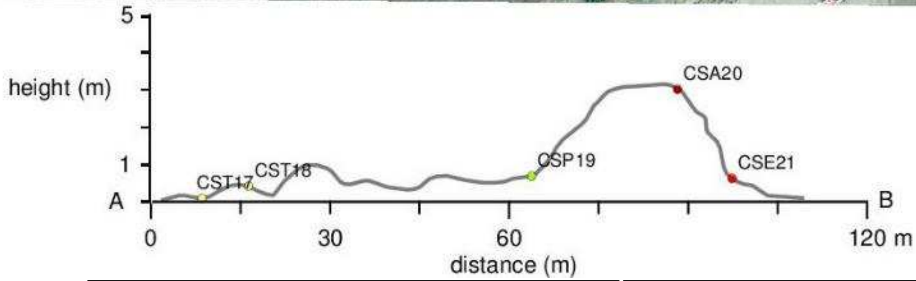


a – The almost flat inactive dune area and the campsite are landward.
b and c – Low inactive dune ridge and embryo dune area.

APPENDIX C - Geomorphological maps - Transect 4 – Ca' Savio

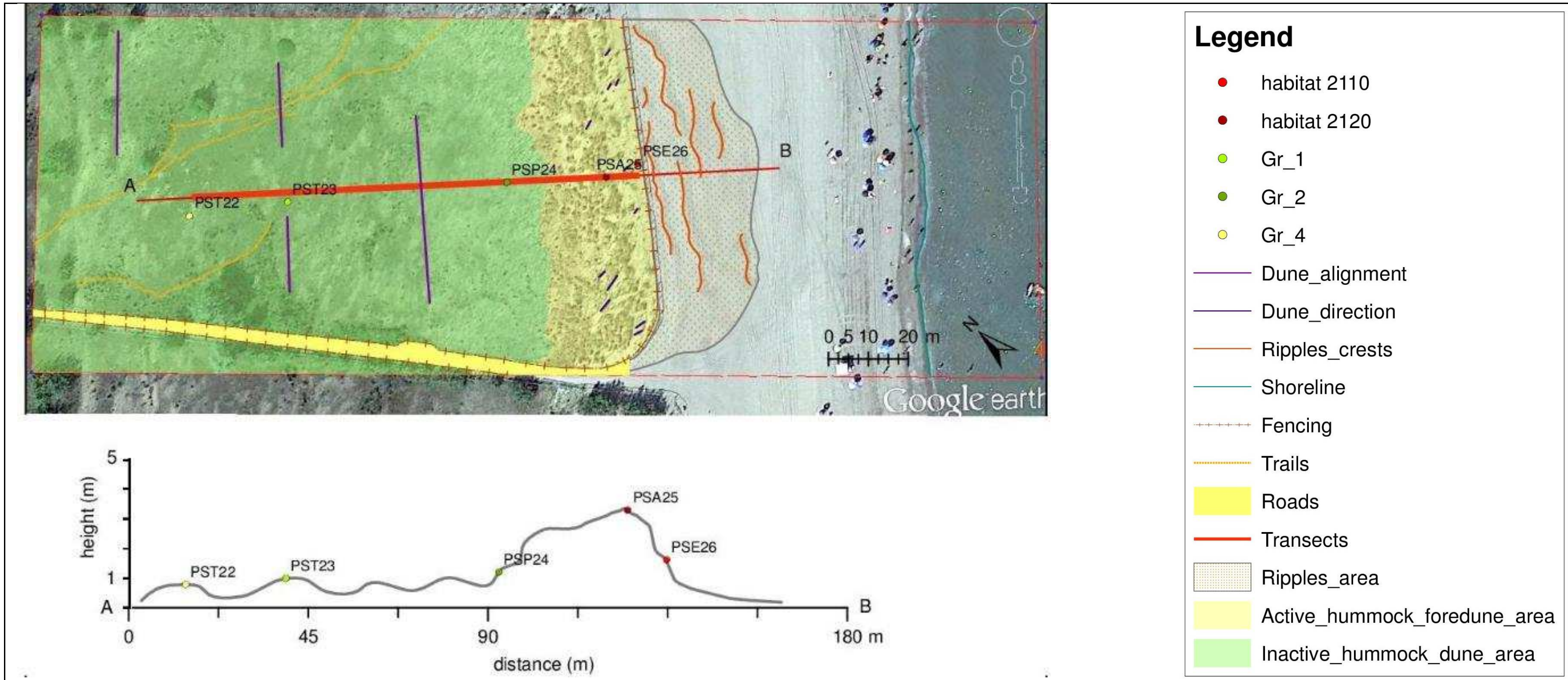






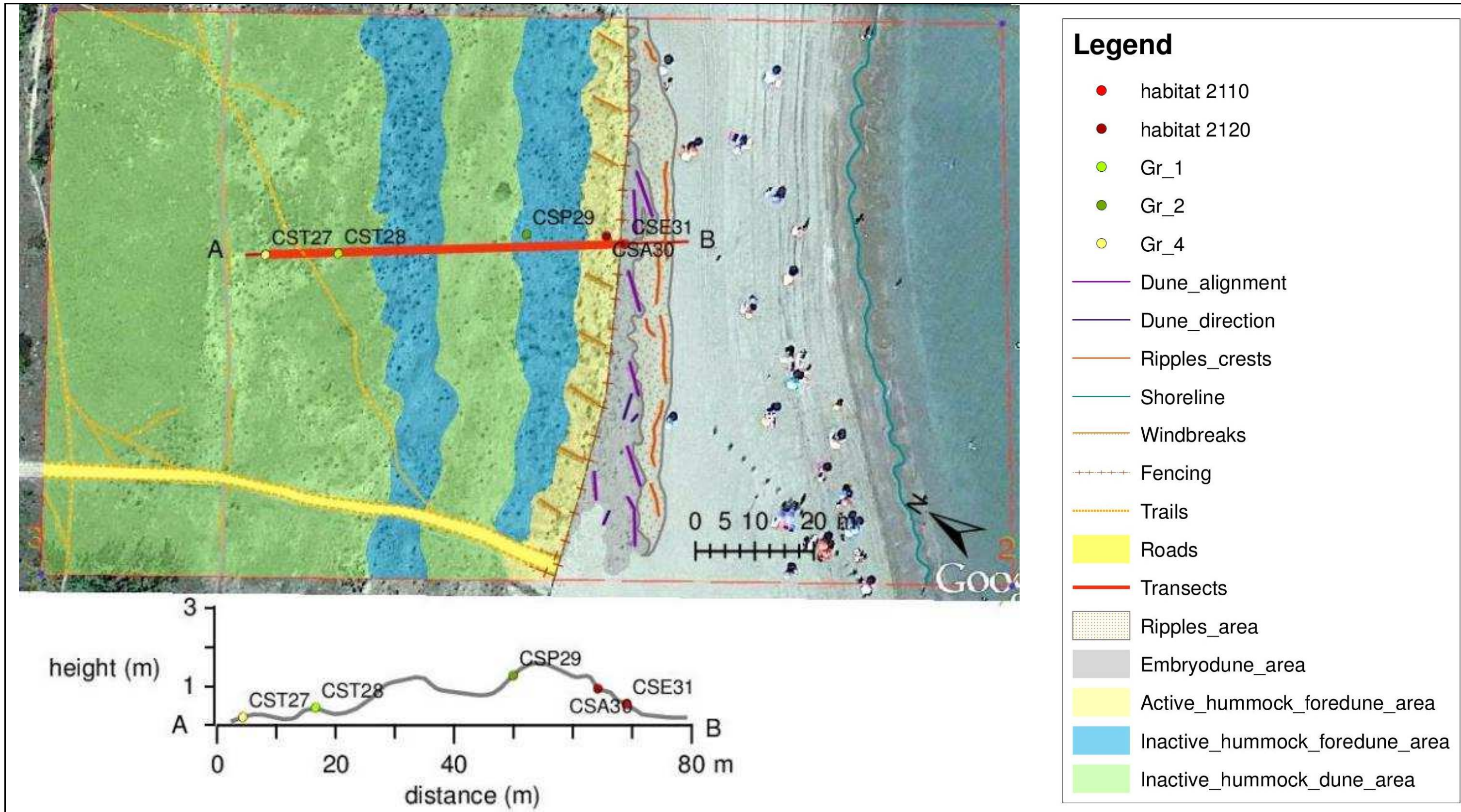
a – The inactive dune area with scattered large hummock dunes with a gentle slope.
b – The well-developed active foredune.
c – The fence delimitating the dune area.

