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Assessment of coastal dune restoration viability in the Veneto Region (Northeastern Italy)

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Abstract

Coastal environments around the world have been severely degraded by human activities, especially in the last century. This has resulted in serious structural and functional damage to the ecosystems of these transitional areas, which are as dynamic as they are fragile, and in a net loss of crucial ecosystem services, especially in the face of climate change threats. The implementation of sustainable coastal management measures or actions to restore degraded ecosystems are urgently needed. In this context, we revised and used several indices regarding geomorphology, biology, and ecology of dune systems along the Venetian coast to define the current conservation status and assess the viability of coastal dune restoration actions along the entire coast. The application of indices provided important indications on the sites and the actions to be taken to improve the functionality of the dune systems. Moreover, the indices provided useful insights to implement management strategies aimed at ensuring the current and future supply of ecosystem services from coastal ecosystems and to promote their sustainable use along the entire Venetian coast.

Chapter 1. Introduction

Coastal dunes are aeolian deposits arranged parallel to the coastline (Hesp 2002; Benavente et al. 2006; Bird 2011). Their size depends on the availability of sediments, the width of the upper beach, the prevailing winds, and the presence of plants that favour the deposition and consolidation of sandy substrates (Hesp 1991; Hesp & Walker 2013; Martínez & Psuty 2004). Dune systems provide a wide range of ecosystem goods and services (Martínez et al. 2013). The best understood and recognised services are cultural, recreational, and educational, but coastal dunes also provide life support, provisioning, and, most importantly, regulating services (Everard et al. 2010; Millennium Ecosystem Assessment 2005). This category includes coastal protection, which is important not only for mitigating current natural stressors, but also for addressing future threats from climate change impacts (Antonioli et al. 2017; Gracia et al. 2018; Spalding et al. 2014).

Coasts worldwide have experienced intense urbanisation and drastic habitat loss. Particularly in the Mediterranean area, dune systems have been replaced with hotels, holiday villages, and other infrastructures designed to accommodate and entertain the public during the summer months (Anthony et al. 2014; Vallés et al. 2011). As a result, human visitation to coastal areas has increased over time, leading to negative alterations of the remaining dune systems, which were already fragmented by past activities (Defeo et al. 2009; Sperandii et al. 2021). Human impacts have severely affected coastal ecosystems and their biological communities by altering the physical conditions (Defeo et al. 2009; Sperandii et al. 2021), ultimately leading to the loss of ecosystem goods and services they provide, including protection of coastal areas.

The loss and degradation of natural areas coupled with the loss of the services they provided claims an urgent need of preserving and restoring remnant ecosystems. To mitigate the impact of threats on coastal systems, humans have mainly intervened through grey engineering structures (Bezzi et al. 2018; Williams et al. 2018). However, these structures have often failed to achieve the expected results, as they are often unable to follow the natural coastal dynamics (Morris et al. 2018; Weisner

& Schernewski 2013). Measures such as beach nourishment have been partially successful in mitigating coastal erosion, but they are not definitive solutions and must be repeated over time (James 1975; Nordstrom 2005). For this reason, green solutions, also called nature-based solutions, have been increasingly used in restoration projects in recent years to mimic natural dynamics and mitigate threats in coastal areas (Doody 2013; Pontee et al. 2016).

For a proper planning of dune restoration and mitigation of human impact, it is of utmost importance to assess the current condition of degraded dune systems as well as their potential for restoration (Garcia-Lozano et al. 2020; Lithgow et al. 2015). To fully assess the potential for a coast to host and maintain an intact and functioning dune system, analysis of the geomorphological, climatic, biological, and management characteristics provides valuable information for actions to be taken in coastal planning (Bertoni et al. 2019; Ciccarelli et al. 2017). In this way, indices represent an important tool to support decision-making processes and are becoming increasingly important (Ciccarelli et al. 2017; Lithgow et al. 2015).

Several indices have been developed to assess the conservation status of dune systems and their vulnerability, but few analysed the restoration needs of coastal dunes, and the potential of a sandy coast to host a dune system, if it has been altered by humans. For this reason, this research develops indices that provide information that has rarely been considered in the literature. To this aim, a set of indicators aimed at evaluating geomorphological characteristics, meteo-hydrological and marine conditions, biological and ecological features, and the management approach were collected to define (i) the current conservation status of the dune system; (ii) the potential of a given beach stretch to host a dune system; (iii) the impacts related to management practises. These sub-indices have been then combined and applied to the Venetian coast in different ways to (iv) assess the restoration needs of coastal dune systems and (v) evaluate tailored management actions to be adopted to improve the suitability of the coast to host dune systems.

1.1 Coastal dune system formation, evolution, and vulnerability

Coastal areas are typical transitional ecosystems where natural processes associated with the interaction of terrestrial and marine environments influence the geomorphological, physical, and biological characteristics as well as the temporal evolution of coastal systems (Bertoni et al. 2020; Provoost et al. 2011). Sediments, mainly transported by rivers, are rehashed by marine currents, tides, wave action and wind, resulting in constant changes in the geomorphology of shorelines, coastlines, and land surfaces, even in the short term (Anthony et al. 2014; Bird 2011; Jackson & Nordstrom 2011; Wright & Thom 1977). The balance between these natural processes governs the sediment budget and leads to two possible outcomes, i.e., shoreline advance or retreat. When more sediment is added than removed, a surplus of sediment is created and the shore advances, i.e., builds seaward. The tidal regime controls the wave motion and hydrodynamics of the area, so that three main sectors can be distinguished in the morphological profile of a beach (*Fig. 1.1*), where very different geomorphological structures occur (Davis & Fitzgerald 2009; Ritter et al. 2002). These sectors are distinguished as follows:

- The shoreface represents the part of the beach that is always inundated and whose profile is constantly modified by the interaction between sediments and wave base. The lower limit of the shore area is defined by the absence of interaction of the waves with the bottom. The bidirectional movement of sediment on the bottom caused by wave action leads to the formation of one or more submarine bars to which the respective troughs are connected (Dashtgard et al. 2012).
- The foreshore is defined as the stretch of beach that is alternately exposed to the atmosphere and the sea, depending on the tidal regime of the area. Its width depends on the slope of the beach and the tidal regime of the area. The tidal range determines the time at which waves impact the bottom, and thus the formation of morphological structures such as ridges and runnels typical of a low-lying, dissipative beach (Orford & Wright 1978), and the position of the shoreline, which defines the boundary between terrestrial and marine environments (Ritter et al. 2002).

- The backshore represents the section of the beach that emerges from the sea and is continuously exposed to the atmosphere. In this section, the ordinary berm may develop in summer, while the storm berm occurs in winter (Dubois 1988). The backshore sediments are reshaped by the sea only during storm surges, while the winds can cause reshaping throughout the year, and the lower the humidity at the substrate level, the stronger the reshaping. The upper boundary is formed by the shoreline separating the uplifted beach from the dune system behind it and is reached only by exceptional storm waves (Davis & Fitzgerald 2009).

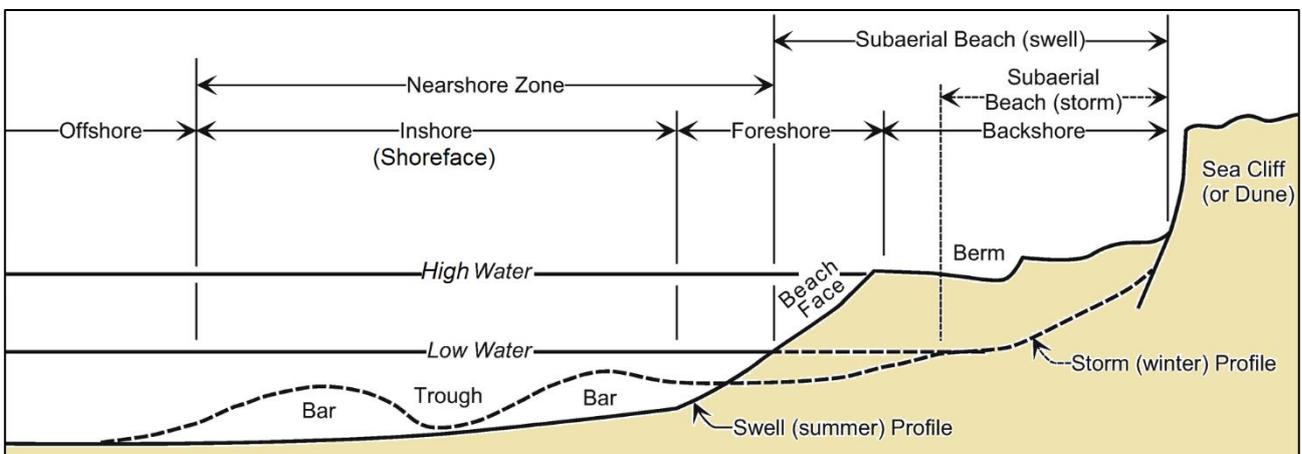


Figure 1.1: Morphological profile of a beach with main sectors and landforms (from Dingler 2019, modified).

The formation and morphology of the emerged part of the beach-dune system, i.e., the coastal dunes, are strongly influenced by wind energy and direction (McLachlan & Defeo 2017). High-energy winds blowing perpendicular to the shoreline are the most effective in transporting the sediment. Their contribution to the dune formation is proportional to the availability of sediment (i.e., the width of the backshore) and to the grain size. As a result, dune formation is enhanced when a high quantity of sediment is available, as in wide beaches, and when the grain size is small, since small particles can be more easily transported by winds than large particles (Davidson-Arnott & Bauer 2009; Goldsmith 1978).

However, coastal dune formation and evolution result not only from the interactions among wind, sediment and beach topography, but also from the interaction with plant communities (Durán &

Moore 2013). The initial dunes are the incipient foredunes, located above the high spring tide mark, on the backside of the beach. They form thanks to the presence of roughness-inducing elements, that reduce wind energy, resulting in sediment accumulation (Hesp 1999, 2002). Driftwood sometimes forms the focus for the initial accumulation of sand dunes, but vegetation is the most common element that contributes to the formation of incipient dunes (Psuty 1989). Incipient foredunes are sometimes ephemeral features, tending to be eroded or completely removed by severe storm events, or develop to form a larger established foredune (Hesp 2002).

When sediment accumulation prevails, incipient dunes become more coalesced and favour the formation of established foredunes (Feagin et al. 2010). Thus, foredunes parallel to the shoreline are formed through the continuous accumulation of windblown beach sand that is trapped by burial-tolerant vegetation. They have a greater height, width, age, and/or morphological complexity (Hesp 2002). From an ecological perspective, once pioneer salt-tolerant strand species colonize a shore in the presence of active aeolian transport, trapped sand acts as a positive mechanism for burial-tolerant “dune-building” grasses (*Fig. 1.2*). Burial-tolerant grass species often produce foliage and deep root systems that assist in the formation of a sand dune over time (Hesp 1991; Psuty 1992). Their foliage reduces wind velocity and filters sand from the wind, while their deep root systems help to stabilize dunes. They also have the ability to grow through accumulations of windblown sand (Chapman 1976; Maun 1998). As foredunes build up, sand inundation and salt spray levels decrease, while nutrient levels and vegetation cover increase, resulting in more stable dunes (Psuty 2008). As new incipient forms and new foredunes develop opposite, old foredunes will tend to become stabilised dunes over time and natural factors such as wind or waves are unlikely to change their shape because they are sheltered (Psuty 1989).

The development of vegetative cover on dunes and the reduced intensity of environmental stressors create favourable conditions for the colonisation and growth of a wider range of plant species and succession (Doing 1985).

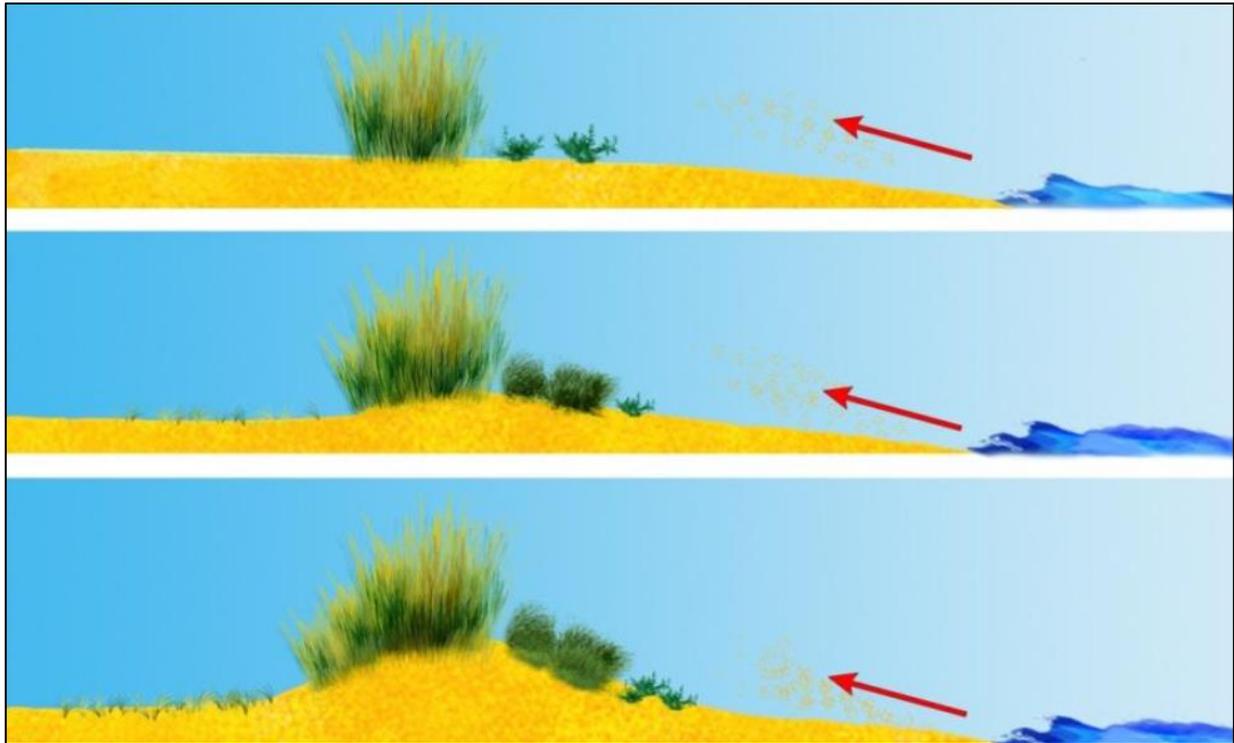


Figure 1.2: Representation of the dune formation process by the interaction between sand burial and plant communities (from Acosta and Ercole 2015).

1.1.1 Coastal vegetation zonation

With increasing distance from the sea, environmental conditions change along a gradient determined by natural stressors (Fenu et al. 2013; Ciccarelli 2015). Disturbances caused by wind and marine aerosols decrease, while the nutrient content and compactness of the substrate increase thanks to the action of colonising plants (Ciccarelli 2015; Du & Hesp 2020). For this reason, a series of environmental conditions parallel to the coastline develop within the dune system, leading to the formation of the so-called vegetation zonation (Acosta et al. 2007; Doing 1985). Communities found in coastal dune systems are therefore characterised by a considerable variation in species composition, richness, and dominance along the sea-inland gradient (Acosta et al. 2007; Del Vecchio et al. 2015).

The different plant communities occurring along the sea-inland gradient are for the most part recognized as habitat types under the Habitats Directive 92/43/EEC (Fig. 1.3). Starting from the beach and moving inland, a first strip near the berm on the emerged beach is characterised by annual pioneer plant communities (Habitat 1210 - *Annual vegetation of drift lines*). This is followed by typical

communities of the embryonic dunes, represented by paucispecific coenosis (Habitat 2110 - *Embryonic shifting dunes*) and perennial communities of unconsolidated white dunes dominated by *Calamagrostis arenaria* L. Roth (Habitat 2120 - *Shifting dunes along the shoreline with Ammophila arenaria (white dunes)*). Landward of the shifting sand dunes, there are several plant communities typical of environments with moderate natural disturbance and belonging to the continental biogeographic region (Habitat 2130* - *Fixed coastal dunes with herbaceous vegetation (grey dunes)*, 2160 - *Dunes with Hippophae rhamnoides*) or to the Mediterranean region (Habitat 2210 - *Crucianellion maritimae fixed beach dunes*, 2230 - *Malcolmietalia dune grasslands*, 2240 - *Brachypodietalia dune grasslands with annuals*). In the inter-dune wet depressions, semi-natural wet slacks with tall herbaceous plants, such as Habitat 6420 (*Mediterranean tall humid herb grasslands of the Molinio-Holoschoenion*) or Habitat 7210* (*Calcareous fens with Cladium mariscus and species of the Caricion davallianae*), are found. Further inland, the dune system is characterised by stable dunes on which woody sclerophyll scrub communities are found (Habitat 2250* - *Coastal dunes with Juniperus spp.*, 2260 - *Cisto-Lavanduletalia dune sclerophyllous scrubs*), while the innermost areas, where natural disturbance is much lower, are characterised by Mediterranean sclerophyll forest communities, i.e., *Quercus ilex* L. (Habitat 9340 - *Quercus ilex and Quercus rotundifolia forests*), and pine forests, i.e., *Pinus pinea* L. and/or *Pinus pinaster* Aiton forests (Habitat 2270* - *Wooded dunes with Pinus pinea and/or Pinus pinaster*).

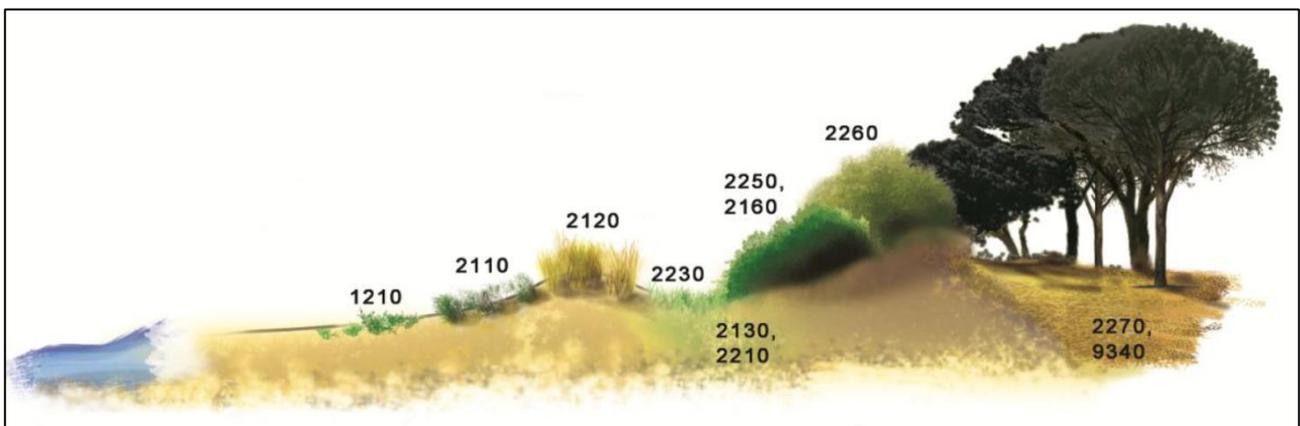


Figure 1.3: Coastal habitat types under Habitat Directive 92/43/CEE along Italian coasts (from Acosta & Ercole 2015).

1.2 Coastal dunes ecosystem services

Ecosystem services can be divided into four main categories (Millennium Ecosystem Assessment 2005):

- Supporting services, i.e., those processes that enable the ecosystem to exist and sustain itself, such as soil formation, primary production, and nutrient cycling.
- Provisioning services, i.e., those processes by which an ecosystem is able to provide useful goods to society, such as food, water, or other raw materials.
- Regulatory services, services that help regulate climate, the water cycle, the spread of disease, and other natural processes, keep the planet in balance, and counteract negative phenomena that could affect the well-being of society.
- Cultural services, which refer to the ability of ecosystems to provide a positive element for the spiritual, recreational, and educational spheres by their mere existence.

In coastal dune systems, there are many ecosystem services that can be found in each of the categories listed (Martínez et al. 2013). The most easily understood ecosystem service provided by coastal dune environments are those related to the cultural domain. Although these services are generally intangible, their benefits affect a large segment of society in the context of tourism and recreational activities where people can psychophysically benefit from the use of coastal environments (Drius et al. 2019; Everard et al. 2010; Liquete et al. 2013). Another very important service related to the cultural domain is the presence of a unique habitat composition, which makes coastal dunes biodiversity hotspot (Mehvar et al. 2018). The strong environmental gradient between sea and land, results in a richness of highly specialised plant and animal species that give coastal areas high aesthetic and educational value and are ideal model systems for understanding natural processes (Daily 2003; Everard et al. 2010).

In addition, the biodiversity of dune ecosystems can generate processes that allow the ecosystems themselves to exist (Drius et al. 2019; Martínez et al. 2013). Indeed, pioneer plant species favour the increase of organic matter content in the inland substrate, which promotes nutrient cycling and forms stable soils. Consequently, inland areas can host plant and animal species that do not tolerate the harsh conditions of shifting sand dunes further increasing nutrient cycling and soil stabilisation (Acosta et al. 2007; Fenu et al. 2013; Martínez et al. 2013). In addition, in many regions of the world, coastal areas are important for the supply of food, water, and timber, as well as goods that can be used directly and support local populations (Liquete et al. 2013; Martínez et al. 2013).

Finally, coastal dune ecosystems are extremely important due to their regulatory functions (Martínez et al. 2013). These include protection against flooding during storm surges. The presence of a structurally intact dune system makes it possible to counteract the intrusion of the sea during sea storms, which mainly occur in winter (Van der Meulen & Salma 1996). In addition, an intact and functioning beach-dune system is also important in counteracting coastal erosion. Coastal habitats and their vegetation play a key role as root systems stabilise and retain sediments, controlling the erosion process, especially in foredunes (Hesp 1991; Martínez et al. 2013). Climate regulation represents another very important regulatory service, as the primary production of plant species provides carbon sequestration, which in turn accumulates in the soil and contributes to the carbon stock. In this way, coastal ecosystems, along with their wide distribution, play an important role in regulating greenhouse gases in the atmosphere (Drius et al. 2019). Coastal dune ecosystems also regulate the amount of sediment and marine aerosol that would otherwise move inland. Another important service provided by coastal habitats is the ability to provide pollinators and support pollination networks, which are essential for plant reproduction in coastal ecosystems, as well as in other environments (Fantinato 2019; Ghazoul 2005).

All ecosystem services are provided only in the presence of healthy coastal habitats and are essential for coping not only with current threats, but also with future climate change threats (Spalding et al.

2014). However, coastal dunes are subject to direct and indirect anthropogenic pressures that threaten the existing biodiversity and the many ecosystem services they provide (Burkhard & Maes 2017; Crossman et al. 2013; Finkl & Makowski 2015).

1.3 Pressures and threats

The overall stability of a coastal dune ecosystem depends on the sediment budget, i.e., the difference between incoming and outgoing sediment (Giudice & Preziosi 2020; Psuty et al. 2014; Fig. 1.4). When this budget is positive, the likelihood that the dune system will expand and grow both laterally and vertically increases (Psuty 1992).