APPENDIX D - Geomorphological maps - Transect 5 – Punta Sabbioni



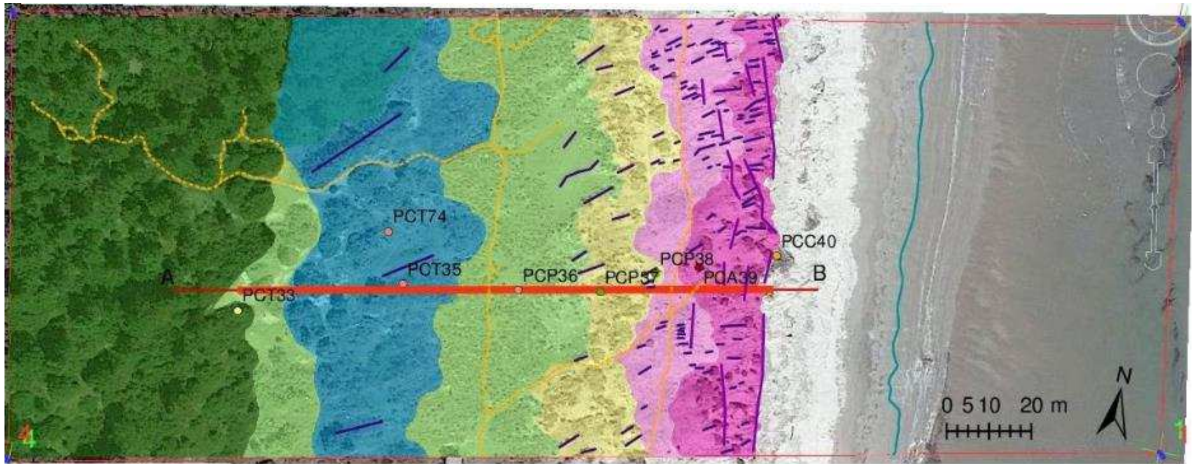
a – The inactive hummock dune area (landward). b – The inactive hummock dune area and the leeslope of the foredune. c – The active hummock foredune.

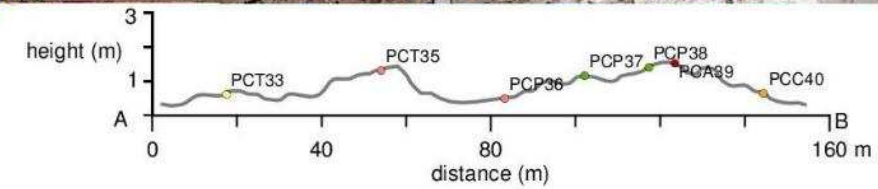
APPENDIX E - Geomorphological maps - Transect 6 – Ca' Savio

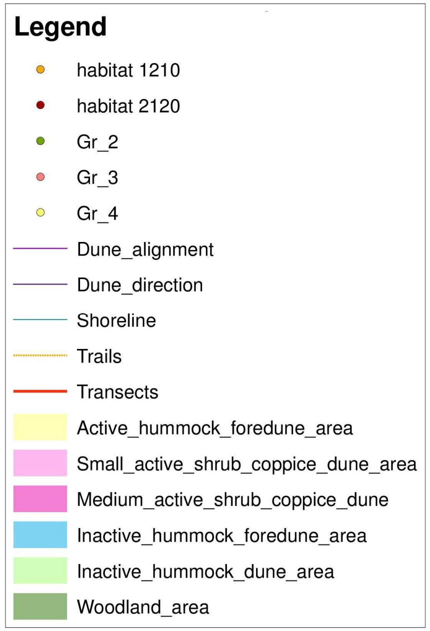


a – The inactive dune area with an inactive hummock foredune (landward).
b – The inactive dune area with an inactive hummock foredune (seaward).
c – The active hummock foredune with the windbreaks.