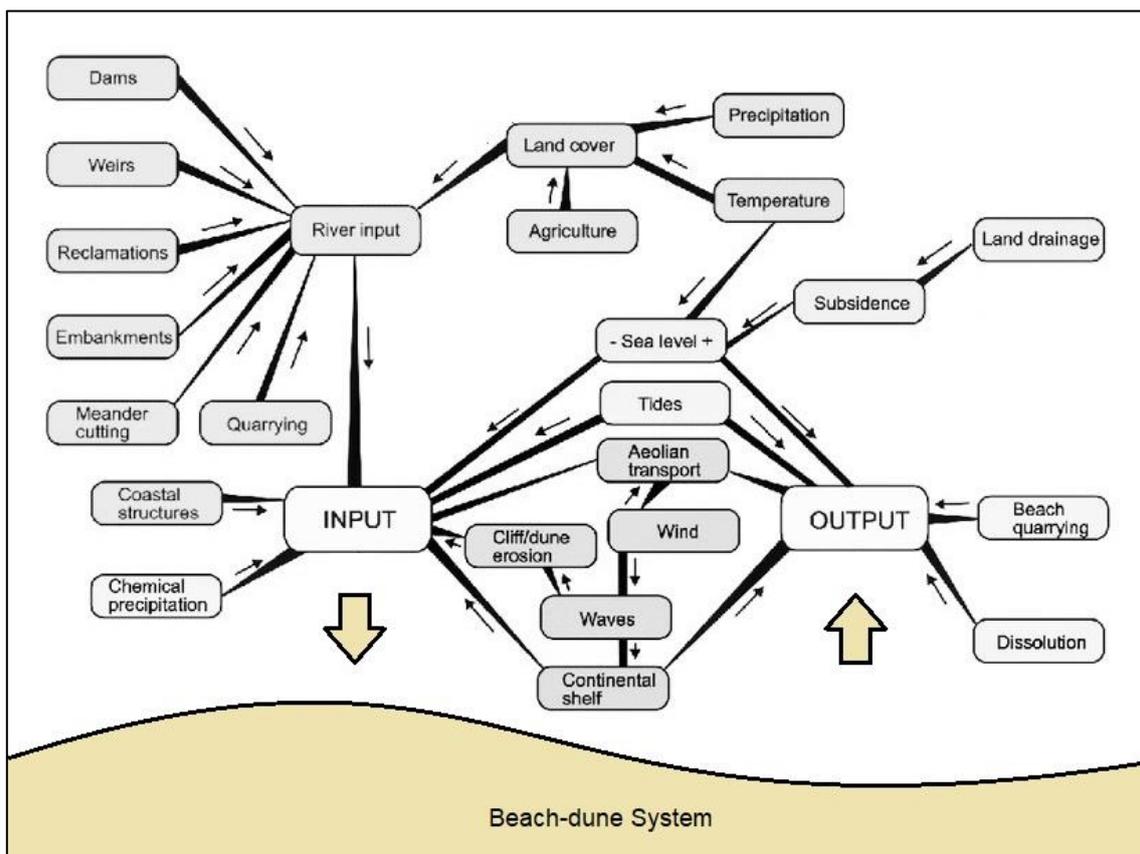


Figure 1.4: Sediments inputs and outputs in a beach-dune coastal system (from Pranzini & Williams 2021, modified).

Natural forcings, such as tectonic uplift, isostatic adjustment, marine transgression or regression, can reverse the trend of coastal accretion and erosion by naturally altering sediment input and output

(Anthony et al. 2014; Steffen & Wu 2011). However, these natural changes generally occur on a large time scale. In contrast, humans can cause significant changes in the short term. Since World War II, humans have greatly altered the territory through economic growth and technological development, leading to direct and indirect changes in coastal areas at both local and regional scales (Anthony et al. 2014). Humans have significantly affected the sediment budget of coasts and dune systems by removing variability in topography, altering coastal geomorphology, and impairing existing biological communities, resulting in the loss of biodiversity and of the proper functioning of coastal ecosystems (Acosta et al. 2007; Provoost et al. 2011), thereby leading to the loss of coastal dune resilience (Defeo et al. 2009; Lithgow et al. 2013; Nordstrom 2021) and changes in overall coastal development trends (Syvitski 2003).

1.3.1 Local pressures

At local-scale, coastal systems around the world have been largely exploited by human activities such as the construction of industrial and commercial complexes and by urban expansion (Everard et al. 2010). Coastal ecosystems are as dynamic as they are sensitive, and urban development, infrastructures, and the presence of human activities such as tourism and recreation have exerted intense pressure on surrounding natural habitats, which are then affected by pollution, overexploitation, and fragmentation (Buffa et al. 2012; Vallés et al. 2011). The natural habitats that remain today are smaller than in the past, have less biodiversity, and have very limited connectivity (Dixo et al. 2009; Sheaves 2009). Habitat loss and fragmentation, in turn, are leading to a progressive loss of coastal resilience, particularly in the face of future threats, especially from climate change (Martinez et al. 2017; Masselink & Lazarus 2019; Morris et al. 2020).

Unsustainable use of coastal areas is the main cause of biodiversity degradation and loss (Pinna et al. 2019; Sperandii et al. 2021; Vallés), which leads to severe changes in ecosystem conditions and natural dynamics (Vallés et al. 2011). Activities such as trampling or driving on beaches and dunes by tourists affect their structure and integrity (Prisco et al. 2021; Šilc et al. 2017), while mining of

mineral resources directly on the coast can also affect coastal systems if mining activities do not take into account the need to protect the natural environment (Thornton et al. 2006).

Human management of coastal areas can also have negative impacts (Davenport & Davenport 2006; Pranzini et al. 2020). In some cases, the geomorphology of entire coastal systems is completely reshaped to make the coastal environment more suitable for economic activities (Martínez et al. 2013). This ranges from reshaping the beach to accommodate visitors during the summer to creating artificial dune ridges to protect structures during the winter season (Nordstrom et al. 2015). In addition, the geomorphological dynamics of coastal dunes can be altered by management of adjacent areas. For example, the construction of rigid structures both behind and in front of the beach prevents the natural mobility of sediment (Syvitski 2003). Similarly, the daily mechanical cleaning of the beach to remove stranded material or the placement of coarse material that is more resistant to wind transport also alter the amount of sediment that contributes to the formation of new geomorphological forms and ensures the natural dynamics of coastal dune systems (Morton et al. 2015; Pranzini et al. 2020).

1.3.2 Regional pressures

Coastal systems are also influenced by human activities in seemingly distant areas (Syvitski 2003). Since coastal systems are connected to both terrestrial and marine environments, any activity or change in these environments can have indirect effects on them (Anthony et al. 2014).

An important example is the construction of dams to store water for irrigation or energy purposes. Water catchment by dams alters the solid load of the river (Willis & Griggs 2003), as large amounts of sediment are deposited upstream (Inman & Jenkins 1985). Therefore, sediments no longer reach the river mouth and cannot be redistributed by sea currents, resulting in a deficit in the sediment budget available to coastal areas near the river mouth (Willis & Griggs 2003; Warrick et al. 2015).

Riverbed's modifications are also an important action affecting sediment availability in coastal areas (Kesel et al. 1992). Channelization and embankment limit the amount of sediment that a river can

transport along its course, while straightening a riverbed can increase the velocity of water at the mouth so that sediment is thrown too far out to sea and does not become part of the circulation along the coast (Aiello et al. 2013; Billi & Rinaldi 1997). In addition, interventions at the estuary or along the coast, such as hydraulic and marine structures, can be a barrier to the progressive input of sediments and their flow along the coast (Syvitski 2003).

However, not only physical changes in the environment can alter the dynamic equilibrium of a coast. Other human activities in the hinterland can also have significant impacts on the coastal environment. Chemicals, pesticides, or fertilisers used in industrial processes enter coastal systems mainly through the aqueous medium (De Francesco et al. 2019; Díez et al. 2003). These products can interact with biological communities by chemical interference, sometimes irreversibly (Díez et al. 2003). In some cases, large amounts of man-made material are introduced by river floods and storm surges and can affect coastal biological communities through physical interference (Menicagli et al. 2020; Thushari & Senevirathna 2020). Thus, various forms of pollution can affect the proper functioning of coastal ecosystems.

1.3.3 Climate change

The impacts of ongoing climate change will affect the entire planet, but regional and local impacts will vary depending on local factors, requiring downscaling models (Wood et al. 2004). Overall, sea level will tend to rise as average atmospheric temperatures increase (IPCC 2021). Higher temperatures will lead to an increase in water mass in the oceans as glaciers melt and water volume increases due to the lower density caused by higher temperatures (Gornitz 1991; Houghton et al. 1990). This will lead to a rise in mean sea level, estimated to be between 28 cm and 188 cm by 2100 in the worst scenario (IPCC 2021). In some areas of the world, sea level rise will be exacerbated by natural coastal subsidence (Lambeck et al. 2011; Nicholls et al. 2021).

The term “coastal squeeze” refers to the prevention of natural landward transgression of coastal habitats that would naturally occur in response to sea level rise in conjunction with other coastal

processes (Doody 2004; Pontee 2013). This is related to the loss of natural habitats or their degradation due to the presence of fixed structures or highly damaging anthropogenic activities (Defeo et al. 2021; Lithgow et al. 2019). Therefore, coastal planning has important implications, particularly with respect to the potential impacts of climate change and mean sea level rise (Martinez et al. 2017; Masselink & Lazarus 2019).

1.4 Protection of coastal areas

The management of coastal areas must consider different points of view, because from an anthropocentric point of view, coasts are a resource used by society, but from an ecological point of view, they are also modified by the society (Turner et al. 1998; Wood et al. 2018). Therefore, it makes sense to consider and select measures that ensure both use and protection of coasts, and development opportunities should be balanced with conservation efforts (Cetin 2016).

Over the past century, various coastal management practises have been implemented around the world that aim to defend coasts, limit erosion, and ensure the presence of a usable beach (Davidson-Arnott et al. 2018; Pranzini et al. 2018). Intervention implementation can be associated with two contrasting approaches, hard engineering and soft engineering (Klein et al. 2001; Williams et al. 2018). The main difference concerns the rigidity of the structures. The hard engineering approach mainly involves man-made structures, which are defined as rigid because they are made of reinforced concrete and because they are not affected by the influence of the marine environment but counteract it by reflecting or dissipating its energy (Nordstrom 2014; Pranzini et al. 2018). On the other hand, soft engineering is less invasive and involves using natural materials and working with natural dynamics to maximise effectiveness (Morris et al. 2018). The two categories have different implications, especially from a landscape and sustainability perspective. Rigid structures have significant impacts on the environment and landscape due to their rigidity and entirely man-made construction (Morris et al. 2018; Pranzini 2018). These structures are static, do not follow the natural

dynamics of the coast, require maintenance, and are unable to provide multiple goods and services as they are designed with the single purpose of protecting the coastline (Morris et al. 2018; Pontee et al. 2016). As nature-based solutions, soft interventions mimic natural ecosystems and processes. They are more cost-effective, provide many ecosystem services, repair themselves after adverse phenomena, and adapt to climate change (Morris et al. 2018; Pontee et al. 2016).

1.4.1 Hard engineering

The main purpose of the rigid structures is to counteract wave energy. They are first distinguished according to their orientation with respect to the coastline and then divided into transverse and parallel defences (Pranzini et al. 2018; Williams et al. 2018).

For transverse defences, can be distinguished groynes and jetties (Van Rijn 2011). Groynes are built specifically to protect the shoreline and have the purpose of intercepting the longshore solid load by depositing sediment on the upstream side. The length and shape of groynes are fundamental to their effectiveness and have important effects on meteomarine climate and transport along the coast (Van Rijn 2011). Incorrect design can lead to severe erosion on the downstream side, making the groyne inefficient on the landward side in the worst case (Choufu et al. 2019). Finally, construction materials can also affect the durability of these structures and their maintenance (Williams et al. 2016). Jetties are very similar to groynes but are built for a different purpose. They are built near tidal inlets or river mouths to prevent channel filling (Ferreira et al. 2016).

Defensive structures parallel to the shoreline are of different types, but all have the common goal of counteracting waves or dissipating their energy. Seawalls are vertical walls that have different profiles depending on the context (Williams et al. 2018). However, in the long term, wave counteraction can damage the base of the seawall and lead to its collapse (Nordstrom 2014; Plant & Griggs 1992). For this reason, well-designed foundations and coarse material are required at the base of seawalls (Plant & Griggs 1992). Other structures, such as revetments, include steps and rocky embankments made of coarse material and dissipate wave energy by simulating the slope of the foredune (Nordstrom 2014).

Breakwaters are structures parallel to the shoreline that are constructed beyond the surf zone at the shoreline surface. They can be surfaced or submerged, resulting in different visual effects of the structures (Lamberti et al. 2005). Their effect is mainly to counteract waves, while multiple breakwaters also have a diffraction effect (McCormick 1993). The length of breakwaters, their distance from the shoreline, and from other breakwaters are critical to the shape of the shoreline (Lamberti et al. 2005). A positive sediment balance is achieved by increasing the length of breakwaters and decreasing their distance from the shoreline and between breakwaters, thereby increasing wave counteraction and diffraction (Biggs et al. 2000; McCormick 1993).

1.4.2 Soft engineering

Soft engineering interventions make it possible to mimic the natural function of wave attenuation and protect human coastal infrastructure and activities (Doody 2013). Beach nourishment has been the most widely used intervention in recent decades, also in Italy (Pranzini 2018). This intervention expands the beach through replenishment by artificially adding sediment to the eroding beach. To improve the effectiveness of such interventions, the granulometry, i.e., the average size of the grains and the sorting of the sediment, must be as similar as possible to that of the natural beach (Dean 2002; Nordstrom 2005; James 1975). Otherwise, the added sediment must be volumetrically adjusted to compensate for the difference in grain volume compared to that of the natural beach. If existing natural forces erode the restored beach, it may be necessary to periodically nourish the beach over time, resulting in the need to reinvest the initial capital (James 1975).

Other soft engineering techniques include beach drainage systems to reduce the moisture of beach sediment and facilitate its transport inland by the wind (Damiani et al. 2011), or porous groynes on the emerged beach to intercept sand grains and facilitate their deposition (Van Rijn 2011). Recently, dune systems have been recognised as natural elements of coastal protection and more and more studies are showing the interventions that need to be carried out along coasts to ensure a healthy dune system, that can best fulfil its coastal protection function (Bezzi et al. 2018; Doody 2013). The most

important process that ensures the survival of the entire beach-dune system is the exchange of sediments with the beach (Nordstrom 2005; Martínez et al. 2013). While dunes grow in summer by accumulating sediment picked up from the beach and transported inland by winds, dunes return sediment to the beach during winter storms, compensating for the loss of sediment from the beach, which is naturally renourish in this way (Psuty et al. 2014; Van der Meulen & Salma 1996).

1.5 The need for restoration and conservation

Protecting biodiversity supports climate change resilience, adaptation, and mitigation, and enhances human well-being by providing ecosystem services. The rapid elimination and degradation of coastal dunes and their habitats highlights the urgent need to conserve these ecosystems and restore those that have already been degraded (Lithgow et al. 2013).

The Society for Ecological Restoration identifies key principles and standards that should be considered when planning and implementing restoration and conservation actions (Higgs et al. 2018; McDonald et al. 2016; *Fig. 1.5*). In practise, however, coastal dune ecosystem restoration actions can vary widely and sometimes can even be in contrast. Therefore, the selection of the measures to be implemented must be adapted to the specific area (Martínez et al. 2013). For this reason, a prior analysis of the problem is necessary, followed by a correct planning of the restoration projects during the intervention. It is important to understand how habitats and plant communities are organised and interact, and to understand how they have changed in order to predict how they will change in response to natural and human influences. Therefore, it is necessary to distinguish changes related to the natural dynamics of coastal dune processes from those due to human impacts (Doody 2013; Martínez et al. 2013; Nordstrom 2021).



Figure 1.5: The eight principles for the practice of ecological restoration defined by the Society for Ecological Restoration (from Gann et al. 2019).

From an economic perspective, the decision to intervene or not is based on a cost-benefit analysis, as costs and benefits represent the loss or gain in system value after interventions (De Groot et al. 2013). Depending on the ecosystems and their threats, different methods have been developed to upgrade the ecosystem from the current state to the target state through own interventions. In general, restoration actions should be based on ecological, geomorphological, and social criteria to maximise the goods and services provided by restored dunes. Furthermore, when effective and sustainable ecosystem restoration is coupled with conservation and sustainable use, it results in a reversal of trend in conservation status, i.e., from deteriorating to better conditions (McDonald et al. 2016). In general, two baseline situations can be distinguished in coastal areas, namely degraded coastal dunes and removed coastal dunes (Martínez et al. 2013).

1.5.1 Degraded coastal dunes

In degraded dune systems, the primary need is to prevent erosion and promote sediment accumulation in the foredune, as this allows protection of the remaining portion of the dune system to the hinterland and facilitates its natural or artificial recovery (Doody 2013). The most common measure to promote sediment accumulation and foredune growth is the planting of native dune-forming species such as *Calamagrostis arenaria* (L.) Roth (De Lillis et al. 2004). An alternative way to promote sediment accumulation in the dune area is through sand trapping fences (Doody 2013; Nordstrom & Jackson 2013). These can be made of a variety of materials, from wood to geotextiles, and have the purpose of acting as a barrier, reducing wind speed, and promoting the deposition of transported material (Doody 2013; Nordstrom 2021). Unlike vegetation, the rigidity of structures does not follow the growth of the dune, resulting in its failure to stabilise in the absence of colonisation by plant species (Elko et al. 2016). Possible solutions to encourage the natural or artificial establishment of new seedlings and ensure the formation of a plant community that helps increase the size of the dune over time include irrigation systems and fertilisation practises (Doody 2013; Martínez et al. 2013).

If the lack of sediment is one problem, the removal of sediment from beach-dune systems is another. Mechanical cleaning of the beach removes much sediment that would normally be discarded, which affects the sediment budget of the coastal area (De Falco et al. 2008). In addition, improper mechanical cleaning can damage the base of the dune, which subsequently tends to lose sediment (Bertoni et al. 2019).

Another need in degraded coastal systems is the restoration of the plant communities. From trampling by tourists to cattle grazing, human activities have damaged native species and altered the physical conditions of dune habitats, encouraging invasion by ruderal plants and alien species and often altering natural vegetation zonation over time (Šilc et al. 2017; Sperandii et al. 2021). The planting of native species, coupled with the eradication of alien species could be a practical way to restore ecosystems (Buffa et al. 2021).

1.5.2 Eliminated coastal dunes

Severely fragmented or, in the worst cases, completely eliminated dune systems require extensive interventions to restore all abiotic, chemical, and physical factors on which coastal dune systems are built (Doody 2013; Fernández-Montblanc et al. 2020). Dunes can be fully reconstructed by depositing sediments directly where the dune system or ridge is missing (Fernández-Montblanc et al. 2020). The deposited material is then shaped with earth-moving machines into the desired form, which should be as close as possible to the natural one (Castelle et al. 2019; Doody 2013). This technique is also used to build dune ridges during the winter to protect infrastructure from storm surges and to create an artificial reservoir of sand that is redistributed along the beach the following season. However, such artificial dune ridges cannot be considered a dune system because they would not be able to sustain themselves over time (Nordstrom et al. 2015). To promote the maintenance of the reconstructed dune and trigger the natural developmental dynamics of a coastal dune, native species should be planted immediately (Martinez et al. 2013).

Dune reconstruction should use sediments that have the same physical and chemical properties as natural ones so that the interventions are sustainable over time (Martinez et al. 2013). In addition, natural environments are characterised by spatial variability, particularly in topographic features (Castelle et al. 2019; Nordstrom et al. 2009). Replicating this variability in sediment modelling contributes to make coastal dunes immediately efficient and able to counteract adverse phenomena. In addition, winds can alter the dune in two ways once it is rebuilt. On the one hand, winds will continue their erosive action by removing sand from dunes if they are not consolidated by vegetation (Hesp 2002). On the other hand, winds will transport sediments from beaches to dune systems. In this case, sedimentation in dune areas could be accelerated by building sand trapping fences in addition to planting seedlings (Nordstrom & Jackson 2013).

Chapter 2. Materials and methods

2.1 Study area

The study focuses on the coast of the Veneto region (northern Adriatic), between the mouths of the Adige River in the south and the Tagliamento River in the north. In particular, the study focused on the Venetian province, which is 95 km long, and includes the coastal municipalities of Chioggia, Venice (Lido-Pellestrina district), Cavallino Treporti, Jesolo, Eraclea, Caorle and San Michele al Tagliamento (*Fig. 2.1*).



Figure 2.1: The Venetian coast investigated (— ; ESRI Satellite, <https://www.esri.com/>).

The evolution of the Venetian coast is the result of the balance between the transgressive regime of the sea, caused by the subsidence of the area, the rise of the average sea level, and the fluvial contribution following the last ice age (Tosi et al. 2007). Characteristic is the predominance of sandy beaches (Fontolan et al. 2014), which are composed by Quaternary deposits with high carbonate content, due to the contribution of sediments from the Alpine and resurgence rivers represented

mainly by the Tagliamento, Piave, Sile, Brenta and Adige rivers (Franco 1973). The average width of the beaches is about 70 m, and they are mainly composed of well-classified fine sand that determines a slight slope of the emerged beach, reflecting their morphodynamic structure as a dissipative beach (Fontolan et al. 2014).

The Venetian coast falls under the temperate macro-bioclimate and is characterised by an average temperature of 14.4 °C and precipitation of about 1090 mm per year (Della Bella et al. 2021). The prevailing winds that play an important role in the formation of coastal dunes are the Bora and the Scirocco. The Bora is a NE wind, blowing especially in winter, while the Scirocco is a SE wind, typically blowing during the summer season (Rossetti & Scotton 2017). The average wind speed is 3.1 m/s, causing wave motions that are typically bimodal, with a significant wave height of about 0.47 m on annual average (Bezzi et al. 2018), while the tidal regime is of semidiurnal and microtidal type, with an average excursion of 70 cm and a counterclockwise circulation characteristic of the Adriatic basin (Silvestri et al. 2005). According to the classification system of Psuty (1988) and Hesp (2002), the most abundant dunes on the coast are the established foredunes which are in close contact with the emerged beach where they originate and with which they actively exchange sediment (Bezzi et al. 2018). Given the variation in coastal orientation, with respect to prevailing winds, beach width and integrity of plant communities, established foredunes height ranges from 2 m to 9 m along the Venetian coast (Bezzi et al. 2018).

The coastal dynamics of the region have been altered by human interventions since Roman times (Zunica 1971), but the most invasive interventions that have profoundly changed the Veneto coast have been made since 1950, as the coast underwent intense urban development, mainly to promote the tourism (Bezzi et al. 2009; Caniglia 2007). According to statistical surveys conducted by the Veneto Region, there are approximately 3.7 million arrivals and almost 24 million presences of tourists along the Venetian coast annually (Regione Veneto 2020; <https://statistica.regione.veneto.it/>; accessed January 2022; *Table 2.1*).

Table 2.1: Tourism data 2019 for the Venetian coast (<https://statistica.regione.veneto.it/>).

Local Turistic System	Arrivals	Presences
Chioggia	269.875	1.376.237
Cavallino	781.692	6.269.451
Jesolo-Eraclea	1.241.290	5.933.744
Caorle	648.272	4.319.483
Bibione	810.497	5.851.482
<i>Total</i>	3.751.626	23.750.397

In 1950, almost the entire coast of Veneto was characterised by the presence of natural coastal dunes that could reach a height of 10 m (Bezzi & Fontolan 2003). In the 1960s, at least 20 km of the entire Veneto coastline was affected by coastal erosion, corresponding to about 15% of the coastline. Despite the construction of hard coastal defences, now present on more than 60% of the Veneto coast (Fontolan et al. 2014; Fig. 2.2), the total length of erosion sectors increased to 52 km in 2012 (MATTM-Regioni & T.N.E.C. 2018).

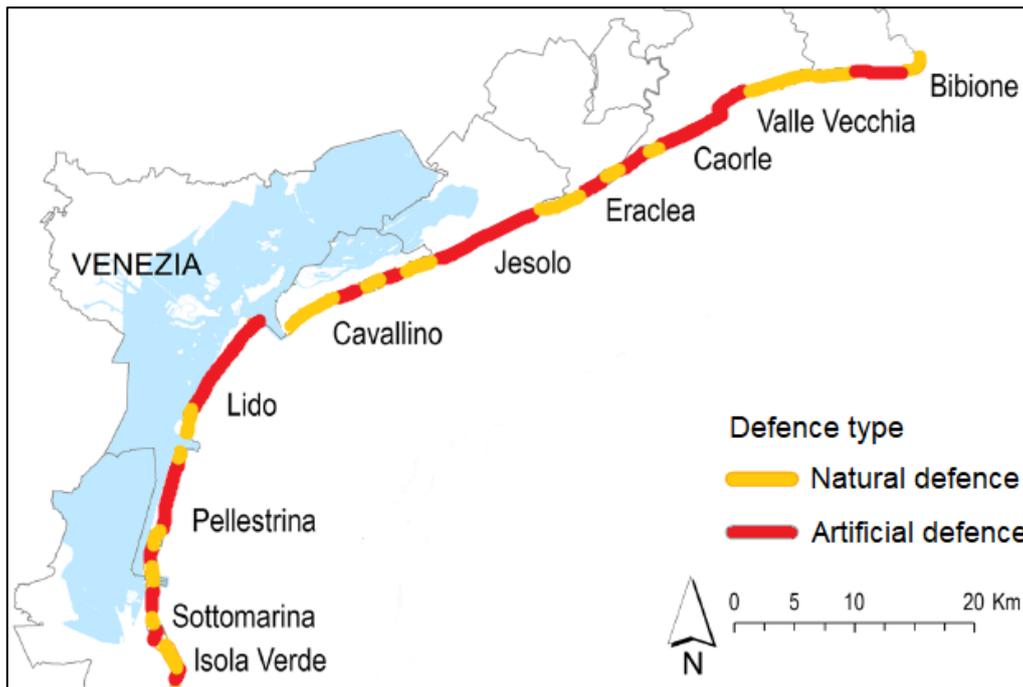


Figure 2.2: Defence types along the Venetian coast (from Fontolan et al. 2014, modified).

Since hard structures have not been able to reverse the erosion trend, especially on the beaches most frequented by tourists, it was decided in 1995 to proceed with beach nourishment to support the local economy in sites with wide and usable beaches (Ruol et al. 2018). Between 2003 and 2015, 4.8

million square metres of sediment were replenished on the most affected coastal sectors (MATTM-Regions & T.N.E.C. 2018), i.e., those near the main tourist centres, namely Jesolo, Eraclea, Caorle, and Bibione. However, in Jesolo, despite the presence of rigid coastal protection structures and regular beach nourishment, beaches can lose several metres within a few hours, even during the storms that occasionally occur in summer (Legambiente 2021).

Today, dune systems are limited to about 59 km of the entire Veneto coastline (Bezzi et al. 2018). In the province of Venice, the currently existing dunes measure a total length of about 34 km (Fontolan et al. 2014; Fig. 2.3).

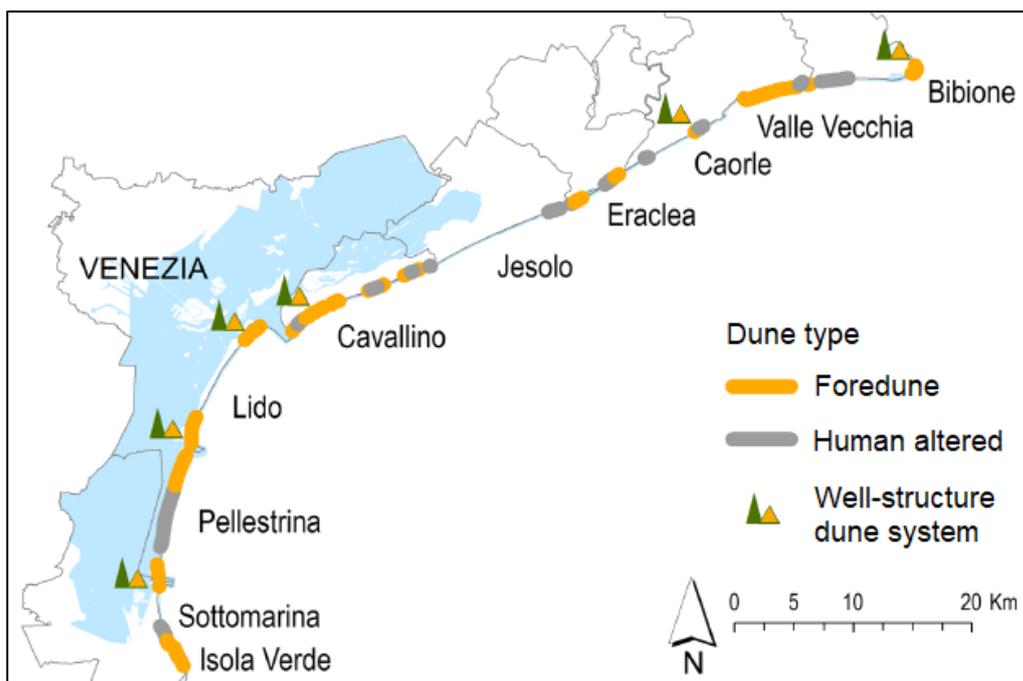


Figure 2.3: Dune types along the Venetian coast (from Bezzi et al. 2018, modified).

Thanks to the Habitats Directive 92/43/EEC, the remaining dune systems in Veneto have been better protected. The presence of habitats of Community interest, including priority habitats such as Habitat 2130*, whose occurrence in Italy is limited to the northern Adriatic due to a temperate macrobioclimate (Silan et al. 2017), has allowed the designation of 7 between *Sites of Community Interest (SCIs)* and *Special Protection Areas (SPAs)* which fall within the investigated coastal sectors (Fig. 2.4; Table 2.2).

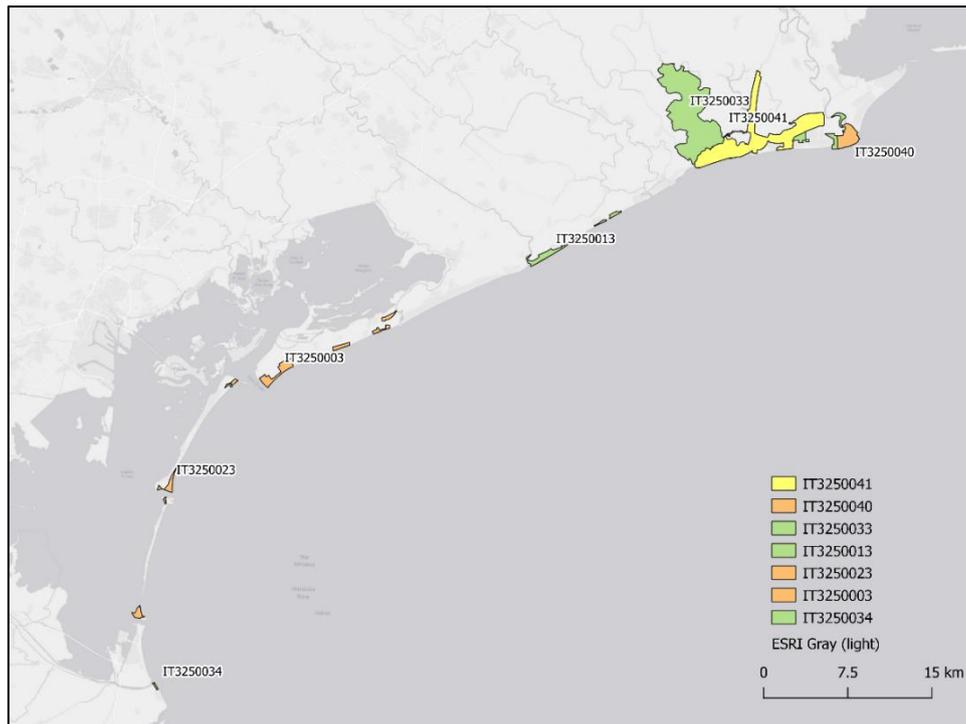


Figure 2.4: — SCI; — SPA; — SCIs and SPAs within the study area (ESRI Gray, <https://www.esri.com/>).

Table 2.2: Data of SCIs and SPAs within the study area (Ruol et al. 2016).

<i>Site code</i>	<i>Type</i>	<i>Site name</i>	<i>Area (ha)</i>
IT3250003	SCI & SPA	Penisola del Cavallino	315
IT3250013	SCI	Laguna del Mort e Pinete di Eraclea	214
IT3250023	SCI	Lido di Venezia: biotopi litoranei	166
IT3250033	SCI	Laguna di Caorle - Foce del Tagliamento	4386
IT3250034	SCI	Dune residue del Bacucco	13
IT3250040	SCI & SPA	Foce del Tagliamento	280
IT3250041	SPA	Valle Vecchia - Zumelle - Valli di Bibione	2089

2.2 Physiographic units and littoral cells

The definition of sectors (physiographic units and cells) followed the classification proposed by Fontolan et al. (2014), based on geomorphological criteria. Specifically, the Venetian coast was first divided into 12 physiographic units (Fontolan et al. 2014; *Fig. 2.5*), geographically distinguished by the presence of dissections such as estuaries and tidal inlets. Each unit was then further subdivided by Fontolan et al. (2014) into sectors (littoral cells) with homogeneous characteristics such as hydrodynamics, sedimentation, and morphological structure. As a result, 65 sectors were defined along the Venetian coast (*Table 2.3*) each one corresponding to a site.

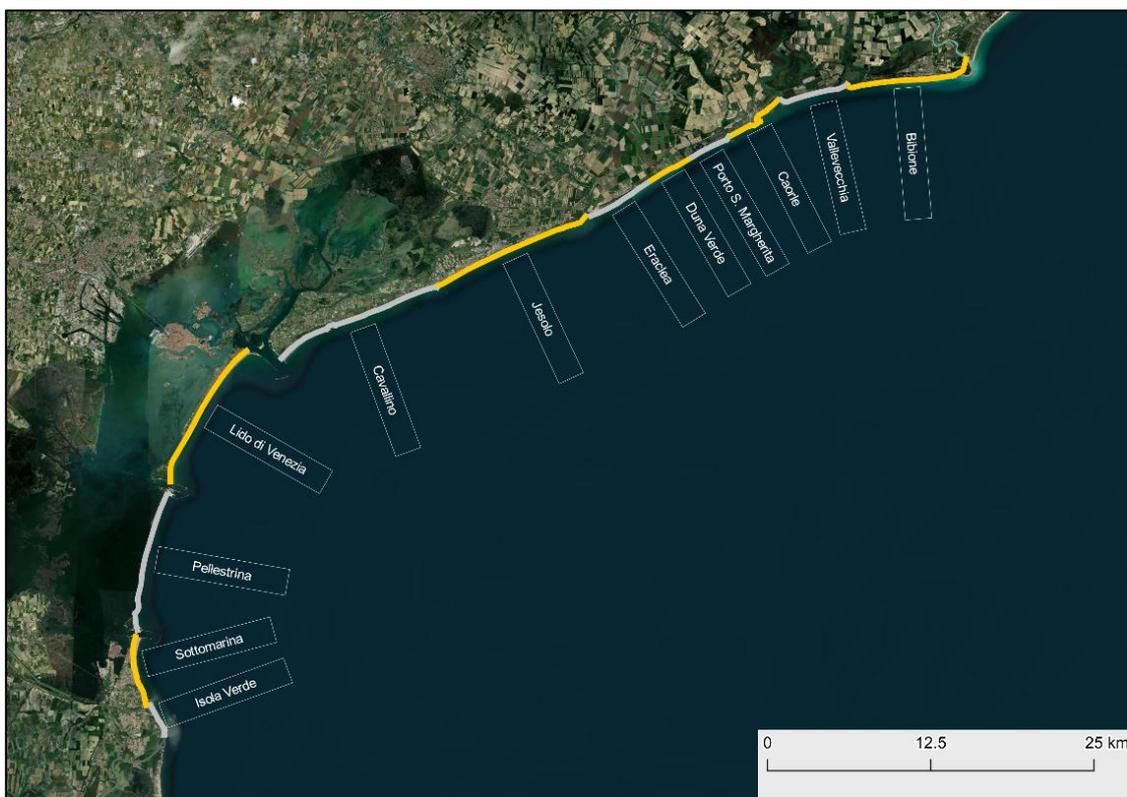


Figure 2.5: Physiographic units identified within the study area (ESRI Satellite, <https://www.esri.com/>).

Table 2.3: Physiographic units and respective littoral cells in the study area.

ID	Physiographic unit	Littoral cell	Length (m)	Tot. length (m)
1	Isola Verde	IVC1	422	
2	Isola Verde	IVC2	298	
3	Isola Verde	IVC3	315	
4	Isola Verde	IVC4	306	
5	Isola Verde	IVC5	649	
6	Isola Verde	IVC6	158	
7	Isola Verde	IVC7	230	
8	Isola Verde	IVC8	323	2701
9	Sottomarina	SC1	445	
10	Sottomarina	SC2	1290	
11	Sottomarina	SC3	869	
12	Sottomarina	SC4	1771	
13	Sottomarina	SC5	1900	6275
14	Pellestrina	PC1	1251	
15	Pellestrina	PC2	1521	
16	Pellestrina	PC3	1709	
17	Pellestrina	PC4	2051	
18	Pellestrina	PC5	1650	
19	Pellestrina	PC6	1353	
20	Pellestrina	PC7	1335	10870

(continued)

<i>ID</i>	<i>Physiographic unit</i>	<i>Littoral cell</i>	<i>Length (m)</i>	<i>Tot. length (m)</i>
21	Lido di Venezia	LC1	2476	
22	Lido di Venezia	LC2	2672	
23	Lido di Venezia	LC3	2035	
24	Lido di Venezia	LC4	979	
25	Lido di Venezia	LC5	1188	
26	Lido di Venezia	LC6	2696	12046
27	Cavallino	CVC1	2470	
28	Cavallino	CVC2	1477	
29	Cavallino	CVC3	273	
30	Cavallino	CVC4	648	
31	Cavallino	CVC5	1424	
32	Cavallino	CVC6	1943	
33	Cavallino	CVC7	2700	
34	Cavallino	CVC8	2747	13682
35	Jesolo	JC1	753	
36	Jesolo	JC2	3101	
37	Jesolo	JC3	2078	
38	Jesolo	JC4	2915	
39	Jesolo	JC5	1173	
40	Jesolo	JC6	344	
41	Jesolo	JC7	1306	
42	Jesolo	JC8	1126	12796
43	Eraclea	EC1	783	
44	Eraclea	EC2	364	
45	Eraclea	EC3	403	
46	Eraclea	EC4	879	
47	Eraclea	EC6	1255	
48	Eraclea	EC7	725	
49	Eraclea	EC8	1233	5642
50	Duna Verde	DVC9	3712	3712
51	Porto Santa Margherita	SMC10	857	
52	Porto Santa Margherita	SMC11	817	
53	Porto Santa Margherita	SMC12	1252	
54	Porto Santa Margherita	SMC13	390	3316
55	Caorle	CC1	1681	
56	Caorle	CC2	760	
57	Caorle	CC3	2727	5168
58	Vallevecchia	VC1	1129	
59	Vallevecchia	VC2	2153	
60	Vallevecchia	VC3	2233	5515
61	Bibione	BC1	905	
62	Bibione	BC2	2944	
63	Bibione	BC3	2079	
64	Bibione	BC4	2332	
65	Bibione	BC5	1983	10243

2.3 Definition of restoration needs and potential to host dune systems

To analyse the restoration needs of Venetian coastal systems and to define the potential of a given coastal strip to host a dune system, we developed a set of indices by combining several indicators.

Indicators represent variables with high explanatory power as they are descriptors of a component or a process of systems (Bernard, 2002), and have been widely used in environmental management monitoring processes because they allow to simplify reality by concisely summarising the state of a system (Failing et al. 2013). To be effective, indicators should be selected that are easily measurable, sensitive to anthropogenic pressures and natural disturbances, and provide early warnings (Prach et al. 2019). In coastal ecosystems that are ruled by several different interacting factors, the set of indices should consider both abiotic (e.g., geomorphological characteristics, climatic conditions), and biotic (biological and ecological features) factors, as well as the management approach they are subjected to. In this way, when properly integrated together, they allow summarising the state of the analysed system, its possible weakness, and assessing the degree of restoration that it needs (Garcia-Lozano et al. 2020; Ciccarelli et al. 2017; Lithgow et al. 2014), thereby providing decision makers with clear indications of the actions that need to be taken at each site.

2.4 Selection of indicators

While several indices have been developed to assess the conservation status of dune systems and their vulnerability (e.g., to erosion), a few analysed the restoration needs, and the potential of a sandy coast to host a dune system, when altered.

To select indicators, we conducted an extensive literature search in Scopus (<https://www.scopus.com/>) and ISI Web of Science (<https://www.webofscience.com>). The search considered articles published up to September 30, 2021. Articles were selected by keywords such as 'index', 'restoration', and 'coastal dune'. The search returned 118 articles. The complete list is provided in *Annex I*.

Successively, the search was screened according to the article topic, aim, and the type of indicators. Articles that did not relate to sandy coastal dunes were removed, as were those that did not specifically relate to restoration. Most papers and indices concerned the vulnerability to flooding or erosion. Since the set of indicators proposed did not address the needs of restoration and the potential of a given sandy coastal strip to host a dune system, they were also discarded.

This further screening reduced the list to only two articles in which the proposed index allowed to comprehensively evaluate the conservation status of dune systems and the potential to restore them.

The first one is the *ReDune Index* (Lithgow et al. 2014), which was first applied to the Gulf of Mexico coast. The index is defined by the difference between positive factors (e.g., ‘relative length of foredune’; ‘high priority species’; ‘protection from storms and hurricanes’) that contribute to the formation and maintenance of the dune system and negative factors that cause its degradation (e.g., ‘destabilization by trampling and overgrazing’; ‘pressure by visitors and vehicles’; ‘proximity of touristic sites’). The index allows dune systems to be classified according to their restoration needs. ‘Conservation’ is defined when the positive factors outweigh the negative ones, reflecting a healthy system; ‘Restoration’ is established when the negative factors affect the dune system, but it is possible to intervene because the effects are reversible; while ‘Rehabilitation’ is defined for those sites where the negative impacts have affected the dune system and its restoration can be achieved only through massive interventions.

The second study (Garcia-Lozano et al. 2020) took place in the Mediterranean context. It proposes several indices that can be used to determine the type of management required for a given coastal site. As with the *ReDune Index* (Lithgow et al. 2014), the application of the indices developed by Garcia-Lozano et al. (2020) allows the evaluation of the most appropriate management measure in each sector analysed. According to the state of conservation of the coastal dunes, the potential of the beach to host a dune system and the impacts of coastal management, it is possible to identify, in order of intensity of actions to be taken, ‘Conservation’, ‘Restoration’, ‘Recovery’ or ‘Renaturalisation’.

In this research, we applied the latter (Garcia-Lozano et al. 2020), although properly modified to adapt indicators and indices to the local situation. Moreover, some new indices to summarise a) *Coastal Management Requirement (CMR)*, and b) *Dune Boosting Potential (DBP)* are also proposed.

The selected index is based on the checklist method (Davies et al. 1995), and includes 30 indicators grouped in the following 4 sub-indices (*Table 2.4*): (i) *StaDun*, which defines the current conservation status of coastal dunes based on geomorphological, physical, and biotic (vegetation) variables; (ii) *BeaPot*, which analyses the potential of a beach to host a dune system based on its physical characteristics; (iii) *CoMan*, which identifies the pressures resulting from management; (iv) *SurLan*, which classifies the different sites based on the landscape elements behind the beach-dune system. Details on measurements of each indicator and calculation are provided in *Annex II*.

2.5 Sub-indices description

2.5.1 *StaDun*: Geomorphological and ecological status of dunes

The *StaDun* index is based on 11 indicators (*Table 2.4*). These variables allow to understand the current state of coastal dunes by describing their conservation status and evolution over time (Hesp 2002). Specifically, indicators 1-7 examine the morphology of the dunes (e.g., type, structure, height, extent) and their evolution over time. Indicators 8-11 evaluate the status of existing plant communities by analysing, in particular, species composition in term of typical sand dune species (species resistant to sand burial and able to promote the formation of dune systems, i.e., Type III species according to García-Mora et al. (2001)), native and focal species, invasive alien species, and ruderal species.

Geomorphological and topographic variables were assessed by using digital orthophotos, satellite imagery, and digital terrain models, while plant communities were assessed through a database of 1078 georeferenced vegetation plots of 1m x 1m size x 208 species (*Annex II*). The plots were surveyed from 2010 to 2021 by the Plant Ecology research team of Ca' Foscari University along the dune systems on the Venetian coast. For the dune systems of Lido di Venezia, published plots,

available in Filesi et al. (2017) were used. Native and focal species of the northern Adriatic dune systems were defined according to Acosta & Ercole (2015), alien species according to Galasso et al. (2018), and ruderal species according to Del Vecchio et al. (2019).

2.5.2 *BeaPot*: Beach potential to host dunes

The potential of a beach to host dunes is defined by 9 indicators (*Table 2.4*). This index includes variables describing the morphodynamic state in relation to erosion or accretion (e.g., beach profile, recent shoreline evolution, sediment budget), and other drivers such as upper beach slope and width, wind intensity, and sediment sorting. Indicator values were obtained from orthophotos, digital terrain models, literature, or databases (*Annex II*).

With respect to Garcia-Lozano et al. (2020), indicator 8 was modified by replacing ‘Area of the beach covered by pebbles’ with ‘Sediment budget during the period 2004-2010’ (data retrieved from Fontolan et al. 2014).

2.5.3 *CoMan*: Conservation actions and management of the beach-dune systems

According to Garcia-Lozano et al. (2020), the *CoMan* index includes 12 indicators to describe the management and protection of the beach-dune system. Here, we propose a modified approach which involves considering the 12 variables as indicators of impact, namely, improper use and lack of management and/or protection. In this way, the higher the value of *CoMan*, the greater the negative impacts on the beach-dune system resulting from (the lack of) management. The different approach used in the calculation of *CoMan* is aimed at enabling us to hypothesise tailored management actions to enhance the capability of a site to host a dune system and maintain it over time.