APPENDIX F - Geomorphological maps - Transect 7 – Porto Caleri







a – Woodland area with relict dunes.

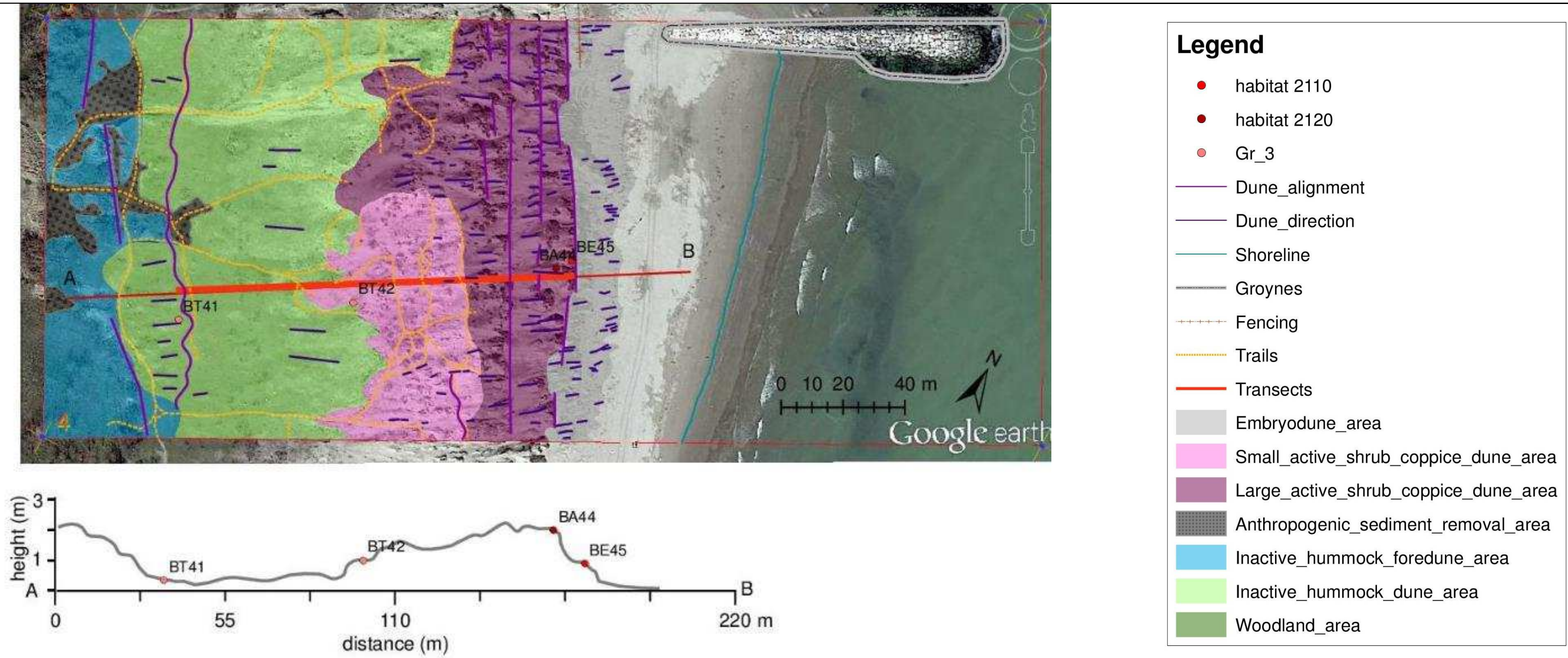
b – Inactive hummock dune ridge with shrub vegetation.

c – Inactive hummock dune area having very gentle slopes covered by herbaceous vegetation and clumps.

d – Active hummock foredune.

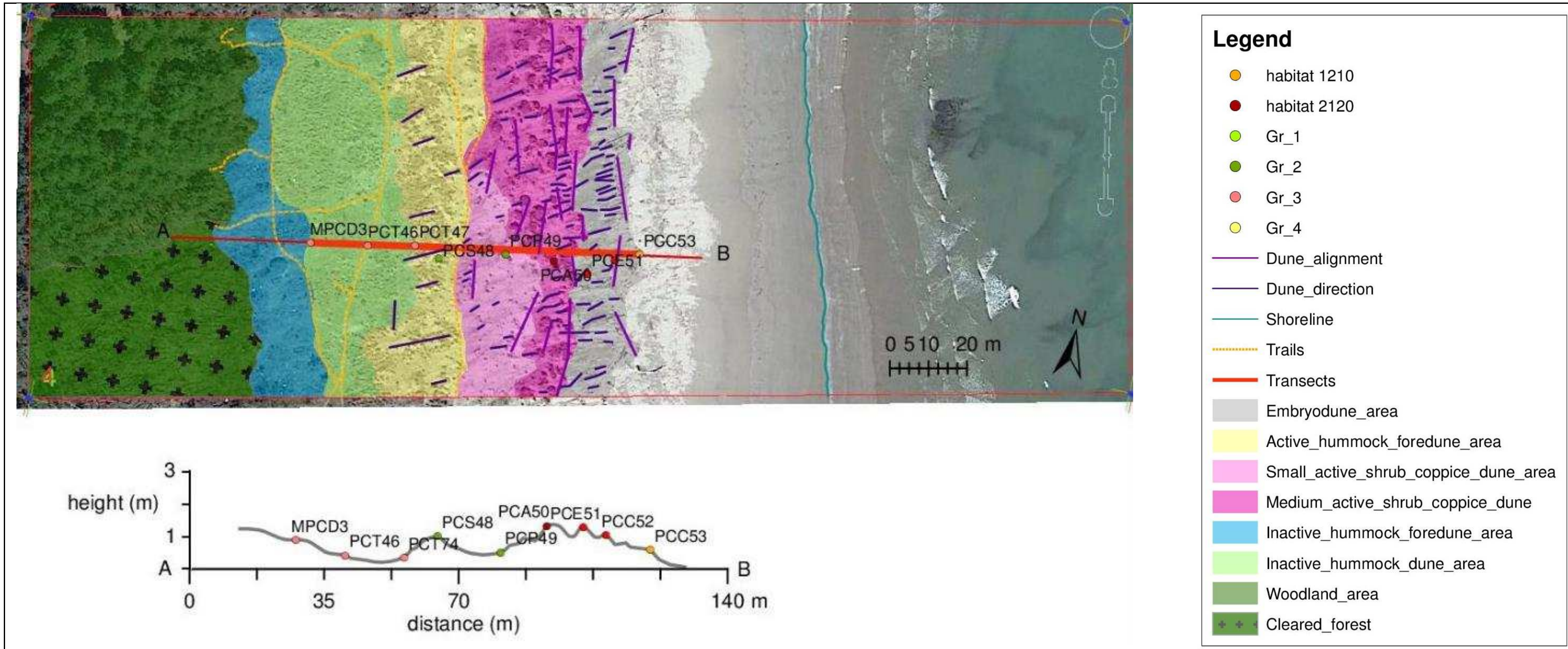
e - Active shrub coppice dune area.