Moreover, three indicators were removed, namely those related to revegetation and alien species eradication, because they were assumed to be intrinsic attributes of the condition of coastal dunes, and the level of protection according to the IUCN classification (Dudley 2008), because it was redundant with the other management measures evaluated.

The tourism pressure indicator (indicator 1) was defined differently than in Garcia-Lozano et al. (2020). The data available for the area were expressed based on the number of visitors per unit area, and the thresholds for class assignment were redefined as shown in *Table 2.4*. In addition, the ratio of the area occupied by temporary and permanent structures (indicators 7, 8) was extended to the entire beach-dune system and not limited to the dune system as indicated in Garcia-Lozano et al. (2020). This is because any temporary or permanent structure on the emerged beach also alters the sediment transport towards the dune system.

As a result, 9 indicators were included, which regard to a) the pressure exerted to the system by tourists and tourist facilities (indicators 1, 7, and 8); b) management actions to limit the impact on the existing dune systems (indicators 2, 3, 4, and 9); c) management practises potentially affecting the sediment budget and the natural dynamics of the system (indicator 6); d) active measures aimed at promoting the development of the dune system through sediment accumulation (indicator 5). Indicator values were defined on the basis of field trips, communication with local administrators, literature, and orthophoto analysis (*Annex II*).

2.5.4 *SurLan*: Surrounding landscape

The *SurLan* index considers impacts associated with landscape elements in contact with the beach-dune system. Differently from Garcia-Lozano et al. (2020), we proposed assessing only the predominant category behind the beach-dune system, since it includes information from all the indicators proposed by the authors. However, it maintains a descriptive function for the context in which the studied area is embedded as originally. The indicator was assessed by analysing the landscape context (composition, according to *Corine Land Cover* categories, i.e., urban, agricultural, and natural areas) behind the beach-dune systems using thematic cartography and orthophotos in a GIS environment (*Annex II*).

Table 2.4: Indicators investigated for each subindex and related scoring ranges.

StaDun indicator	Unit	Score				
		0	1	2	3	4
1 Types of dunes according to Garcia-Lozano and Pinto (2018)	-	Absent	Incipient	Dune ridge	Dune ridge with semi-fixed dunes	Dune field
2 Surface area of the dune system	ha	<0.1	<5	<10	<15	>15
3 Area occupied by the dunes in relation to the beach-dune system	%	<5%	<25%	>25%	>50%	>75%
4 Maximum height of the foredune	%	<1	>1	>3	>4	>5
5 Incipient morphologies on the dune face	%	0%	<5%	>5%	>25%	>50%
6 Evolution of the dune front since 1956	-	Disappearance	Retreated	Stability	Recovery	Progression
7 Structural status of the foredune according to Hesp (2002)	-	5	4	3	2	1
8 Type III species on the dune front according to García-Mora et al. (2001)	-	<5		>5		>10
9 Beach-dune system restricted plants according to Acosta & Ercole (2015)	-	<10		>10		>15
10 Invasive species according to Galasso et al. (2018)	-	>4	3	2	1	0
11 Ruderal species according to Del Vecchio et al. (2019)	-	>7	>5	>3	>1	<1
BeaPot indicator	Unit	Score				
		0	1	2	3	4
1 Slope of the beach	degrees	>0.2		<0.2		<0.1
2 Evolution of the beach during the period 2004-2010	m/y	<-3	<-2	<-1	<0	>0
3 Beach orientation in relation to the prevailing winds	-	Perpendicular seaward	Oblique seaward	Parallel	Oblique landward	Perpendicular landward
4 Average intensity of the wind	m/s	<3		<3.5		>3.5
5 Significant Wave Height	m	>1		>0.7		<0.7
6 Diameter of the sediment	d50	>2	>1	>0.5	>0.25	<0.25
7 Sands <0.5 mm	%	<5%	>5%	>15%	>25%	>50%
8 Sediment budget during the period 2004-2010 *	(m ³ /m)/y	<-25	<0	<25	<50	>50
9 Width of dry beach	m	<15	>15		>35	>50
CoMan indicator	Unit	Score				
		0	1	2	3	4
1 Touristic use pressure *	user/m ²	<1	<2	<3	<4	>4
2 Information boards	-	Efficient				Absent or inefficient
3 Managed paths	-	Lateral	Suspended	On land	In access	Not regulated
4 Dune area with restricted access	%	100%	>75%	>50%	>25%	<25%
5 Sand traps	-	Efficient/unnecessary		Stable		Inefficient or absent
6 Mechanical cleaning/levelling	-	Absent	Occasionally	Weekly	Daily	Causing dune scarp
7 Surface area occupied by seasonal services on beach-dune system*	%	0%	<5%	>5%	>10%	>15%
8 Surface area occupied by permanent services on beach-dune system*	%	0%	<25%	>25%	>50%	>75%
9 Protection of the system and the immediate environment	%	100%	>75%	>50%	<25%	0%
SurLan indicator	Unit	Score				
		0	1	2	3	4
1 Impact according to the predominant land category in the first 100m	-	Concentrated urban areas	Dispersed urban areas	Urban land	Croplands	Natural areas

* Indicators changed compared to Garcia-Lozano et al. (2020). Explanations in Annex II.

Each indicator was measured following the guidelines provided by Garcia-Lozano et al. (2020), and measures were ranked on a 0 to 4 scale. Afterwards, a summarizing value for each sub-indices was then calculated using the following formula (Eq. 2.5.1):

$$SV = \frac{\sum IS_{current}}{\sum IS_{max}} \quad Eq. 2.5.1$$

where SV ('Sub-index Value') is the summarizing value of the subindex, $IS_{current}$ (current 'Indicator Score') is the score assumed by each indicator according to the measurements, and IS_{max} (maximum 'Indicator Score') is the maximum score that can be assumed by each indicator. In this way, SV ranges from 0 to 1.

Following Garcia-Lozano et al. (2020), each index was then classified as a) 'Low', for scores <0.33; b) 'Medium', for values between 0.33 and 0.66; and c) 'High', for scores >0.66, depending on the values obtained. Then, using the approach proposed by Garcia-Lozano et al. (2020), the sub-indices were then combined to obtain a value expressing a) the management requirement of each coastal strip, and b) the restoration potential. Sub-indices have been calculated for each cell, thereby allowing to classify them accordingly. However, the changes concerning some indicators, in particular the approach used in the calculation of the index *CoMan* involved also changing the combination of sub-indices. The proposed indices, their calculation and the range of values are reported below.

2.6 Coastal Management Requirement (CMR)

To define the status of each cell and obtain indications on the most appropriate management actions, the *Coastal Management Requirement (CMR)* index was defined. It derives from the combination of *StaDun* (current status of dunes in each cell) and the product of *CoMan* and *BeaPot*, which expresses the effect of human impact (lack of management) on the intrinsic potential of the beach-dune system. By combining the classes assumed by *StaDun* and *BeaPot* * *CoMan*, each cell has been assigned to a management requirement (Table 2.5).

Table 2.5: Management measures needed according to definition method elaborated by Garcia-Lozano et al. (2020).

<i>CMR</i>	<i>StaDun</i>	<i>BeaPot * CoMan</i>
<i>Conservation</i>	High	Low
	Medium	Low
<i>Restoration</i>	Medium	Medium
	Medium	High
<i>Recovery</i>	Low	Medium
<i>Renaturalisation</i>	Low	High

‘Conservation’ identifies sites where dune conservation status is good and supported by good management practices of the coastal system (i.e., low impact). ‘Restoration’ identifies sites where the dune system is degraded but could recover through interventions to restore the biotic component of dune systems, followed by better management practices. ‘Recovery’ includes sites where dunes do not currently exist, but where the physical characteristic of the beach has the potential to host a dune system and maintain it over time if it is recreated and adequate management practices are implemented. ‘Renaturalisation’ includes sites where the recreation of the beach-dune system would require a combination of hard and soft engineering interventions since currently neither the physical nor management characteristics would allow the natural development.

2.7 Dune Boosting Potential (DBP)

To assess the actual ability of a cell to host a dune system, the *Dune Boosting Potential (DBP)* index was developed. It is a combination of the potential of a given cell to host a dune system based on physical and morphological characteristics of the beach, and the intensity of human impacts. The index is calculated as follows (Eq. 2.7.1):

$$DBP = BeaPot - CoMan \quad \text{Eq. 2.7.1}$$

It follows that the lack or poor management may outweigh the natural potential of a beach to host and maintain a dune system. The index ranges from -1 to +1. The more negative the index, the lower the chances that a cell will host a persistent dune system over time. On the contrary, positive values

indicate that management is correct, or the effects of a not efficient management is limited, thus allowing the potential of the beach to develop and form a healthy dune system.

Each cell has been assigned to a specific class based on its *DBP* value to define the degree of the system to improve its current potential. Specifically, cells with negative values were assigned to the 'Low' class, cells with values between 0 and +0.33 were assigned to the 'Medium' class, while cells with values above +0.33 were assigned to the 'High' class. The class name defines the degree of potential of a cell to promote the formation of a dune system if it is not present, or to promote its implementation if it is already present. In this way, cells in the 'Low' class correspond to areas where the physical potential of the beach is overwhelmed by highly impactful management activities that prevent the formation and development of a dune system. The 'Medium' class identifies cells where the positive features of the beach are almost equalled by the negative effects of management activities and the formation and development of a dune system may be stunted. Finally, cells in the 'High' class represent areas where the management activities conducted would allow the coexistence with a dune system permitting a proper formation and development.

2.8 Management actions hypotheses

The management of coastal areas should consider different points of view to allow the selection of measures that ensure a balance between economic development and protection.

To understand which management actions can enhance the ability of a site to host a dune system and maintain it over time (i.e., increasing value of *DBP* index) at the same time safeguarding economic activities, *CoMan* indicators (*CoMan* 3-9, *Table 2.4*) were progressively modified. The score of each selected *CoMan* indicator was shifted by one (light blue arrows in *Fig. 2.6*) or by two classes (dark blue arrows in *Fig. 2.6*) to simulate a lower impact achieved by improved management actions.

CoMan indicator	Unit	Score				
		0	1	2	3	4
1 Touristic use pressure *	user/m ²	<1	<2	<3	<4	>4
2 Information boards	-	Efficient			Absent or inefficient	
3 Managed paths	-	Lateral	Suspended	On land	In access	Not regulated
4 Dune area with restricted access	%	100%	>75%	>50%	>25%	<25%
5 Sand traps	-	Efficient/unnecessary		Stable	Inefficient or absent	
6 Mechanical cleaning/levelling	-	Absent	Occasionally	Weekly	Daily	Causing dune scarp
7 Surface area occupied by seasonal services on beach-dune system*	%	0%	<5%	>5%	>10%	>15%
8 Surface area occupied by permanent services on beach-dune system*	%	0%	<25%	>25%	>50%	>75%
9 Protection of the system and the immediate environment	%	100%	>75%	>50%	<25%	0%

Figure 2.6: Shifting in CoMan indicators by 1 class (light blue arrows) or 2 classes (dark blue arrows).

Changes were applied from the easiest and most inexpensive management measures that local authorities could change, to the most demanding. ‘Low effort’ measures include the management of paths, installing sand traps, or regulating the frequency of mechanical cleaning (CoMan 3, 5 and 6). ‘Medium effort’ measures, i.e., changes in management measures that are more challenging to modify from a practical point of view because they involve high initial investment, include the fencing of the dunes or reducing the extent of coverage of permanent or temporary structures on the dune beach system (CoMan 4, 7 and 8). ‘High effort’ measures, i.e., actions with higher costs continuity over years, include the active surveillance of dune systems (CoMan 9). Changes in variables related to tourism pressure (CoMan 1) were not considered, as the objective was to evaluate enhancement in the suitability of a site to host a dune system without affecting tourism activities and, therefore, the source of coastal economic revenues. Management related to information boards (CoMan 2) was also excluded from the possible changes, as the installation of information boards may have a non-efficient improvement if, despite their presence, they are ignored by tourists.

Specifically, the least changes in management actions able to improve the number of low potential sites by 25%, 50% and 75% were defined, as well as the best hypothesis tested. Then, some illustrative cells were selected to show alternatives and differences in actions and starting situations to be considered during management planning.

Chapter 3. Results

The overall results of the different sub-indices (*StuDun*, *BeaPot*, *CoMan*, *SurLan*), *Coastal Management Requirement (CMR)*, and *Dune Boosting Potential (DBP)* are presented below. The values of each sub-index (*StuDun*, *BeaPot*, *CoMan*, *SurLan*), *CMR*, and *DBP* for each site, along with maps showing the distribution of *CMR* and *DBP* for each physiographic unit are provided in *Annex III*.

3.1 *StuDun*: Geomorphological and ecological status of dunes

The application of the *StuDun* subindex revealed that 60% of the analysed sectors belonged to the intermediate class ('Medium'; values between 0.33 and 0.66), covering about 53 km of the Venetian coast (*Table 3.1*; *Fig. 3.1*). The indicators that most contributed to this result included the 'Maximum height of the foredune' which was limited in most sites of this class (e.g., in cells *EC1*, *VC1*, *VC2*; *Annex III*), as limited was the presence of 'Incipient morphologies on the dune face' (e.g., in cells *IVC1*, *EC1*, *VC1*; *Annex III*). Other indicators that influenced the state of the dune systems concerned the plant communities present, i.e., the scarce presence of 'Type III species on the dune front according to García-Mora et al. 2001' (e.g., *EC7*, *LC6*, *BC5*; *Annex III*) and the marked presence of 'Alien species' in the dune system (e.g., *LC1*, *CVC2*, *BC1*; *Annex III*).

Twenty-five sites belonged to the lowest class ('Low'; scores <0.33) of the conservation status, with a total length that covers almost 40% of the coast (*Table 3.1*; *Fig. 3.1*). The majority of these sites were characterised by the absence of a true dune system, which has led to the assignment of a 0 score to all the indicators of the index in examination. The cell *DVC9* (Duna Verde; *Annex III*) represented an example of particularly degraded dune system, because in this cell it was poorly developed and characterised by a limited height and by the absence of incipient forms, as well as by a limited number of species typical of coastal dunes.

Only one sector has been classified as ‘High’ (score >0.66) and corresponded to the westernmost end of Cavallino (i.e., *CVC1*; Annex III), 2.47 km long (Table 3.1; Fig. 3.1). It was characterised by the presence of a dune system that has considerably progressed since 1956 and was now highly developed, even in relation to the total surface of the beach-dune system. Moreover, fragmentation appeared to be limited and there were vegetation communities rich in species typical of the beach-dune system.

Table 3.1: Number of sites and total length for each class identified for the StaDun index.

Class	Total sites	Percentage sites (%)	Total length (km)
<i>High</i>	1	1,54	2,470
<i>Medium</i>	39	60,00	53,458
<i>Low</i>	25	38,46	36,038

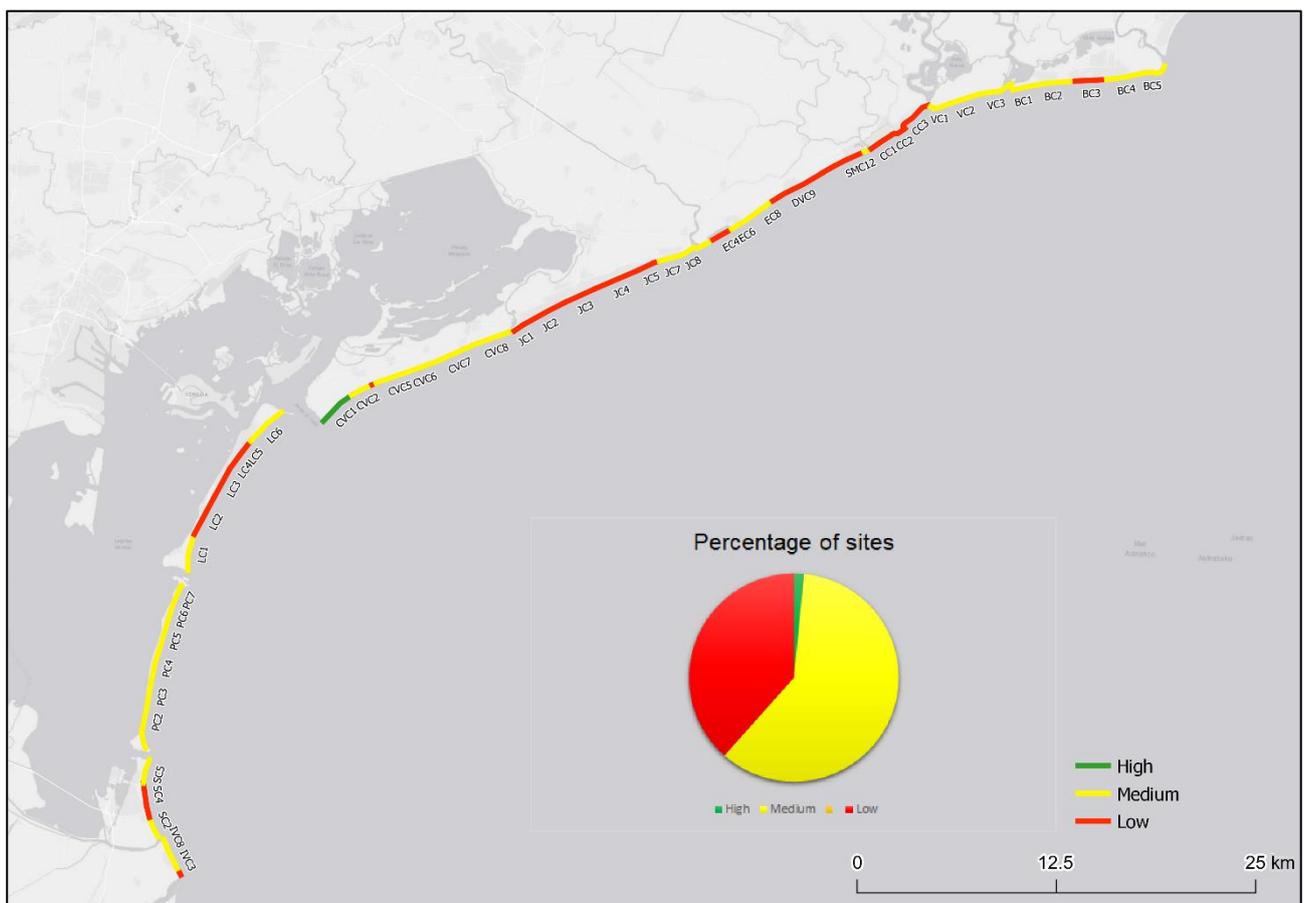


Figure 3.1: Representation of StaDun index values for each cell analysed along the Venetian coast (ESRI Gray, <https://www.esri.com/>).

3.2 *BeaPot*: Beach potential to host dunes

The analysis of the natural potential of the beaches to host a dune system revealed that more than 80% of the investigated sectors had characteristics that would guarantee a high potential ('High'; scores >0.66), covering more than 80 km of the Venetian coast (*Table 3.2; Fig. 3.2*). Indeed, almost all the sites showed high values for the 'Slope of the beach', due to the gentle slope of most of the sites (e.g., *IVC8, JC1, CC3; Annex III*), as well as for the 'Significant wave height', the 'Diameter of the sediment' and the percentage of 'Sand <0.5 mm', which had favourable characteristics along the whole Venetian coast.

The central sector of Caorle (i.e., *CC2; Annex III*) did not present a real beach in its 760 m of length (*Table 3.2; Fig. 3.2*). The absence of the beach in this section resulted in all the indicators of *BeaPot* subindex being assigned a value of 0, with a consequent low potential ('Low'; scores <0.33).

The remaining sites have been classified as 'Medium' (values between 0.33 and 0.66) and covered more than 10% of the coastline (*Table 3.2; Fig. 3.2*). The indicators that mainly affected the potential were 'Slope of the beach' (e.g., *PC7, EC3, SMC10; Annex III*) and 'Width of dry beach' (e.g., *JC8, PC7, SMC10; Annex III*).

Overall, two indicators were highly variable along the Venetian coast, sometimes assuming low values, even in sites which presented a high natural potential. The first of these indicators was the 'Evolution of the beach during the period 2004-2010' which showed 10 sites (e.g., *IVC1, JC5, CC3; Annex III*) with a shoreline retreat of 3 m per year and a total of 27 eroding sites. The remaining sites fell into stable (n=21; e.g., *LC3, CVC8, EC3; Annex III*) or accretive (n=17; e.g., *IVC8, PC1, BC1; Annex III*) conditions. The second indicator was the 'Sediment budget during the period 2004-2010' which showed the presence of 24 sites in sediment deficit (e.g., *PC3, VC2, BC4; Annex III*) and the remaining 41 in sediment surplus (e.g., *PC1, SC5, VC3; Annex III*).

Table 3.2: Number of sites and total length for each class identified for the BeaPot index.

Class	Total sites	Percentage sites (%)	Total length (km)
<i>High</i>	55	84,62	80,863
<i>Medium</i>	9	13,85	10,343
<i>Low</i>	1	1,54	0,760

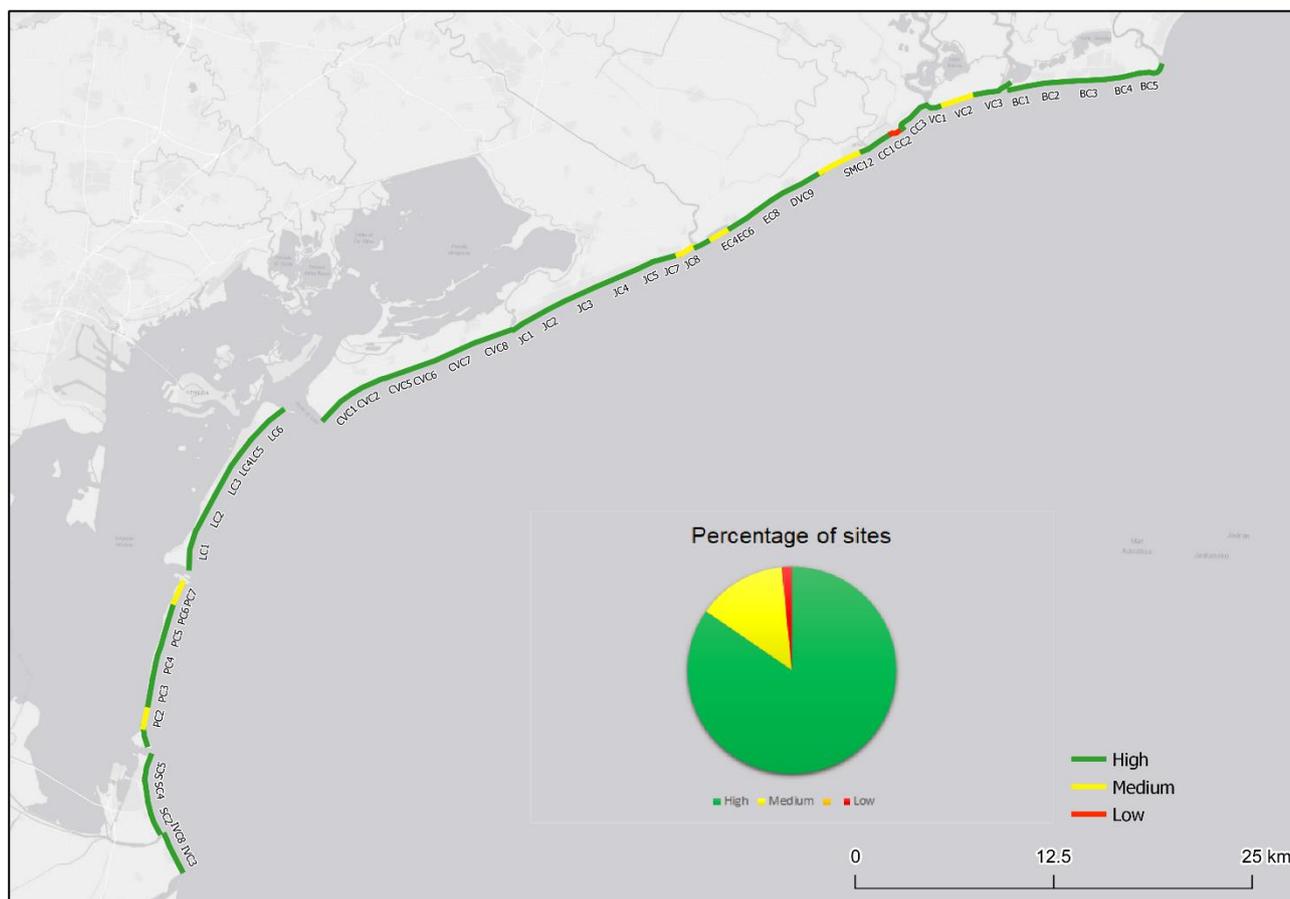


Figure 3.2: Representation of BeaPot index values for each cell analysed along the Venetian coast (ESRI Gray, <https://www.esri.com/>).

3.3 CoMan: Conservation actions and management of the beach-dune systems

The analysis of the *CoMan* subindex showed that more than 40% of the investigated sectors belonged to the highest impact class (score >0.66) and covered half of the total length of the Venetian coast (Table 3.3; Fig. 3.3). Several indicators contributed to the assignment of sites to this class. ‘Touristic use pressure’ showed high impact values for the majority of sites (e.g., *CVC7*, *EC6*, *BC2*; Annex III). ‘Information boards’ were absent or ineffective in most of sites, as was also the case for the indicator ‘Sand traps’, which has taken on high impact values for the same reason (e.g., *CVC5*, *EC6*, *BC4*;

Annex III). The strong impact was also due to the absence of fencing to dune systems ('Dune area with restricted access') at almost all sites (e.g., *CVC5, EC6, BC4; Annex III*), and to the high frequency (namely daily) of the 'Mechanical cleaning/levelling the beach in high season'.

About 50% of the sites (n=34) has been classified in the 'Medium' class (values between 0.33 and 0.66) and had a slightly lower total length than the highest impact class, namely 41 km (*Table 3.3; Fig. 3.3*). The lower impact compared to the 'High' class sites was mainly related to a lower 'Touristic use pressure' (e.g., *IVC8, EC1, BC1; Annex III*) and the presence of effective or unnecessary 'Sand traps' (e.g., *IVC8, LC6, EC1; Annex III*). Other aspects that determined a minor impact were the lesser presence of temporary and permanent structures on the whole dune beach system (e.g., *LC1, EC8, VC3; Annex III*).

Only three sectors fell into the lowest impact class (score <0.33), covering less than 5% of the assessed coastline (*Table 3.3; Fig. 3.3*). These were sites belonging to the Vallevicchia (i.e., *VCI, VC2; Annex III*) and Pellestrina (i.e., *PC1; Annex III*) physiographic units. Compared to the 'Medium' class sites, they had better characteristics especially in terms of the presence and effectiveness of information boards and the limited mechanical cleaning and levelling of the beaches.

The indicator 'Protection of the system and the immediate environment' had the highest impact value at all sites, including all impact classes. This underlined the lack of active protection as a common impact throughout the Venetian coast.

Table 3.3: Number of sites and total length for each class identified for the CoMan index.

<i>Class</i>	<i>Total sites</i>	<i>Percentage sites (%)</i>	<i>Total length (km)</i>
<i>High</i>	28	43,08	46,292
<i>Medium</i>	34	52,31	41,141
<i>Low</i>	3	4,62	4,533

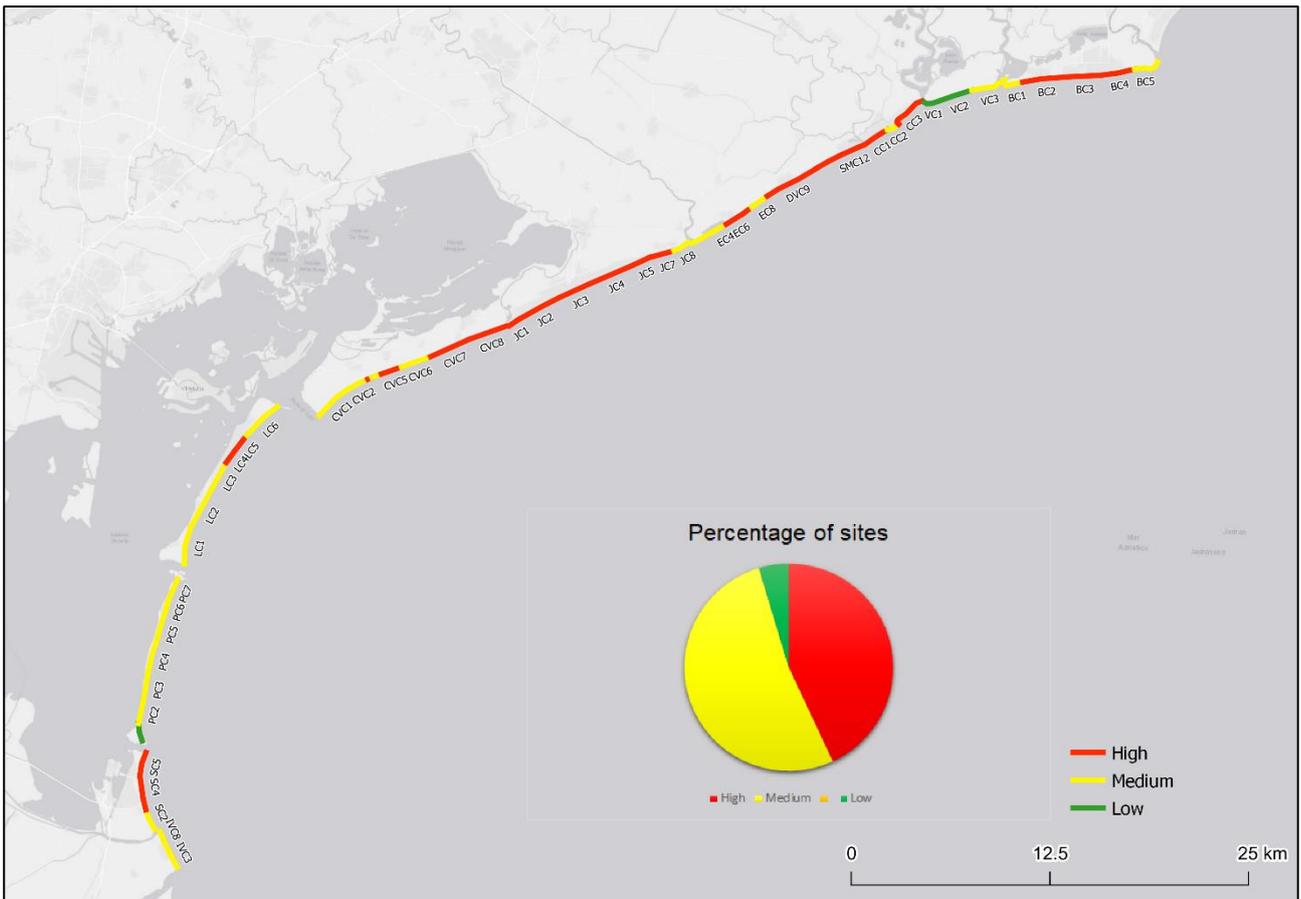


Figure 3.3: Representation of CoMan index values for each cell analysed along the Venetian coast (ESRI Gray, <https://www.esri.com/>).

3.4 SurLan: Surrounding landscape

The analysis of the landscape behind the beach-dune system revealed that only 20% of the sites (e.g., *EC1*, *VC1*; *Annex III*), representing about 15% of the total length of the coast, could be classified in the lowest impact category ('Low', score >0.66) because they are in contact with natural areas and croplands (*Table 3.4*; *Fig. 3.4*). The *SurLan* index took intermediate values ('Medium', between 0.33 and 0.66) for about 35 km corresponding to 22 sites (e.g., *IVC1*, *BC1*; *Annex III*) that were in contact with urban land (*Table 3.4*; *Fig. 3.4*). Finally, almost half of the Venetian coast fell into the highest impact class ('High', score <0.33 ; *Table 3.4*; *Fig. 3.4*) with a total of 30 sites in contact with concentrated and dispersed urban areas (e.g., *JC4*, *CC1*; *Annex III*).

Table 3.4: Number of sites and total length for each class identified for the SurLan index.

Class	Total sites	Percentage sites (%)	Total length (km)
<i>High</i>	13	20,00	13,903
<i>Medium</i>	22	33,85	34,235
<i>Low</i>	30	46,15	43,828

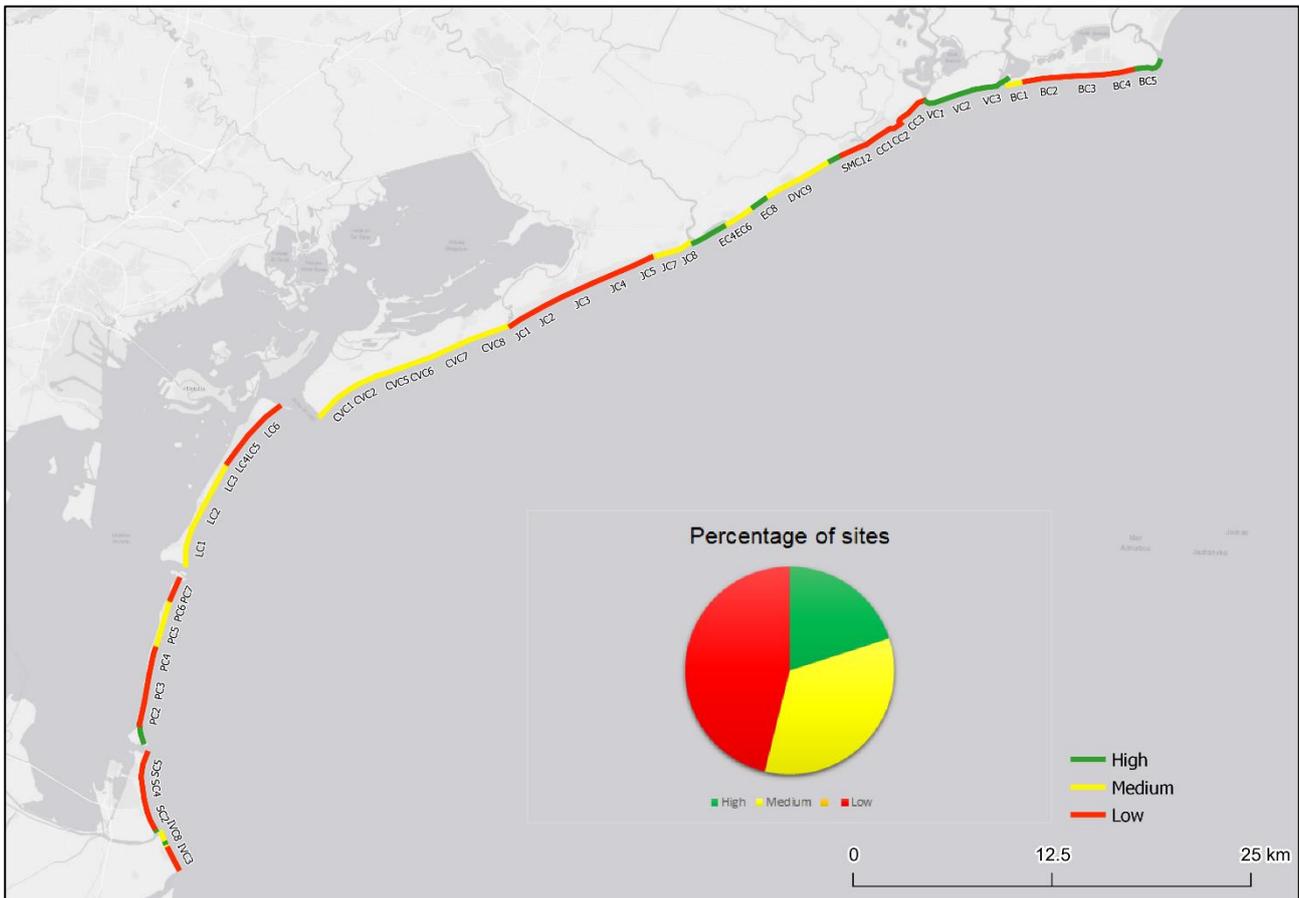


Figure 3.4: Representation of SurLan index values for each cell analysed along the Venetian coast (ESRI Gray, <https://www.esri.com/>).

3.5 Coastal Management Requirement (CMR)

The *CMR* (‘Coastal Management Requirement’) index revealed substantial differences in the actions to be taken along the Venetian coast, and different number of sites have been identified for each category (Table 3.5; Fig. 3.5).

The *CMR* values showed that only 10 sites had geomorphological, physical, biological, and management characteristics that allowed them to classify them into the best status category, i.e., ‘Conservation’. This included not only the unique site with a dune system in good state (i.e., *CVCI*;

Annex III), but also sites where the dune system demonstrated intermediate conditions ('Medium' *StaDun*) that were supported by high natural beach potential ('High' *BeaPot*) and management systems (*CoMan*) with low (e.g., *PC1; Annex III*) or medium (e.g., *EC1; Annex III*) impacts. In one case, good management compensated for the medium natural potential of the site and resulted in inclusion in the 'Conservation' category (i.e., *VC2; Annex III*).

The majority of sites (n=30), covering almost half of the Venetian coast, fell into the 'Restoration' category, i.e., sites where the dune system is degraded but could easily recover. Sites assigned to this category were characterised by a coastal dune system in an intermediate condition, resulting from the combination of a) beaches with high natural potential and management with medium impact (e.g., *IVC8, LC1; Annex III*); b) an intermediate level of both management and beach potential (e.g., *JC8; Annex III*); c) or sites with lack of management (i.e., high impact) compensated by high natural potential of the existing beach (e.g., *BC4; Annex III*).

The 'Recovery' category included only 6 sites. In this case, sites were characterised by the absence of a dune system and by a negative management, coupled with a high natural potential of the beach (e.g., *SC3, JC1; Annex III*). In these sites, coastal dunes could be reconstituted due to the good physical and morphological characteristics of the beach if management would improve.

Finally, the 'Renaturalisation' category included 19 sites, where the recreation of the beach-dune system would require a combination of hard and soft engineering interventions. All sites in this category were characterised by the absence or the poor condition of the dune system (i.e., *DVC9; Annex III*), coupled with a highly (e.g., *CC3; Annex III*) or moderately (e.g., *IVC1; Annex III*) impactful management. Some sites fell into this category due to intermediate potential and high (e.g., *SMC10; Annex III*) or medium (e.g., *EC3; Annex III*) impact management.

Table 3.5: Number of sites and total length for each class identified for the CMR index.

<i>Class</i>	<i>Total sites</i>	<i>Percentage sites (%)</i>	<i>Total length (km)</i>
<i>Conservation</i>	10	15,38	14,748
<i>Restoration</i>	30	46,15	41,180
<i>Recovery</i>	6	9,23	11,795
<i>Renaturalisation</i>	19	29,23	24,243

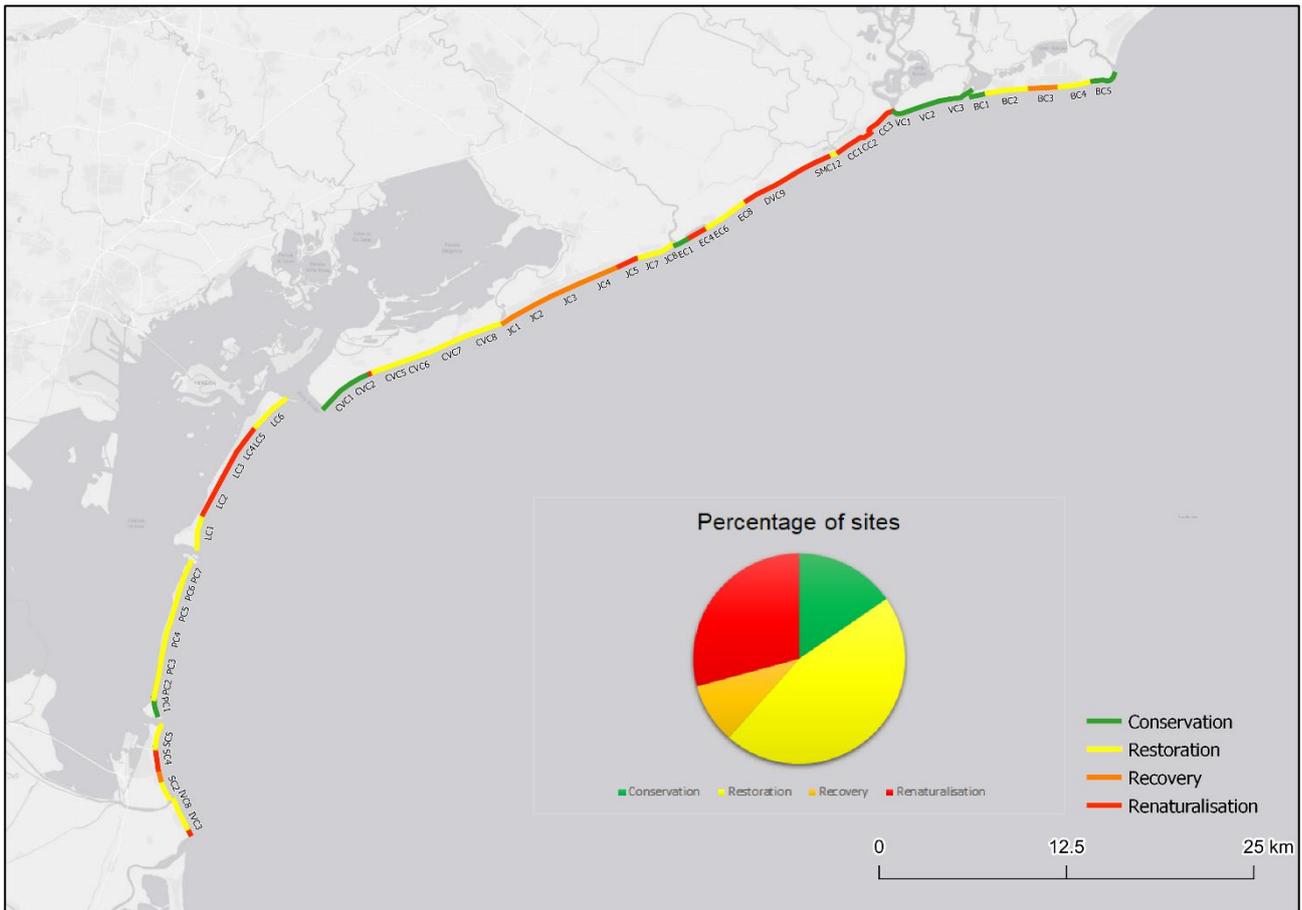


Figure 3.5: Representation of CMR index values for each cell analysed along the Venetian coast (ESRI Gray, <https://www.esri.com/>).

3.6 Dune Boosting Potential (DBP)

The *DBP* (‘Dune Boosting Potential’) index allowed to classify the studied sites into the three different categories (i.e., ‘High’, ‘Medium’, ‘Low’) that summarize the potential of each site to host and maintain a dune system over time (Table 3.6; Fig. 3.6).

Approximately 12% of the sites (n=8) had physical and management conditions suitable (‘High’, score >0.33) for the formation and maintenance of a dune system. The *DBP* high value was mainly linked to the presence of accretionary and widely developed beaches, the granulometric

characteristics (e.g., *PCI, BC1; Annex III*), and the presence of a good management based on practices with limited impacts on coastal dunes, such as the limited frequency of beach cleaning (e.g., *LC6, VC1; Annex III*).

Most sites (n=43, about 66% of the Venetian coast) were included in the ‘Medium’ class (values between 0 and 0.33). In these sites, the overall good or medium physical potential to host a system was largely limited by impacts due to improper management. The main causes of medium impact management were related to the low effectiveness of information boards and the absence of access restrictions to the coastal dunes (e.g., *LC1, EC1; Annex III*), while in the intermediate potential sites with high impact management the strong tourist pressure and the high frequency of mechanical beach cleaning prevailed (e.g., *JC2, BC3; Annex III*). Only one site fell into this category despite very good management, due to actual limited beach potential linked to the erosional trend of the area (i.e., *VC2; Annex III*).

Finally, the ‘Low’ class (negative values) included 14 sites where the beach potential to host dunes was almost completely counteracted by the lack of management. These sites were characterized by a highly impactful management, mainly due to the absence access restrictions to dunes (i.e., *DVC9; Annex III*), as well as the strong tourist pressure, the high frequency of beach cleaning and the high proportion of temporary structures on the beach-dune system present at both high potential (e.g., *JC5, CC1; Annex III*) and medium potential (e.g., *SMC10, SMC12; Annex III*) beaches. Two exceptions deviated from this pattern. The first was associated with the combination of an intermediate potential outperformed by a medium impact management (i.e., *JC8, Annex III*), while the second was associated with the absence of beach natural potential (i.e., *CC2; Annex III*).

Table 3.6: Number of sites and total length for each class identified for the DBP index.