APPENDIX G - Geomorphological maps - Transect 8 – Isola Verde

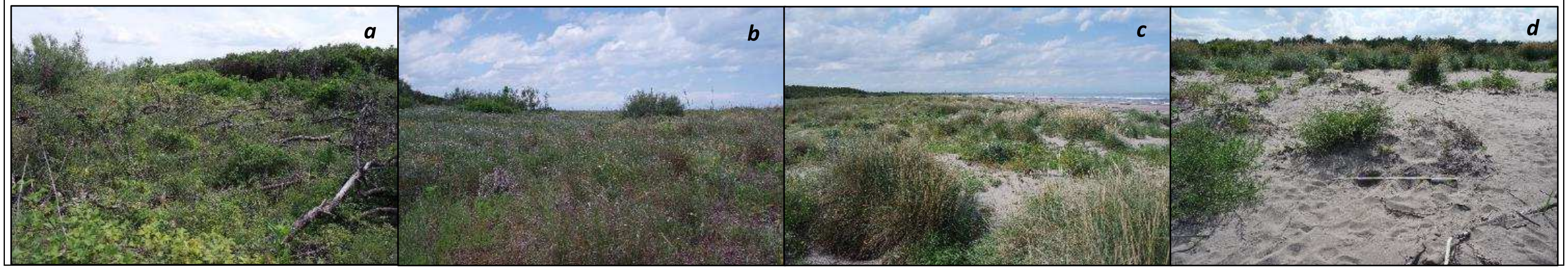


a – Inactive dune area with with inactive hummock foredune landward. b – Inactive hummock dune area. c – Small scattered shrub coppice dune area. d – Large shrub coppice dune area.

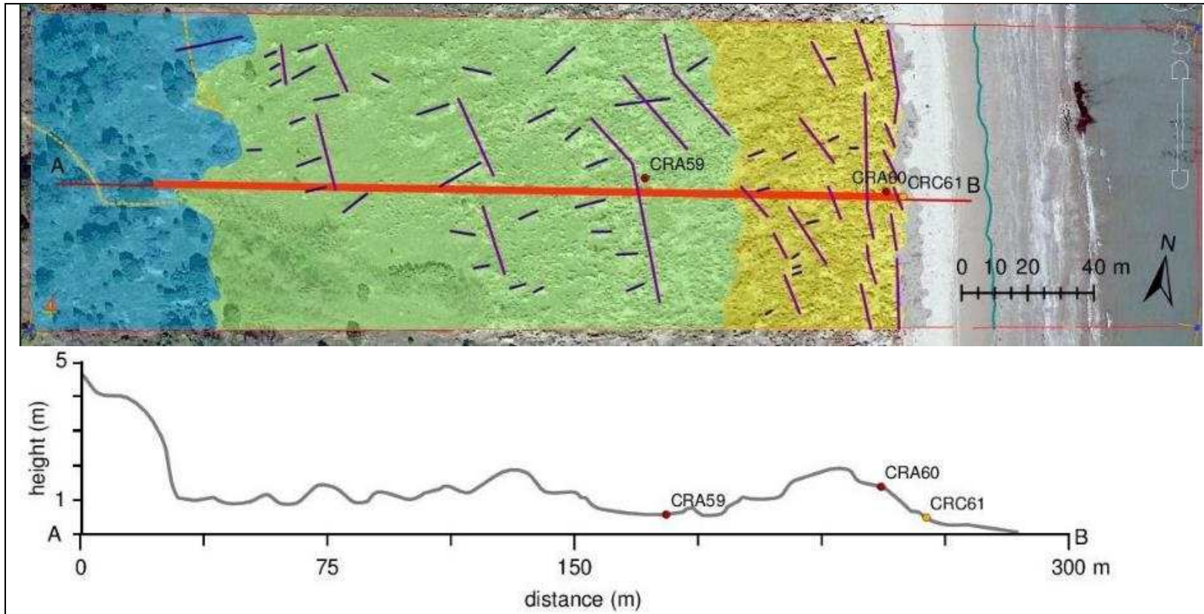
APPENDIX H - Geomorphological maps - Transect 9 – Porto Caleri