<i>Class</i>	<i>Total sites</i>	<i>Percentage sites (%)</i>	<i>Total length (km)</i>
<i>High</i>	8	12,31	12,484
<i>Medium</i>	43	66,15	58,614
<i>Low</i>	14	21,54	20,868

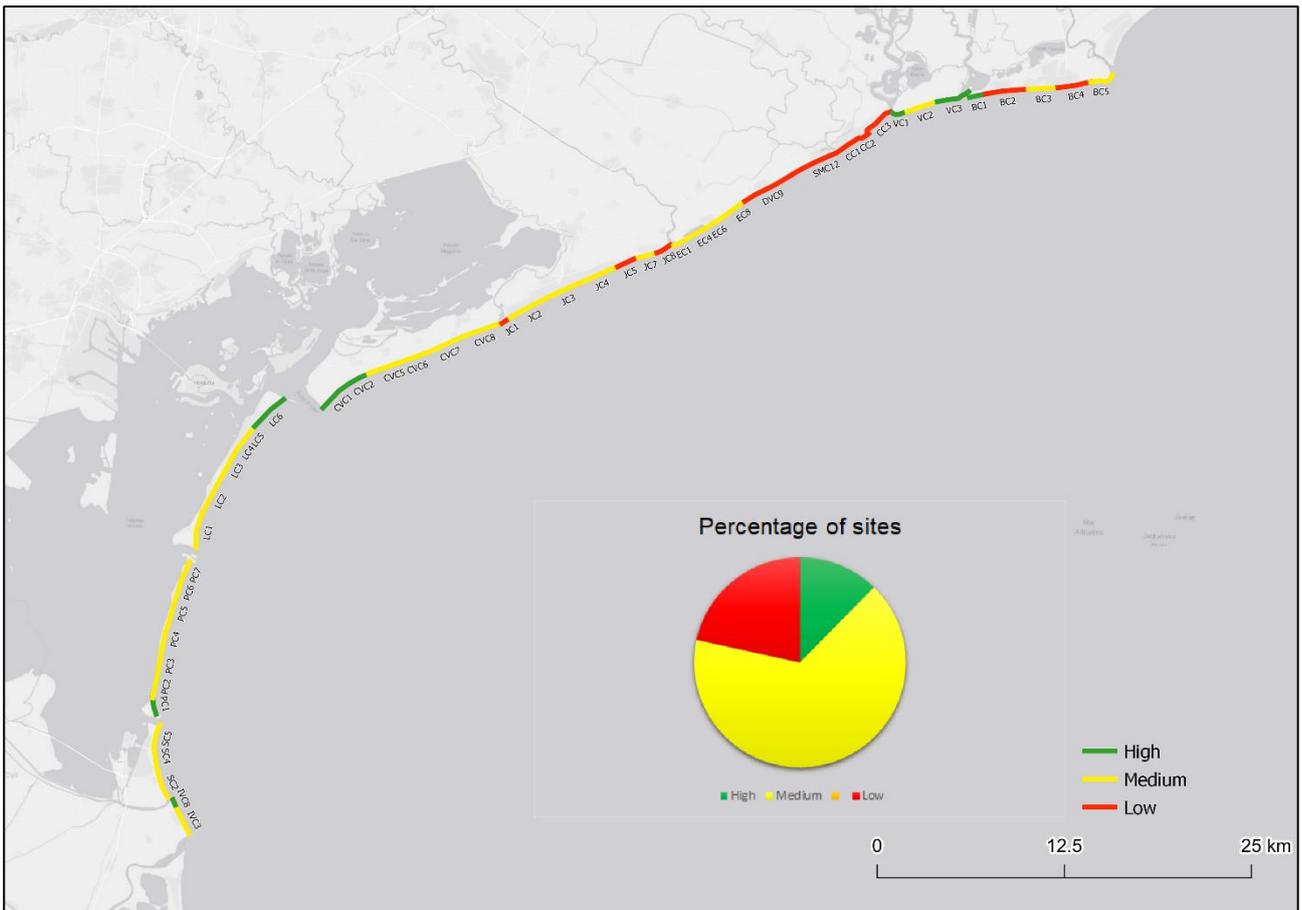


Figure 3.6: Representation of DBP index values for each cell analysed along the Venetian coast (ESRI Gray, <https://www.esri.com/>).

3.7 Management actions hypotheses

The 35 hypothetical scenarios, i.e., the combinations of possible changes to be implemented at each site, are reported in *Annex IV*.

Twelve out of the 35 hypotheses could improve the *DPB* at 25% of the low potential sites. Management practices included low effort interventions such as improving the management of the accesses to the beach, installing sand traps, or reducing the frequency of beach cleaning.

For example, ‘Hypothesis 1’ (*Annex IV*) guaranteed that all beaches had at least regulated accesses (or delimited accesses in sites where regulated accesses were already present); ‘Hypothesis 2’ envisaged the installation of sand traps to provide the stability of the dune, or a more efficient sand accumulation; ‘Hypothesis 3’ envisaged weekly or occasional beach cleaning.

Five out of the 35 hypotheses could improve the *DPB* in 50% of the low potential sites. In this case, solutions included the implementation of (i) several coupled low effort actions (e.g., regulating accesses to the beach coupled with the installation of sand traps, and the reduction of the frequency of the beach cleaning; hypotheses 9, 11; *Annex IV*); (ii) single medium effort actions such as ‘fencing’ the dunes (e.g., hypothesis 16; *Annex IV*) or (iii) single high effort actions as providing surveillance of the entire dune system (e.g., hypothesis 33; *Annex IV*).

Seventeen out of the 35 hypotheses could improve the *DBP* in 75% of the low potential sites. Most of these hypotheses were characterized by the coupling of several low effort actions such as regulating accesses to the beach, installing sand traps, or limit beach cleaning, with one medium effort action, such as fencing a portion of the dunes (e.g., hypotheses 17, 21, 23; *Annex IV*) or high effort actions such as dune system surveillance (e.g., hypotheses 26, 27; *Annex IV*).

One of the 35 hypotheses was able to improve the potential of all sites with low *DBP*, except for one site with zero natural potential. This hypothesis (i.e., hypothesis 31; *Annex IV*) combined several low effort actions (i.e., regulating accesses to the beach, installing sand traps, and limit beach cleaning up to weekly) with a medium effort action such as fencing all the dune systems and a high effort action such as providing surveillance of the entire dune system.

As an example, *Table 3.7* shows possible hypotheses that could improve *DBP* in 25%, 50%, 75% of low *DBP* sites (hypotheses number 3, 16, 35) and the best hypothesis (number 31) for 9 sites with different starting situations (‘Hypothesis 0’, *Table 3.7*), from high to low *DBP*. The hypotheses presented in *Table 3.7* have increasing implementation effort. *DBP* increased with increasing implementation effort of the management measures.

Table 3.7: Example of DBP implementation through a limited number of actions with different efforts.

Hypothetical measures				Regulating accesses
				Installing sand traps
				Limit beach cleaning
			Fencing dunes	Fencing dunes
	Limit beach cleaning	Fencing dunes	Guarding dune system	Guarding dune system

Hypothesis			0	3	16	35	31	
Cell	BeaPot	CoMan	DBP	DBP	DBP	DBP	DBP	
VC1	0,67	High	0,31	0,361	0,389	0,472	0,583	0,639
IVC8	0,89	High	0,56	0,333	0,361	0,444	0,556	0,611
CVC1	0,83	High	0,50	0,333	0,361	0,361	0,472	0,528
CVC4	0,78	High	0,56	0,222	0,250	0,333	0,444	0,500
IVC1	0,78	High	0,64	0,139	0,167	0,250	0,361	0,472
EC7	0,78	High	0,69	0,083	0,111	0,194	0,306	0,417
BC3	0,83	High	0,83	0,000	0,028	0,111	0,222	0,333
CC3	0,72	High	0,75	-0,028	0,000	0,083	0,194	0,306
JC6	0,67	High	0,78	-0,111	-0,083	0,000	0,111	0,222

On the other hand, the same sites could achieve similar improvement of *DBP* by implementing different management actions. *Table 3.8* shows other possible hypotheses that could improve *DBP* in 25%, 50%, 75% of low *DBP* sites (hypotheses number 3, 10, 11) and the best hypothesis (number 31). In this example, hypotheses 3, 10, and 11 (*Table 3.8*) could also improve the *DBP* in 25%, 50% and 75% of the low potential sites as well, but were based on the combination of several low-effort management actions. By comparing the *Tables 3.7* and *3.8* it is possible to see that *DBP* increased with similar values.

Table 3.8: Example of DBP implementation through low effort actions differently combined.

Hypothetical measures			Regulating accesses
			Installing sand traps
	Delimiting paths	Planning entrances	Limit beach cleaning
	Installing sand traps	Installing sand traps	Fencing dunes
	Limit beach cleaning	Limit beach cleaning	Rarefy beach cleaning

		Hypothesis		0	3	11	10	31
Cell	BeaPot	CoMan	DBP	DBP	DBP	DBP	DBP	DBP
VC1	0,67	High	0,31	0,361	0,389	0,444	0,417	0,639
IVC8	0,89	High	0,56	0,333	0,361	0,417	0,417	0,611
CVC1	0,83	High	0,50	0,333	0,361	0,417	0,417	0,528
CVC4	0,78	High	0,56	0,222	0,250	0,306	0,306	0,500
IVC1	0,78	High	0,64	0,139	0,167	0,278	0,278	0,472
EC7	0,78	High	0,69	0,083	0,111	0,167	0,222	0,417
BC3	0,83	High	0,83	0,000	0,028	0,083	0,139	0,333
CC3	0,72	High	0,75	-0,028	0,000	0,111	0,111	0,306
JC6	0,67	High	0,78	-0,111	-0,083	-0,028	0,028	0,222

Moreover, the improvement of some management actions did not lead to an increase in *DBP* in all the investigated sites. For example, the application of hypothesis number 2, which provides ‘Installation sand traps’, improved *DBP* in all sites reported, except sites for which the ‘Conservation’ category has been attributed (i.e., *PC1* and *EC1*, Table 3.9). This means that the indicator modified by the hypothesis already had the maximum value in the present condition of these two sites (‘Hypothesis 0’). A similar situation was found when analysing hypothesis number 16, which envisages the implementation of measures to completely fence off the coastal dunes. In this case, both sites listed above showed an improvement in *DBP* compared to the initial situation (‘Hypothesis 0’). On the other hand, the same solution did not improve a site identified in the ‘Restoration’ category (i.e., *IVC4*, Table 3.9), highlighting that the implementation of given measures may have no effect regardless of the *CMR* classification of the site.

Table 3.9: Example of differential DBP implementation through actions with different efforts starting from different situations.

		Hypothetical measures							
		Installing sand traps	Limit beach cleaning	Fencing dunes	Fencing dunes	Guarding dunes	Guarding dunes	Regulating accesses	
			Installing sand traps		Limit beach cleaning		Regulating accesses	Installing sand traps	
					Limit beach cleaning		Fencing dunes	Limit beach cleaning	
							Fencing dunes	Fencing dunes	
							Guarding dunes	Guarding dunes	
Hypothesis		0	2	8	16	20	33	35	31
Cell	CMR	DBP	DBP	DBP	DBP	DBP	DBP	DBP	DBP
PC1	Conservation	0,583	0,583	0,583	0,694	0,722	0,694	0,806	0,833
EC1	Conservation	0,306	0,306	0,306	0,417	0,444	0,417	0,528	0,556
CVC4	Restoration	0,222	0,222	0,250	0,333	0,389	0,333	0,444	0,500
IVC4	Restoration	0,111	0,167	0,194	0,111	0,222	0,222	0,222	0,333
JC4	Recovery	0,000	0,056	0,083	0,111	0,222	0,111	0,222	0,333
BC3	Recovery	0,000	0,056	0,083	0,111	0,222	0,111	0,222	0,333
CC3	Renaturalisation	-0,028	0,028	0,056	0,083	0,194	0,083	0,194	0,306
JC5	Renaturalisation	-0,194	-0,139	-0,111	-0,083	0,028	-0,083	0,028	0,139

Chapter 4. Discussion

The selected set of indices, based on the integration of multiple indicators of system state, proved to be effective in analysing different aspects of a coastal sand system. Integrated together, they allowed to summarise the state of the analysed systems, their possible weaknesses, and to assess the degree of restoration that they need. Results provided clear indications of the actions that need to be taken at each site thereby facilitating informed decision-making.

According to geomorphological and ecological characteristics (*StaDun index*), most of the dune systems along the Venetian coast are not in a good state of conservation. Overall, well developed beach-dune systems are completely absent in highly urbanised areas such as Jesolo and Caorle, i.e., where the major tourist centres are located along the coast. In these areas, the absence of dunes is the result of post-World War II urban development as coastal cities have replaced coastal dune systems, resulting in a large loss of coastal dune habitats and in the fragmentation of the remaining portions of coastal dunes (Bezzi & Fontolan 2003; Caniglia 2007). Well-developed dune systems are present only in marginal areas, where tourism development is lower (e.g., in the westernmost sites of Cavallino, *CVC1* and *CVC2*, or Eraclea, *EC1* and *EC2*), in areas where tourism is somehow regulated by the management authority (e.g., Vallevicchia), or in areas where *Special Areas of Conservation* (SACs) have been established due to the Habitats Directive (*Fig. 2.4; Chapter 2*).

The most critical aspects that have emerged in the degradation of coastal dunes were the scarce presence of incipient dunes, the low height of foredunes, the lack of typical sand dune species that are resistant to sand burial and can promote the formation of dune systems (Type III species, *sensu* García-Mora et al. 2001), and the presence of invasive alien species.

From a geomorphological perspective, the limited height and the scarce presence of incipient forms indicate low sediment accumulation, and consequently less developed and flattened coastal dunes (Bezzi et al. 2018; Davidson-Arnott et al. 2018). Despite favourable conditions in term of sediments characteristics and meteomarine climate, 30% of physiographic units have foredunes less than 3 m

high, and twenty-two sites have low incipient formations. In both cases, the lack or a reduced height are mostly linked to a reduced width of the upper beach and a negative sediment budget reflected in the recent erosion trend as detected e.g., for the central area of Vallevicchia (*VC2*) and one site in Bibione (*BC4*). This situation is exacerbated by the absence of Type III species in the primary dunes, which further reduces the possibility to intercept and consolidate sediments (García-Mora et al. 1999, Hesp 2002). The efficiency of the dune system is also compromised by the presence of invasive alien species, which have been shown to disrupt dune plant communities and their proper function (Del Vecchio et al. 2015; Lazzaro et al. 2020).

Interestingly, the evaluation of the factors that condition the presence and typology of dunes on a beach (*BeaPot index*), such as sediment granulometry, wind intensity and direction, and meteomarine climate, had ideal values for coastal dune development for most of the sites studied. Only in ten physiographic units, the conditions were less favourable, mostly due to a poorly developed beach with a high slope, as occurs in Porto Santa Margherita sites (*SMC10*, *SMC11*, *SMC12*) and in the central site of Vallevicchia (*VC2*). An exception is the central sector of Caorle (*CC2*) where there is no beach and consequently no potential to host any dune morphology.

The most crucial issue raised by our results concerns the management, which resulted directly correlated to both the current state of conservation of the dune system and the natural potential of the beach.

Physiographic units characterised by the lack or underdeveloped incipient dunes or foredunes mostly corresponded to sites where surveillance, regulation of beach access or fenced dunes were absent, and where mechanical beach cleaning was applied at high frequency, as in the central sites of Isola Verde (*IVC3*, *IVC4*). Thus, it can be assumed that the lack or underdevelopment of incipient dunes and foredunes is partly related to the poor management of beach-dune systems which affects the presence of such coastal morphologies and the availability of sediment for their formation.

Human disturbance has been proven to have a strong influence on the integrity of both geomorphological and biological features (Buffa et al. 2012; Sperandii et al. 2021), often resulting in degraded to very degraded dune systems condition.

For example, mechanical beach cleaning proved to be a highly impactful action, especially when repeated on a daily frequency (Roig-Munar et al. 2009). Generally carried out using heavy machinery, beach cleaning completely removes incipient dunes, levelling the beach, and sometimes causing foredune scarp if the operation is too invasive (Nordstrom et al. 2000). In addition, the removal of beached material embeds a large amount of sediment that is generally displaced outside the beach-dune system, resulting in a loss in the sediment budget (Roig-Munar et al. 2009).

The lack of management also impacts on the biological characteristics, and in particular on the presence of typical species (i.e., Type III species). The element of greatest disturbance to the plant communities is represented by trampling on coastal dunes, both locally along paths and randomly (Šilc et al. 2017). Direct damage to individuals, which is more evident where disturbance is concentrated, i.e., on paths, represents the immediately visible and understandable impact. Depending on the growth form of the species, the effects and the responses induced vary with the species but, globally, all typical species have been shown to be particularly sensitive (Della Bella et al. 2021; Seer et al. 2015). Furthermore, human trampling induces profound changes that are manifested by moving to the community level. Plant communities experience a decrease both in the number of typical species and in their cover (Purvis et al. 2015), while species composition is modified by favouring the entry of species that are more resistant to disturbance triggering a turnover of species in the communities (Prisco et al. 2021). Indeed, human trampling has also been proved to favour alien species establishment and spread (Bella 2011; Campos et al. 2004). Human activities frequently conducted on coastal dunes such as trampling have been proven to modify the physical and chemical conditions, creating suitable habitats for the growth of invasive alien species to the detriment of native species communities (Campos et al. 2004; Del Vecchio et al. 2015). In fact, the highest frequency of

invasive alien species has been found near man-made paths, where disturbance is therefore high. Here, tourists may unintentionally carry seeds left hanging on their clothing thereby promoting their dispersal within and between dune systems (Smith & Kraaij, 2020). This contributes to maintaining high propagule pressure, i.e., the frequency of introduction of propagules into a given environment, favouring the invasion of invasive species and the further dispersal of new individuals (Colautti et al. 2006).

The problem linked to the lack of management becomes even more important when considering its effect on the natural potential of the beach-dune system. Although the beaches of most of the investigated sites had a high natural potential for the formation and development of a coastal dune system thanks to the favourable physical and meteo-hydrological characteristics, the lack of management or their current use implicated a significant reduction in the real potential.

All sites are characterised by the absence of surveillance of the dune systems, while the great majority of sites (90%) does not present any form of limitation of tourist access to the dunes. In fact, only a few areas present fenced dunes to limit human disturbance (e.g., the site of Bibione adjacent to the mouth of the Tagliamento River (*BC5*) or the westernmost site of the Cavallino peninsula (*CVCI*). This implies that in most sites, tourists can carry out activities such as trampling directly on the coastal dune system, altering both the fragile vegetal component and the geomorphological landforms. Moreover, the ineffectiveness or absence of information boards in the majority of sites (n=56) reiterates the lack of attention paid to the prevention of direct damage caused by the presence of tourists. Other activities that have been found to play an important role in the impacts involve the frequency of mechanical beach cleaning (n=45) and the failure to install sand traps (n=41). Hence, the large number of impacting actions and the large number of affected sites reflect the unsustainable use to which most of the sites along the Venetian coast are subjected.

The strong economic development that the Venetian coast has undergone in recent decades has led to the implementation of management measures to maximise only one of the many ecosystem services

that coastal environments can provide, namely the recreational service (Caniglia 2007), while other important ecosystem services such as protection against erosion and flooding were neglected (Bezzi et al. 2018; Sperandii et al. 2021). In a context where climate change is becoming an increasing concern for coastal areas, mainly due to sea level rise and to more frequent and intense storm surges, it is essential to consider coastal dunes as a key element of the landscape and to plan coastal management in a way to maximise the ability of dune systems to counteract the negative effects of climate change. This is certainly true for the Venetian coast, where the effects of climate change are exacerbated by the subsidence of the area (Gallina et al. 2020; Rizzi et al. 2017). Restoring or enhancing natural elements of the coastal landscape, such as dune systems, through nature-based solutions is a sustainable option to limit coastal erosion and cope with future threats (Bossard & Lerma 2020; Morris et al. 2018; Toimil et al. 2017).

Then, ecosystem restoration should take multiple elements into account during intervention planning supporting a multidisciplinary approach (Doody 2013). Specifically, it is mandatory to understand the dynamics of coastal areas, from both geomorphological and biological perspectives. In addition, it is necessary to distinguish changes related to the natural dynamics of coastal dune processes from those due to human impacts (Doody 2013; Martínez et al. 2013; Nordstrom 2021).

For instance, if sand dune degradation is mostly linked to erosion, the accumulation of sand either actively transported by humans or intercepted from wind transport by appropriate barriers, e.g., sand traps, can ensure the restoration of a beach-dune system. However, to allow for both the horizontal and vertical growth of the dunes, management plans should also provide for the restoration of plant communities through native Type III species, that are essential to promote further natural accumulation of sediments and their subsequent consolidation (Doody 2013; Nordstrom 2021). Preventing the introduction of alien species or promoting their eradication, if present, are other restoration measures to limit the alteration of current or restored plant communities and promote the ability of the dune system to become self-sustaining (Martínez et al. 2013). In areas where dune

systems no longer exist, as for sites marked with ‘Recovery’ or ‘Renaturalisation’, active human reconstruction of both the dune ridge and the plant community would accelerate the process of dune system formation, allowing the desired goal to be achieved more quickly (Doody 2013).

As the characteristics related to the current conservation status of coastal dunes are not the only elements that need to be considered, it is essential to understand the beach's natural and real potential to host a healthy dune system when planning of actions to promote coastal dune formation and/or development. Moreover, activities in adjacent areas must also be considered and further attention is required in their proper management. Indeed, the interaction between the different landscape components can have a negative impact on the existing dune system (Buffa et al. 2012; Drius et al. 2013), as shown by the results for beach-dune systems in contact with urbanised and densely urbanised areas. Reconstruction and/or restoration interventions on the dune system in areas characterised by a lack of physical potential or management of beaches could result in a waste of resources, as they would not sustain themselves in the long term due to existing impacts (Della Bella et al. 2021).

In areas characterised by a medium potential of the beach, interventions to restore the natural balance by increasing the natural potential of the beach to host a dune system and favour its maintenance over time are first required. Possible solutions include the installation of rigid coastal protection systems in combination with soft interventions, such as beach nourishment (Pranzini 2018). However, in the central area of Caorle (CC2), works of this magnitude are exceptionally not possible because they could affect the scenic value of the coastal stretch, which is an area of significant public interest, according to art. 136 of Legislative Decree no. 42/2004.

However, in areas where the natural potential related to the beach features was high, but management was impactful, results demonstrated that even small changes in coastal management can increase the real potential (*DBP*), e.g., in identified ‘Low’ and ‘Medium’ potential sites. Thus, a more sustainable use of coastal areas would lead to greater sustainability in active interventions in favour of the

formation and development of coastal dune systems, but also in the natural recovery of slightly degraded dune systems and their conservation as is the case of sites designated as ‘Conservation’. Indeed, in other contexts, the use of soft management measures such as regulating beach accesses, limiting beach cleaning, and restricting access to the dunes, has been shown to have a positive effect on existing dune systems, allowing both the natural recovery of degraded systems and the maintenance of systems in good condition (Roig-Munar et al. 2009). Thus, appropriate management allows human activities and natural processes to coexist.

The range of soft measures that can be implemented is wide, and it is possible to choose between low, medium, and high effort management measures. They can also be combined in a variety of ways, especially in terms of the level of effort required: coastal zone managers can choose to apply a small number of resourceful measures or combine several low-effort management measures to enhance the potential of a site to host coastal dunes.

The results that emerged from the analysis of a possible improvement of management actions through different hypotheses highlighted another important aspect, namely that it is not possible to apply the same solution to all sectors, even within the same physiographic unit. Similar to the downscaling applied in climate change prediction models to understand impacts at the local scale (Wood et al. 2004), it is important to consider that different sites have different characteristics. While it is true that many management actions will need to be changed at sites with low potential, it is not always true that the same amount of actions will be needed to improve the condition of sites that currently have good real potential. Indeed, the set of measures that are applicable in low-impacted sites become narrower, and it is not possible to apply the same set of measures that should be reserved for particularly impaired sites. In addition, it is not possible to apply the same measures to sites that have a similar rating, i.e., ‘Conservation’, ‘Restoration’, ‘Recovery’ and ‘Renaturalisation’, as the same current condition may be associated with different combinations of practises applied. For example, the central sites on Isola Verde already have fenced dunes unlike all other ‘Restoration’ sites, so other

measures should be introduced to enhance the potential of the system compared to other sites. Therefore, the selection of measures to be planned must be site-specific.

Moreover, on the one hand, if administrations can actively control their own actions and adopt solutions with lower impacts on the coastal environments, such as decreasing the frequency of beach cleaning or installing sand trapping fences, on the other hand, it is more difficult to control the actions of millions beach users. It is therefore necessary for administrations to promote sustainable exploitation of coastal areas by tourists to prevent conserved and restored ecosystems from being damaged (Della Bella et al. 2021). One of the most important issues in this context is the management of beach access and the limitation of access to dunes. Tourists accessing the beach via managed paths will be prevented from trampling the dunes (Prisco et al. 2021). Boardwalks, possibly elevated, are a good solution to preserve the existing vegetation and geomorphology of the systems (Purvis et al. 2015). Moreover, user awareness and responsibility for protecting the natural environment should be raised. Among the most widely used methods to provide information about the implementation of sustainable use are information boards, while educational tours and guided visits can further help raise society's awareness of the importance of preserving coastal dunes and all their ecosystem services. Such communication efforts have the effect of stimulating and supporting restoration and conservation efforts by increasing community interest in these environments (Druschke & Hychka 2015).

Chapter 5. Conclusions

Differently from other indices proposed in the literature, the research developed in this thesis took into account not only the application of indices, but also the combination of each factor analysed, in order to highlight the specific needs at the local scale, and in turn planning most successful management. The hypothesis model developed allowed to define the framework of actions needed to achieve specific requirements for each coastal sector analysed. The application of the proposed indices in different contexts than the study area can support the understanding of the condition of dune systems at a wider scale and of the real potential of the coasts, identifying areas where important interventions are necessary.

Once the required measures have been identified and applied, it is necessary to regularly monitor the dune system. The application of the proposed indices can significantly contribute to evaluate the outcome of restoration and conservation actions and to determine whether coastal management is compatible with the presence of a healthy coastal dune system.

Finally, the identification of the best economic solutions to be implement in order to enhance the real potential of the beaches can provide an accurate and reliable assessment of the magnitude of the effort of each action. Economic sustainability can be assessed through cost-benefit analyses, taking into account not only the costs related to the implementation of measures and their maintenance over time, but also the benefits deriving from the provision of ecosystem goods and services by coastal dunes, both in terms of revenues and avoided expenditures. Tailored analyses of the dune systems such as those proposed in this thesis coupled with detailed cost-benefit analyses are thus very promising for achieving a sustainable use of coastal areas.

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Annex I

Table A1.1: List of articles evaluated for the identification of indices on the need for coastal dune restoration and on the potential of coastal areas to host coastal dunes.

Authors	Year	Title	Journal
Ahmed, N., Howlader, N., Hoque, M. A. A., & Pradhan, B.	2021	<i>Coastal erosion vulnerability assessment along the eastern coast of Bangladesh using geospatial techniques</i>	Ocean & Coastal Management, 199, 105408
Ajedegba, J. O., Perotto-Baldivieso, H. L., & Jones, K. D.	2019	<i>Coastal dune vegetation resilience on South Padre Island, Texas: A spatiotemporal evaluation of the landscape structure</i>	Journal of Coastal Research, 35
Alquini, F., Bertoni, D., Sarti, G., Ciccarelli, D., Pozzebon, A., de Melo Júnior, J. C. F., & Vieira, C. V.	2016	<i>Vulnerability Assessment of a Coastal Dune System at São Francisco do Sul Island, Santa Catarina, Brazil</i>	IOP Conference Series: Earth and Environmental Science
Anfuso, G., & Del Pozo, J. Á. M.	2009	<i>Assessment of coastal vulnerability through the use of GIS tools in South Sicily (Italy)</i>	Environmental management, 43(3), 533-545
Anfuso, G., Williams, A. T., Martínez, G. C., Botero, C. M., Hernández, J. C., & Pranzini, E.	2017	<i>Evaluation of the scenic value of 100 beaches in Cuba: Implications for coastal tourism management</i>	Ocean & Coastal Management, 142, 173-185
Anfuso, G., Postacchini, M., Di Luccio, D., & Benassai, G.	2021	<i>Coastal sensitivity/vulnerability characterization and adaptation strategies: a review</i>	Journal of Marine Science and Engineering, 9
Angus, S., & Hansom, J. D.	2021	<i>Enhancing the resilience of high-vulnerability, low-elevation coastal zones</i>	Ocean & Coastal Management, 200, 105414
Armaroli, C., Ciavola, P., Perini, L., Calabrese, L., Lorito, S., Valentini, A., & Masina, M.	2012	<i>Critical storm thresholds for significant morphological changes and damage along the Emilia-Romagna coastline, Italy</i>	Geomorphology, 143, 34-51
Aucelli, P. P., Di Paola, G., Rizzo, A., & Roszkopf, C. M.	2018	<i>Present day and future scenarios of coastal erosion and flooding processes along the Italian Adriatic coast: the case of Molise region</i>	Environmental Earth Sciences, 77
Bagdanavičiūtė, I., Kelpšaitė-Rimkienė, L., Galinienė, J., & Soomere, T.	2019	<i>Index based multi-criteria approach to coastal risk assesment</i>	Journal of Coastal Conservation, 23
Balica, S. F., Wright, N. G., & Van der Meulen, F.	2012	<i>A flood vulnerability index for coastal cities and its use in assessing climate change impacts</i>	Natural hazards, 64
Bama, V. S., Rajakumari, S., & Ramesh, R.	2020	<i>Coastal vulnerability assessment of Vedaranyam swamp coast based on land use and shoreline dynamics</i>	Natural Hazards, 100
Barillà, G. C., Barbaro, G., Foti, G., Mancuso, P., Fiamma, V., Malesinska, A., ... & Mandalari, M.	2021	<i>Coastal erosion hazard and vulnerability: case study of Porticello, South Calabria</i>	Sustainable Water Resources Management XI: Effective Approaches for River Basins and Urban Catchments, 250, 181
Bertoni, D., Sarti, G., Alquini, F., & Ciccarelli, D.	2019	<i>Implementing a coastal dune vulnerability index (CDVI) to support coastal management in different settings (Brazil and Italy)</i>	Ocean & Coastal Management, 180, 104916
Bessette, S. R., Hicks, D. W., & Fierro-Cabo, A.	2018	<i>Biological assessment of dune restoration in south Texas</i>	Ocean & Coastal Management, 163, 466-477
Bezzi, A., Fontolan, G., Nordstrom, K. F., Carrer, D., & Jackson, N. L.	2009	<i>Beach nourishment and foredune restoration: practices and constraints along the Venetian shoreline, Italy</i>	Journal of Coastal Research, 287-291
Bio, A., Bastos, L., Granja, H. M., Pinho, J. L., Gonçalves, J. A., Henriques, R. F., ... & Rodrigues, D.	2015	<i>Methods for coastal monitoring and erosion risk assessment: two Portuguese case studies</i>	Journal of Integrated Coastal Zone Management
Boulomytis, V. T. G., Imteaz, M. A., Zuffo, A. C., & Alves, C. D.	2016	<i>Analysis of the urbanisation effects on the increase of flood susceptibility in coastal areas</i>	Theoretical and Empirical Researches in Urban Management, 11
Buosi, C., Porta, M., Trogu, D., Casti, M., Ferraro, F., De Muro, S., & Ibba, A.	2019	<i>Data on coastal dunes vulnerability of eleven microtidal wave-dominated beaches of Sardinia (Italy, western Mediterranean)</i>	Data in brief, 24, 103897
Buosi, C., Tecchiato, S., Pusccheddu, N., Frongia, P., Ibba, A., & De Muro, S.	2017	<i>Geomorphology and sedimentology of Porto Pino, SW Sardinia, western mediterranean</i>	Journal of Maps, 13
Calafat, A., Vírveda, S., Lovera, R., Lucena, J. R., Bladé, C., Rivero, L., & Ninot, J. M.	2021	<i>Assessment of the Restoration of the Remolar Dune System (Viladecans, Barcelona): The Resilience of a Coastal Dune System</i>	Journal of Marine Science and Engineering, 9(2), 113.
Callaghan, K., Engelbrecht, J., & Kemp, J.	2015	<i>The use of Landsat and aerial photography for the assessment of coastal erosion and erosion susceptibility in False Bay, South Africa</i>	South African Journal of Geomatics, 4
Canul, R., Mendoza, E., & Silva, R.	2020	<i>A probabilistic approach to a coastal vulnerability index: a tool for coasta manager</i>	Coastal Engineering Proceedings,
Carapuço, M. M., Taborda, R., Silveira, T. M., Psuty, N. P., Andrade, C., & Freitas, M. C.	2016	<i>Coastal geoindicators: Towards the establishment of a common framework for sandy coastal environments</i>	Earth-Science Reviews, 154, 183-190

<i>Authors</i>	<i>Year</i>	<i>Title</i>	<i>Journal</i>
Castelle, B., Laporte-Fauret, Q., Marieu, V., Michalet, R., Rosebery, D., Bujan, S., ... & Narteau, C.	2019	<i>Nature-based solution along high-energy eroding sandy coasts: preliminary tests on the reinstatement of natural dynamics in reprofiled coastal dunes</i>	Water, 11
Ceia, F. R., Patrício, J., Marques, J. C., & Dias, J. A.	2010	<i>Coastal vulnerability in barrier islands: The high-risk areas of the Ria Formosa (Portugal) system</i>	Ocean & Coastal Management, 53(8), 478-486.
Ciccarelli, D., Pinna, M. S., Alquini, F., Cogoni, D., Ruocco, M., Bacchetta, G., ... & Fenu, G.	2017	<i>Development of a coastal dune vulnerability index for Mediterranean ecosystems: A useful tool for coastal managers?</i>	Estuarine, Coastal and Shelf Science, 187, 84-95
Cohn, N., Brodie, K., Johnson, B., & Palmsten, M.	2021	<i>Hotspot dune erosion on an intermediate beach</i>	Coastal Engineering, 103998
Cuevas Jiménez, A., Euán Ávila, J. I., Villatoro Lacouture, M. M., & Silva Casarín, R.	2016	<i>Classification of beach erosion vulnerability on the Yucatan coast</i>	Coastal Management, 44
Das, S.	2020	<i>Flood susceptibility mapping of the Western Ghat coastal belt using multi-source geospatial data and analytical hierarchy process (AHP)</i>	Remote Sensing Applications: Society and Environment, 20, 100379
Davies, P., Williams, A. T., & Curr, R. H. F.	1995	<i>Decision making in dune management: theory and practice</i>	Journal of Coastal Conservation, 1
de Lima, E. Q., & do Amaral, R. F.	2015	<i>Use of geoindicators in vulnerability mapping for the coastal erosion of a sandy beach</i>	Revista de Gestão Costeira Integrada-Journal of Integrated Coastal Zone Management, 15
De Serio, F., Armenio, E., Mossa, M., & Petrillo, A. F.	2018	<i>How to define priorities in coastal vulnerability assessment</i>	Geosciences, 8
Debaine, F., & Robin, M.	2012	<i>A new GIS modelling of coastal dune protection services against physical coastal hazards</i>	Ocean & coastal management, 63, 43-54
Denner, K., Phillips, M. R., Jenkins, R. E., & Thomas, T.	2015	<i>A coastal vulnerability and environmental risk assessment of Loughor Estuary, South Wales</i>	Ocean & Coastal Management, 116, 478-490
Di Paola, G., Aucelli, P. P. C., Benassai, G., & Rodríguez, G.	2014	<i>Coastal vulnerability to wave storms of Sele littoral plain (southern Italy)</i>	Natural hazards, 71(3), 1795-1819
Di Paola, G., Aucelli, P. P. C., Benassai, G., Iglesias, J., Rodríguez, G., & Roskopf, C. M.	2018	<i>The assessment of the coastal vulnerability and exposure degree of Gran Canaria Island (Spain) with a focus on the coastal risk of Las Canteras Beach in Las Palmas de Gran Canaria</i>	Journal of Coastal Conservation, 22(5), 1001-1015
Di Risio, M., Bruschi, A., Lisi, I., Pesarino, V., & Pasquali, D.	2017	<i>Comparative analysis of coastal flooding vulnerability and hazard assessment at national scale</i>	Journal of Marine Science and Engineering, 5
Dong, Z., Elko, N., Robertson, Q., & Rosati, J.	2018	<i>Quantifying beach and dune resilience using the coastal resilience index</i>	Coastal Engineering, 2
Doukakis, E.	2005	<i>Coastal vulnerability and risk parameters</i>	European Water, 11
Edi, V., Simona, G., & Michele, R. Monitoring	2004	<i>Coastal Erosion Natural Resilience by Indexing Coastal Dunes State</i>	7th AGILE Conference on Geographic Information Science Heraklion, Greece
Enríquez, A. R., Marcos, M., Falqués, A., & Roelvink, D.	2019	<i>Assessing beach and dune erosion and vulnerability under sea level rise: a case study in the Mediterranean Sea</i>	Frontiers in Marine Science, 6, 4
Farrell, E., & Connolly, N.	2021	<i>Historic and contemporary dune inventories to assess dune vulnerability to climate change impacts</i>	Irish Geography, 52
Fernández-Montblanc, T., Duo, E., & Ciavola, P.	2020	<i>Dune reconstruction and revegetation as a potential measure to decrease coastal erosion and flooding under extreme storm conditions</i>	Ocean & Coastal Management, 188, 105075
Furlan, E., Dalla Pozza, P., Michetti, M., Torresan, S., Critto, A., & Marcomini, A.	2021	<i>Development of a Multi-Dimensional Coastal Vulnerability Index: Assessing vulnerability to inundation scenarios in the Italian coast</i>	Science of The Total Environment, 772, 144650
Gallina, V., Torresan, S., Zabeo, A., Critto, A., Glade, T., & Marcomini, A.	2020	<i>A Multi-Risk Methodology for the Assessment of Climate Change Impacts in Coastal Zones</i>	Sustainability, 12
García-Lozano, C., & Pintó, J.	2018	<i>Current status and future restoration of coastal dune systems on the Catalan shoreline (Spain, NW Mediterranean Sea)</i>	Journal of coastal conservation, 22(3), 519-532
García-Lozano, C., Pintó, J., & Roig-Munar, F. X.	2020	<i>Set of indices to assess dune development and dune restoration potential in beach-dune systems on Mediterranean developed coasts</i>	Journal of environmental management, 259, 109754
García-Mora, M. R., Gallego-Fernández, J. B., Williams, A. T., & García-Novo, F.	2001	<i>A coastal dune vulnerability classification</i>	A case study of the SW Iberian Peninsula. Journal of coastal research, 802-811
Ghoussein, Y., Mhawej, M., Jaffal, A., Fadel, A., El Hourany, R., & Faour, G.	2018	<i>Vulnerability assessment of the South-Lebanese coast: A GIS-based approach</i>	Ocean & Coastal Management, 158, 56-63
Gornitz, V.	1991	<i>Global coastal hazards from future sea level rise</i>	Palaeogeography, Palaeoclimatology, Palaeoecology, 89
Hadipour, V., Vafaie, F., & Deilami, K.	2020	<i>Coastal Flooding Risk Assessment Using a GIS-Based Spatial Multi-Criteria Decision Analysis Approach</i>	Water, 12

<i>Authors</i>	<i>Year</i>	<i>Title</i>	<i>Journal</i>
Hopper, T., & Meixler, M. S.	2016	<i>Modeling coastal vulnerability through space and time</i>	PLoS One, 11
Idier, D., Castelle, B., Poumadère, M., Balouin, Y., Bertoldo, R. B., Bouchette, F., ... & Vinchon, C.	2013	<i>Vulnerability of sandy coasts to climate variability</i>	Climate research, 57
Izkin, M., Moore, L. J., Ruggiero, P., Hacker, S. D., & Biel, R. G.	2021	<i>The relative influence of dune aspect ratio and beach width on dune erosion as a function of storm duration and surge level</i>	Earth Surface Dynamics, 9
Jana, A., & Bhattacharya, A. K.	2013	<i>Assessment of coastal erosion vulnerability around Midnapur-Balasore Coast, Eastern India using integrated remote sensing and GIS techniques</i>	Journal of the Indian Society of Remote Sensing, 41
Judge, E. K., Overton, M. F., & Fisher, J. S.	2003	<i>Vulnerability indicators for coastal dunes</i>	Journal of Waterway, Port, Coastal, and Ocean Engineering, 129
Kalb, C., Ibba, A., Batzella, T., Pusceddu, N., Ferrara, C., & Ferraro, F.	2011	<i>Coastal dunes vulnerability. GAVAM checklist method used at three Mediterranean microtidal wave dominated beaches</i>	Rend. Online Soc. Geol. It., Vol. 17 (2011), pp. 77-82
Kaniewski, D., Van Campo, E., Morhange, C., Guiot, J., Zviely, D., Le Burel, S., ... & Artzy, M.	2014	<i>Vulnerability of Mediterranean ecosystems to long-term changes along the coast of Israel</i>	Plos One, 9
Kantamaneni, K., Phillips, M., Thomas, T., & Jenkins, R.	2018	<i>Assessing coastal vulnerability: Development of a combined physical and economic index</i>	Ocean & Coastal Management, 158, 164-175
Kombiadou, K., Costas, S., Carrasco, A. R., Plomaritis, T. A., Ferreira, Ó., & Matias, A.	2019	<i>Bridging the gap between resilience and geomorphology of complex coastal systems</i>	Earth-Science Reviews, 198, 102934
Kumar, T. S., Mahendra, R. S., Nayak, S., Radhakrishnan, K., & Sahu, K. C.	2010	<i>Coastal vulnerability assessment for Orissa State, east coast of India</i>	Journal of Coastal Research, 26
Laranjeira, M. M., Pereira, A. R., & Williams, A. T.	1999	<i>Comparison of two checklist methods for assessment of coastal dune vulnerability</i>	Boletín-instituto español de oceanografía, 15
Lithgow, D., Martínez, M. L., & Gallego-Fernández, J. B.	2013	<i>Multicriteria analysis to implement actions leading to coastal dune restoration</i>	Restoration of Coastal Dunes
Lithgow, D., Martínez, M. L., & Gallego-Fernández, J. B.	2015	<i>The "ReDune" index (Restoration of coastal Dunes Index) to assess the need and viability of coastal dune restoration</i>	Ecological indicators, 49, 178-187
Lithgow, D., Martínez, M. L., Gallego-Fernández, J. B., Hesp, P. A., Flores, P., Gachuz, S., ... & Álvarez-Molina, L. L.	2013	<i>Linking restoration ecology with coastal dune restoration</i>	Geomorphology, 199, 214-224
Maanan, M., Maanan, M., Rueff, H., Adouk, N., Zourarah, B., & Rhinane, H.	2018	<i>Assess the human and environmental vulnerability for coastal hazard by using a multi-criteria decision analysis</i>	Human and Ecological Risk Assessment: An International Journal, 24
Majumdera, D. D., Beraa, S., Purkaitb, B., Paulc, A. K., & Bhandarid, U.	2014	<i>Insights into the dichotomy of coastal dune vulnerability and protection measures from multi-criteria decision analysis: a case study of West Bengal Coast, Bay of Bengal, India</i>	Journal of Coastal Sciences, 1, 47-57
Martinelli, L., Zanuttigh, B., & Corbau, C.	2010	<i>Assessment of coastal flooding hazard along the Emilia Romagna littoral, IT</i>	Coastal Engineering, 57
Martinez, M. L., Gallego-Fernandez, J. B., Garcia-Franco, J. G., Moctezuma, C., & Jimenez, C. D.	2006	<i>Assessment of coastal dune vulnerability to natural and anthropogenic disturbances along the Gulf of Mexico</i>	Environmental Conservation, 33
Martinez, M. L., Taramelli, A., & Silva, R.	2017	<i>Resistance and resilience: facing the multidimensional challenges in coastal areas</i>	Journal of Coastal Research,
Masselink, G., & Lazarus, E. D.	2019	<i>Defining coastal resilience</i>	Water, 11
McFadden, L., Nicholls, R. J., Vafeidis, A., & Tol, R. S.	2007	<i>A methodology for modeling coastal space for global assessment</i>	Journal of Coastal Research, 23
McLaughlin, S., & Cooper, J. A. G.	2010	<i>A multi-scale coastal vulnerability index: A tool for coastal managers?</i>	Environmental Hazards, 9
Mendoza, E., Odériz, I., Martínez, M. L., & Silva, R.	2017	<i>Measurements and modelling of small scale processes of vegetation preventing dune erosion</i>	Journal of Coastal Research,
Merlotto, A., Bértola, G. R., & Piccolo, M. C.	2016	<i>Hazard, vulnerability and coastal erosion risk assessment in Necochea Municipality, Buenos Aires Province, Argentina</i>	Journal of coastal conservation, 20
Morgan, C.	2011	<i>Vulnerability assessments: a review of approaches</i>	IUCN, Asia Regional Office (ARO)
Mukhopadhyay, A., Dasgupta, R., Hazra, S., & Mitra, D.	2012	<i>Coastal hazards and vulnerability: A review</i>	International journal of geology, earth and environmental sciences, 2
Muñoz-Vallés, S., & Cambrollé, J.	2014	<i>Successes and failures in the management of coastal dunes of SW Spain: Status analysis nine years after management decisions</i>	Ecological Engineering, 71, 415-425
Musekiwa, C., Cawthra, H. C., Unterner, M., & van Zyl, F. W.	2015	<i>An assessment of coastal vulnerability for the South African coast</i>	South African Journal of Geomatics, 4
Myers, M. R., Barnard, P. L., Beighley, E., Cayan, D. R., Dugan, J. E., Feng, D., ... & Page, H. M.	2019	<i>A multidisciplinary coastal vulnerability assessment for local government focused on ecosystems, Santa Barbara area, California</i>	Ocean & Coastal Management, 182, 104921
Narra, P., Coelho, C., & Sancho, F.	2019	<i>Multicriteria GIS-based estimation of coastal erosion risk: Implementation to Aveiro sandy coast, Portugal</i>	Ocean & Coastal Management, 178, 104845