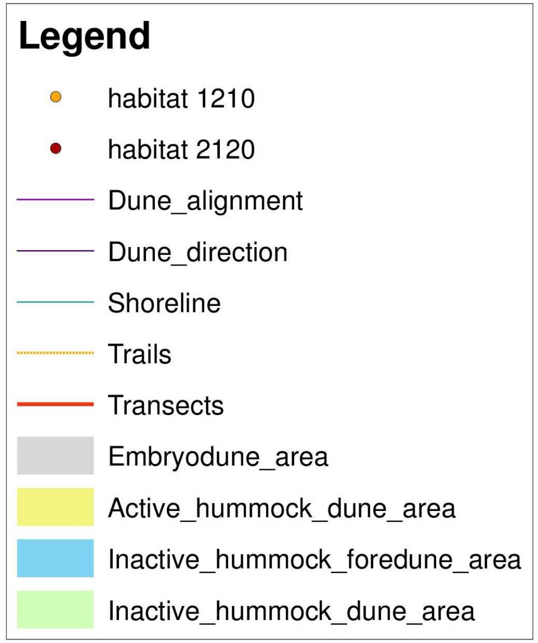


a – The cleared forest. b – The inactive hummock dune ridge and the inactive hummock dune area. c –The active shrub coppice dune area. d – The embryodune area.



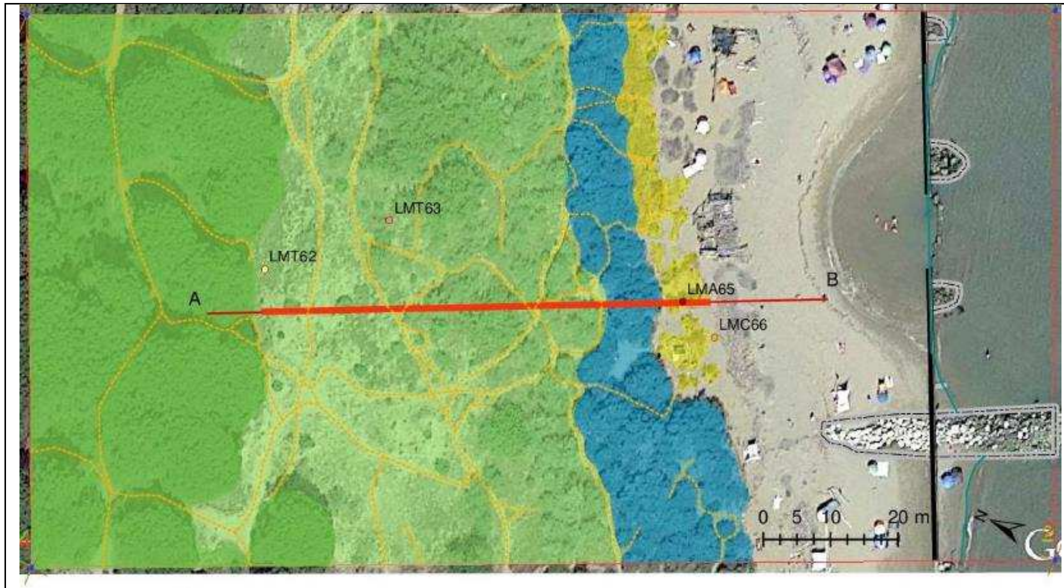
APPENDIX I - Geomorphological maps - Transect 10 – Ca' Roman

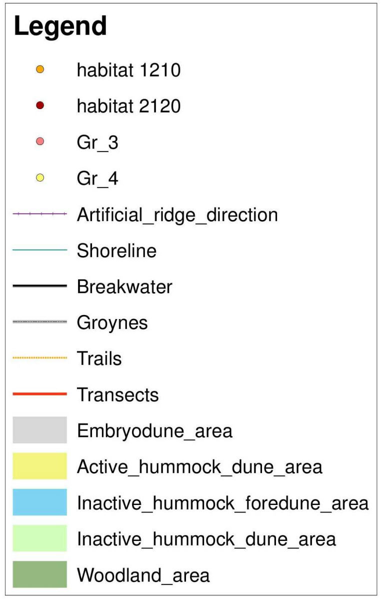


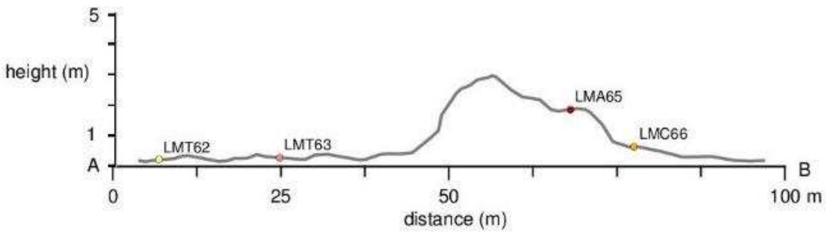


a – The inactive hummock dune area viewed from a high relict dune. b – The inactive hummock dune ridge landward and the inactive hummock dune area. c –The active hummock dune area. d – Active hummock dunes from the beach.

APPENDIX J - Geomorphological maps - Transect 11 – Mort Lagoon



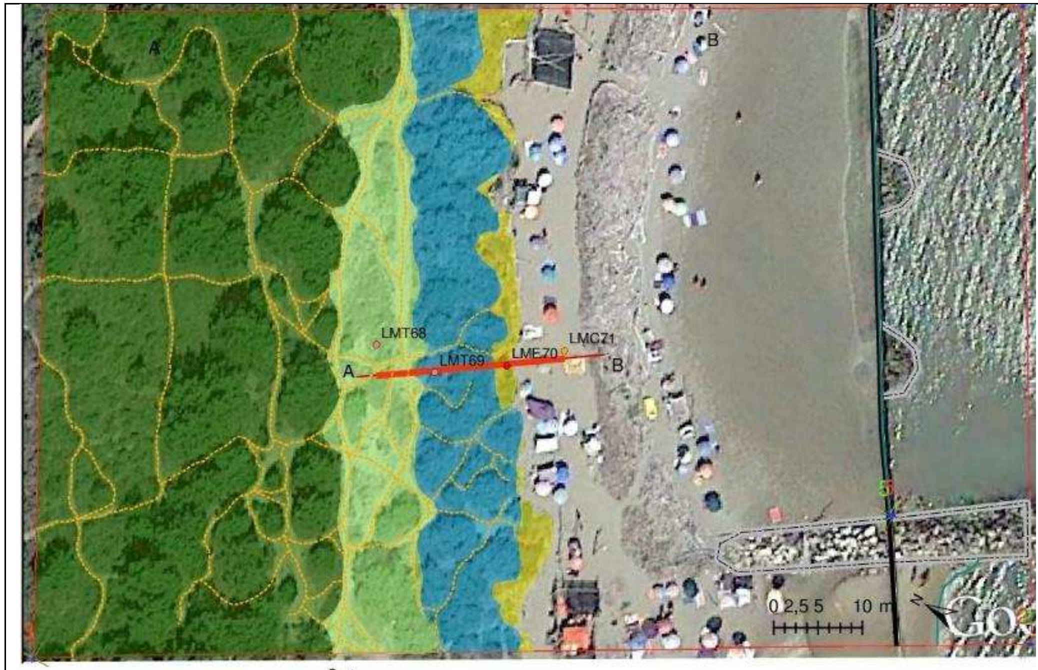




a – The inactive hummock dune area strongly affected by a dense network of trails.

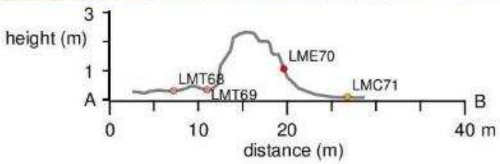
b and c – The inactive hummock dune ridge, stabilized by dense shrubs, with some small active hummock dunes on the seaward side.

APPENDIX K - Geomorphological maps - Transect 12 – Mort Lagoon



Legend

- habitat 1210
- habitat 2110
- Gr_3
- Shoreline
- Breakwater
- Groynes
- Trails
- Transects
- Active_hummock_dune_area
- Inactive_hummock_foredune_area
- Inactive_hummock_dune_area
- Woodland_area



a – The inactive hummock dune area strongly affected by a dense network of trails.

b – The inactive hummock dune ridge, stabilized by dense shrubs.

c – Rudimentary fence built with driftwood.

d – Coastal defences (groynes and a brakewater).