<i>Authors</i>	<i>Year</i>	<i>Title</i>	<i>Journal</i>
Narra, P., Coelho, C., Sancho, F., & Palalane, J.	2017	<i>CERA: An open-source tool for coastal erosion risk assessment</i>	Ocean & Coastal Management, 142, 1-14
Oropeza-Orozco, O., Sommer-Cervantes, I., Carlos-Gómez, J., Preciado-López, J. C., Ortiz-Pérez, M. A., & Lopez-Portillo, J.	2011	<i>Assessment of vulnerability and integrated management of coastal dunes in Veracruz, Mexico</i>	Coastal Management, 39
Palmer, B. J., Van der Elst, R., Mackay, F., Mather, A. A., Smith, A. M., Bundy, S. C., ... & Parak, O.	2011	<i>Preliminary coastal vulnerability assessment for kwazulu-natal, south africa</i>	Journal of Coastal Research, 1390-1395
Pantusa, D., D'Alessandro, F., Riefolo, L., Principato, F., & Tomasicchio, G. R.	2018	<i>Application of a coastal vulnerability index A case study along the Apulian Coastline, Italy</i>	Water, 10
Peña-Alonso, C., Fraile-Jurado, P., Hernández-Calvento, L., Pérez-Chacón, E., & Ariza, E.	2017	<i>Measuring geomorphological vulnerability on beaches using a set of indicators (GVI): A tool for management</i>	Journal of environmental management, 204, 230-245
Peña-Alonso, C., Gallego-Fernández, J. B., Hernández-Calvento, L., Hernández-Cordero, A. I., & Ariza, E.	2018	<i>Assessing the geomorphological vulnerability of arid beach-dune systems</i>	Science of the Total Environment, 635, 512-525
Peña-Alonso, C., Hernández-Calvento, L., Pérez-Chacón, E., & Ariza-Solé, E.	2017	<i>The relationship between heritage, recreational quality and geomorphological vulnerability in the coastal zone: A case study of beach systems in the Canary Islands</i>	Ecological Indicators, 82, 420-432
Pennetta, M., Corbelli, V., Gattullo, V., Nappi, R., Brancato, V. M., & Gioia, D.	2018	<i>Beach vulnerability assessment of a protected area of the Northern Campania coast (Southern Italy)</i>	Journal of Coastal Conservation, 22(5), 1017-1029
Pethick, J. S., & Crooks, S.	2000	<i>Development of a coastal vulnerability index: a geomorphological perspective</i>	Environmental conservation, 27
Pintó, J., Martí, C., & Fraguell, R. M.	2014	<i>Assessing current conditions of coastal dune systems of Mediterranean developed shores</i>	Journal of Coastal Research, 30
Prasad, P., Loveson, V. J., Das, B., & Kotha, M.	2021	<i>Novel ensemble machine learning models in flood susceptibility mapping</i>	Geocarto International, 1-23
Prisco, I., Acosta, A. T., & Stanisci, A.	2021	<i>A bridge between tourism and nature conservation: boardwalks effects on coastal dune vegetation</i>	Journal of Coastal Conservation, 25
Ramieri, E., Hartley, A., Barbanti, A., Santos, F. D., Gomes, A., Hilden, M., ... & Santini, M.	2011	<i>Methods for assessing coastal vulnerability to climate change</i>	ETC CCA technical paper, 1
Rangel-Buitrago, N., & Anfuso, G.	2015	<i>Risk assessment of storms in coastal zones: case studies from Cartagena (Colombia) and Cadiz (Spain)</i>	Springer
Rangel-Buitrago, N., Neal, W. J., & de Jonge, V. N.	2020	<i>Risk assessment as tool for coastal erosion management</i>	Ocean & Coastal Management, 186, 105099
Rizzo, A., Aucelli, P. P. C., Gracia, F. J., & Anfuso, G.	2018	<i>A novelty coastal susceptibility assessment method: Application to Valdelagrana area (SW Spain)</i>	Journal of Coastal Conservation, 22(5), 973-987
Rodríguez-Santalla, I., Díez-Martínez, A., & Navarro, N.	2021	<i>Vulnerability Analysis of the Riumar Dune Field in El Garxal Coastal Wetland (Ebro Delta, Spain)</i>	Journal of Marine Science and Engineering, 9(6), 601
Roig-Munar, F. X., Martín-Prieto, J. A., Rodríguez-Perea, A., Pons, G. X., Gelabert, B., & Mir-Gual, M.	2012	<i>Risk assessment of beach-dune system erosion: beach management impacts on the Balearic Islands</i>	Journal of Coastal Research, 28
Sajjad, M., Li, Y., Tang, Z., Cao, L., & Liu, X.	2018	<i>Assessing hazard vulnerability, habitat conservation, and restoration for the enhancement of mainland China's coastal resilience</i>	Earth's Future, 6
Sancho, F., Oliveira, F. S., & Freire, P.	2012	<i>Coastal dunes vulnerability indexes: A new proposal</i>	Coastal Engineering Proceedings,
Sekovski, I., Armaroli, C., Calabrese, L., Mancini, F., Stecchi, F., & Perini, L.	2015	<i>Coupling scenarios of urban growth and flood hazards along the Emilia-Romagna coast (Italy)</i>	Natural Hazards and Earth System Sciences, 15(10), 2331-2346
Sekovski, I., Del Río, L., & Armaroli, C.	2020	<i>Development of a coastal vulnerability index using analytical hierarchy process and application to Ravenna province (Italy)</i>	Ocean & Coastal Management, 183, 104982
Sigren, J. M., Figlus, J., & Armitage, A. R.	2014	<i>Coastal sand dunes and dune vegetation: restoration, erosion, and storm protection</i>	Shore & Beach, 82
Splinter, K. D., Strauss, D., & Tomlinson, R. B.	2011	<i>Can we reliably estimate dune erosion without knowing pre-storm bathymetry?</i>	Coasts and Ports 2011, 694-699
Sytnik, O., & Stecchi, F.	2015	<i>Disappearing coastal dunes: tourism development and future challenges, a case-study from Ravenna, Italy</i>	Journal of Coastal conservation, 19
Tragaki, A., Gallousi, C., & Karymbalis, E.	2018	<i>Coastal hazard vulnerability assessment based on geomorphic, oceanographic and demographic parameters: The case of the Peloponnese (Southern Greece)</i>	Land, 7(2), 56
Vallés, S. M., Gallego Fernández, J. B., & Dellafiore, C. M.	2011	<i>Dune vulnerability in relation to tourism pressure in central Gulf of Cádiz (SW Spain), a case study</i>	Journal of Coastal Research, 27(2), 243-251
Wamsley, T. V., Collier, Z. A., Brodie, K., Dunkin, L. M., Raff, D., & Rosati, J. D.	2015	<i>Guidance for developing coastal vulnerability metrics</i>	Journal of Coastal Research, 31
Weis, S. W. M., Agostini, V. N., Roth, L. M., Gilmer, B., Schill, S. R., Knowles, J. E., & Blyther, R.	2016	<i>Assessing vulnerability: an integrated approach for mapping adaptive capacity, sensitivity, and exposure</i>	Climatic change, 136

Authors	Year	Title	Journal
Williams, A. T., & Davies, P.	2001	<i>Coastal dunes of Wales; vulnerability and protection</i>	Journal of Coastal Conservation, 7
Williams, A. T., Alveirinho-Dias, J., Novo, F. G., Garcia-Mora, M. R., Curr, R., & Pereira, A.	2001	<i>Integrated coastal dune management: checklists</i>	Continental shelf research, 21
Williams, A. T., Davies, P., Alveirinho-Dias, J. M., Pereira, A. R., García-Mora, M. R., & Tejada, M.	1994	<i>A re-evaluation of dune vulnerability checklist parameters</i>	Gaia, 8, 179-182
Williams, A. T., Davies, P., Curr, R., Koh, A., Bodére, J. C., Hallegouet, B., ... & Yoni, C.	1993	<i>A checklist assessment of dune vulnerability and protection in Devon and Cornwall, UK</i>	Coastal Zone'93
Williams, A. T., Rangel-Buitrago, N., Pranzini, E., & Anfuso, G.	2018	<i>The management of coastal erosion</i>	Ocean & Coastal Management, 156, 4-20
Winters, M. A., Leslie, B., Sloane, E. B., & Gallien, T. W.	2020	<i>Observations and Preliminary Vulnerability Assessment of a Hybrid Dune-Based Living Shoreline</i>	Journal of Marine Science and Engineering, 8
Zhu, Z. T., Cai, F., Chen, S. L., Gu, D. Q., Feng, A. P., Cao, C., ... & Lei, G.	2019	<i>Coastal vulnerability to erosion using a multi-criteria index: A case study of the Xiamen coast</i>	Sustainability, 11

Annex II

Table A2.1: Explanation of selected indicators, methodology for the calculation and sources of StaDun indicators.

<i>StaDun indicator</i>	<i>Explanation</i>	<i>Methodology and source</i>
1 <i>Types of dunes according to García-Lozano and Pinto (2018)</i>	The indicator assesses the presence and development of the dune system, recognising five classes whose value increases as the development of the system increases. Where dunes are absent (0), incipient forms may develop (1) and become coalescent to form a foredune (2). With time, this will favour the formation of semi-fixed dunes (3) and true dune fields (4).	The assessment was made using digital orthophotos (AGEA 2018 Database Veneto Region), in QuantumGIS 3.14.
2 <i>Surface area of the dune system</i>	Large dune systems have often a higher degree of development and consequently provide more, and more efficient ecosystem services.	Determined by creating polygons in GIS overlaid on orthophotos (AGEA 2018 Database Veneto Region).
3 <i>Area occupied by the dunes in relation to the beach-dune system</i>	On equal areas, systems with more developed dunes are more efficient than those in which the beach is more developed than the dune.	The percentage ratio of dunes on beach was calculated by creating polygons in GIS on digital orthophotos (AGEA 2018 Database Veneto Region)
4 <i>Maximum height of the foredune</i>	High dunes have a high amount of accumulated sediment and can respond to adverse phenomena more efficiently.	It was calculated by performing three transects orthogonal to the coastline for each analysed sector on the 1m resolution digital terrain model of Google Earth Pro 7.3.4.8248 software. The highest point corresponding to the foredune was then recorded.
5 <i>Incipient morphologies on the dune face</i>	The presence of incipient dunes indicated new sediment accumulations and the progression of the dune system towards the beach.	It was calculated as the ratio between the areas occupied by incipient dunes and the whole dune system through polygons created on orthophotos (AGEA 2018 Database Veneto Region) in GIS.
6 <i>Evolution of the dune front since 1956</i>	Progradation or retreat of the dune system over the last decades allows to estimate possible conservation or degradation trends of dune systems.	It was calculated by comparing current orthophotos (AGEA 2018 Database Veneto Region) with past aerial photographs of GAI 1954-1955 flight (https://idt2.regione.veneto.it/idt/webgis/viewer?webgisId=47)
7 <i>Structural status of the foredune according to Hesp (2002)</i>	The Hesp classification defines the structural integrity of coastal dunes. Starting from the lowest class, the structural integrity increases up to the condition of an unfragmented dune with no ongoing erosive processes.	The classes were assigned for each analysed sector by comparing orthophotos (AGEA 2018 Database Veneto Region) with the models proposed in Hesp (2002).
8 <i>Type III species on the dune front according to García-Mora et al. (2001)</i>	The presence of Type III species <i>sensu</i> García-Mora et al. (2001) indicate possible growing process of coastal dunes.	They were defined according to the species listed in García-Mora et al. (2001) and counting the species found in the plots within each sector. A database of 1078 georeferenced plots x 208 species surveyed from 2010 to 2016 by the Plant Ecology research team of Ca' Foscari University, and published surveys from Filesi et al. (2017) were analysed. For sectors without plots but with dune systems, data from adjacent sites were considered.
9 <i>Beach-dune system restricted plants</i>	Native and focal species were considered as beach-dune system restricted species, which indicates a condition of equilibrium and little disturbance, and are usually not found in environments other than dunes. On the contrary, ruderal and alien species can grow in many different environments and are proxies of human disturbance.	The list of restricted species of the dune-beach system was based on literature (Acosta & Ercole 2015; Buffa et al. 2007), as well as the list of invasive species (Galasso et al. 2018) and ruderal species (Del Vecchio et al. 2019). The number of beach-dune system restricted species, invasive, and ruderal species for each sector was retrieved from the georeferenced vegetation database of 1078 plots x 208 species and published surveys from Filesi et al. (2017). For sectors without plots but with dune systems, data from adjacent sites were considered.
10 <i>Invasive species</i>		
11 <i>Ruderal species</i>		

Table A2.2: Explanation of selected indicators, methodology for the calculation and sources of BeaPot indicators.

BeaPot indicator	Explanation	Methodology and source
1 <i>Slope of the beach</i>	The profile of the beach are descriptors of its morphodynamic state, e.g., slight slopes allow the transport and accumulation of sand useful for the formation and development of coastal dunes.	Three transects were drawn at random in each sector, and their average slope was retrieved from the Google Earth Pro digital terrain model at 1m resolution.
2 <i>Evolution of the beach during the period 2004-2010</i>	Recent variation of the shoreline allows to identify the growth or erosion of a beach and provide indication on positive or negative sediment budget.	Values were retrieved from Fontolan et al. (2014; Variazioni linea di riva - Media - Recente).
3 <i>Beach orientation in relation to the prevailing winds</i>	The direction of the prevailing wind is important for understanding the transport of sedimentary material. Beaches with a wind perpendicular to the shoreline are more likely to develop coastal dunes.	The prevailing wind direction was sourced from the Venice station of the "Rete Mareografica Nazionale" for the period between 01/01/2016 and 31/12/2020 (https://www.mareografico.it/) and then intersected with the shoreline direction of each sector in GIS environment.
4 <i>Average intensity of the wind</i>	Wind intensity is proportional to the capacity to transport sediment along the coast and to form aeolian deposits.	The quantification of wind speed is based on the annual average in 2020, from the ISMAR-CNR Platform in the northern Adriatic (https://www.comune.venezia.it/it/content/3-piattaforma-ismar-cnr). Data were assumed to be constant along the entire coast.
5 <i>Significant Wave Height</i>	The intensity of the waves determines the amount of sediment brought by the sea onto the emerged beach, but high energy waves can erode the beach and remove sediment useful for the formation of dune belts.	The quantification of the average significant wave height is based on the annual average in 2020, from the ISMAR-CNR Platform in the northern Adriatic (https://www.comune.venezia.it/it/content/3-piattaforma-ismar-cnr). Data were assumed to be constant along the entire coastline.
6 <i>Diameter of the sediment</i>	Sediment diameter is a useful indicator for understanding its suitability to be transported and form wind deposits. The smaller the size of the sandy sediment, the greater its suitability.	The determination of d50 (phi) was based on 53 sediment samples available within the study area surveyed in 2016 by the Plant Ecology research team of Ca' Foscari University. Since the sediment size did not significantly vary among the sites, the average-values of the was assigned to each site.
7 <i>Sands <0.5 mm</i>	The fine sand portion determines the proportion of sediment most involved in coastal dune formation. Sediments with a grain size greater than 0.5 mm are more difficult for the wind to transport. In this way, beaches rich in fine sand are more prone to the formation and development of coastal dunes.	In order to determine the percentage of sediment <0.5 mm, 53 samples available within the study area surveyed in 2016 the by Plant Ecology research team of Ca' Foscari University were used, considering the percentage of fine sand (in Microsoft Office 14.2110.1311.0 - Excel Since the sediment size did not significantly vary among the sites, the average-values of the was assigned to each site.
8 <i>Sediment budget during the period 2004-2010 *</i>	The sediment budget of the area describes the real availability of sediment for the formation of new coastal morphologies. It is defined by the inputs and outputs that affect a coastal area governing its evolutionary dynamics, namely the accretion or erosion of the coastal system.	While Garcia-Lozano (2020) used the percentage of pebbles on the beach surface, we used the sediment budget, because pebbles were absent along the investigated area. Data were sourced from Fontolan et al. (2014; Bilancio sedimentario - Totale - Recente).
9 <i>Width of dry beach</i>	The topographic characteristic of the shoreline such as width is of primary importance to understand the development potential of a coastal dune system. The greater its width, the greater its potential to host dunes, as the more sediment and space ensure the development of coastal processes.	It was determined by photointerpretation in GIS environment, by measuring the distance between the shoreline and the coastline of three transects randomly placed in each sector (AGEA 2018 Database Veneto Region), taking care to consider only the portion of dry sand not affected by the tide.

* Indicators changed compared to Garcia-Lozano et al. (2020).

Table A2.3: Explanation of selected indicators, methodology for the calculation and sources of CoMan indicators.

CoMan indicator	Explanation	Methodology and source
1 <i>Touristic use pressure</i> *	Tourist pressure is decisive in understanding the amount of human activity present in each context. High tourist pressure causes a strong alteration of the biotic and abiotic components of a dune system and favour its degradation.	Contrary to Garcia-Lozano et al. (2020), the available data are expressed as the number of users per surface unit, instead of surface per user. Data were sourced from Fontolan et al. (2014; <i>Pressione antropica - Pressione d'uso turistica</i>). .
2 <i>Information boards</i>	Information panels are an important communication system, whose presence contribute to aware beach users of the possible impacts on coastal dunes and the need to preserve them. However, their presence does not preclude possible negative effects on the system as they can be ignored.	Presence was determined through field trip and effectiveness was assessed through orthophotos (AGEA 2018 Database Veneto Region) in GIS environment: low effectiveness was assumed when unregulated paths were clearly visible.
3 <i>Managed paths</i>	The presence of regulated paths and accesses limits the impacts deriving from the random trampling of tourists going to the beach. In addition, the provision of regulated access paths in such a way that they interfere as little as possible with coastal dynamics is the least impactful solution.	The assessment of the presence and type of regulated path was carried out by means of field trip and orthophotos (AGEA 2018 Database Veneto Region) investigated in QuantumGIS 3.14.
4 <i>Dune area with restricted access</i>	Fencing dune areas is deterrent to trample on them. Their presence and correct design can promote the natural evolutionary dynamics, also allowing the development and connectivity of animal and plant species.	The percentage of areas with restricted access was assessed through field surveys and quantified by calculating their surface in GIS environment (AGEA 2018 Database Veneto Region).
5 <i>Sand traps</i>	In order to promote the accumulation of sediment and encourage the development of dune systems, artificial obstacles can be actively used.	The presence and effects of these structures were assessed through field surveys and orthophoto (AGEA 2018 Database Veneto Region) assessments in QuantumGIS 3.14.
6 <i>Mechanical cleaning/levelling</i>	Large quantities of sediment are removed along with the removal of beached material through mechanical cleaning, while heavy vehicles compact the substrate and alters the natural dynamics. The greater the frequency of cleaning, the greater the negative influence on the formation and development of coastal dunes.	This information was collected through consultation of coastal managers.
7 <i>Surface area occupied by seasonal services on beach-dune system*</i>	The presence of temporary structures on the beach-dune system interferes with natural coastal dynamics and especially with sediment transport. This results in a reduced sediment supply that limits the formation and development of coastal dunes.	The determination of the ratio was done by comparing in GIS environment the areas of the polygons corresponding to the temporary structures with those of the polygons of the whole beach-dune system within each sector by using digital orthophotos (AGEA 2018 Database Veneto Region).
8 <i>Surface area occupied by permanent services on beach-dune system*</i>	The presence of permanent structures on the beach-dune system interferes with the natural coastal dynamics, especially with the transport of sediment, even during the winter period. This results in a reduced sediment supply that limits the formation and development of coastal dunes.	The determination of the ratio was done by comparing in GIS environment the areas of the polygons corresponding to the permanent structures with those of the polygons of the whole beach-dune system within each sector by using digital orthophotos (AGEA 2018 Database Veneto Region).
9 <i>Protection of the system and the immediate environment</i>	The guarding and the protection of natural areas through active control avoids disturbance of the dunes and promotes the sustainable use of coastal areas by tourists.	The data was obtained through consultation of coastal managers.

* Indicators changed compared to Garcia-Lozano et al. (2020).

Table A2.4: explanation of selected indicators, methodology for the calculation and sources of SurLan indicators.

SurLan indicator	Explanation	Methodology and source
1 Impact according to the predominant land category in the first 100m	The type of landscape element in contact with the beach-dune system describes the current pressures from human activities and the possible influences that the surroundings can have on the dune system. The more natural the backdune area is, the greater the positive effects will be.	The determination was made using GIS, intersecting Corine Land Cover category (CLC 2018; https://land.copernicus.eu/) and digital orthophotos (AGEA 2018 Database Veneto Region) with a 100m buffer created from the innermost boundary of the dune-beach system.

Annex III

Table A3.1: Values assigned to each indicator of StaDun index in each analysed cell and relative mean and class rating associated.

Physiographic unit	Cell	StaDun indicator											Mean value	StaDun class	
		1	2	3	4	5	6	7	8	9	10	11			
Isola Verde	IVC1	0	0	0	0	0	0	0	0	0	0	0	0	0,00	Low
	IVC2	0	0	0	0	0	0	0	0	0	0	0	0	0,00	Low
	IVC3	3	1	3	3	0	1	2	0	0	0	0	3	0,36	Medium
	IVC4	3	1	3	3	0	1	1	0	0	0	0	3	0,34	Medium
	IVC5	3	1	3	3	0	1	2	0	0	0	0	3	0,36	Medium
	IVC6	3	1	3	3	2	3	3	0	0	0	0	3	0,48	Medium
	IVC7	3	1	3	3	1	4	3	0	0	0	0	3	0,48	Medium
	IVC8	3	1	3	3	1	4	3	0	0	0	0	3	0,48	Medium
Sottomarina	SC1	3	1	2	2	1	4	2	0	0	0	3	0,41	Medium	
	SC2	3	1	2	3	1	4	2	0	0	0	3	0,43	Medium	
	SC3	0	0	0	0	0	0	0	0	0	0	0	0,00	Low	
	SC4	0	0	0	0	0	0	0	0	0	0	0	0,00	Low	
	SC5	1	1	4	0	3	3	0	0	0	4	4	0,45	Medium	
Pellestrina	PC1	3	4	4	2	1	4	4	2	4	0	1	0,66	Medium	
	PC2	1	1	2	0	4	3	0	0	0	4	4	0,43	Medium	
	PC3	1	1	0	0	4	3	0	0	0	4	4	0,39	Medium	
	PC4	1	1	1	0	4	3	0	0	0	4	4	0,41	Medium	
	PC5	1	1	1	0	4	3	0	0	0	4	4	0,41	Medium	
	PC6	1	1	2	0	4	3	0	0	0	4	4	0,43	Medium	
	PC7	1	1	1	0	4	3	0	0	0	4	4	0,41	Medium	
Lido Venezia	LC1	3	4	4	1	1	4	4	2	4	0	1	0,64	Medium	
	LC2	0	0	0	0	0	0	0	0	0	0	0	0,00	Low	
	LC3	0	0	0	0	0	0	0	0	0	0	0	0,00	Low	
	LC4	0	0	0	0	0	0	0	0	0	0	0	0,00	Low	
	LC5	0	0	0	0	0	0	0	0	0	0	0	0,00	Low	
	LC6	3	4	2	1	2	4	4	0	4	0	1	0,57	Medium	
Cavallino	CVC1	3	4	4	3	1	4	4	2	4	1	2	0,73	High	
	CVC2	3	4	3	3	1	4	4	2	4	0	1	0,66	Medium	
	CVC3	0	0	0	0	0	0	0	0	0	0	0	0,00	Low	
	CVC4	3	2	3	2	2	3	3	2	4	2	3	0,66	Medium	
	CVC5	1	1	4	0	4	0	0	2	4	2	3	0,48	Medium	
	CVC6	3	1	1	2	2	3	2	2	4	1	2	0,52	Medium	
	CVC7	3	1	1	2	2	3	2	2	4	1	2	0,52	Medium	
	CVC8	3	2	2	2	2	3	4	2	4	1	2	0,61	Medium	
Jesolo	JC1	0	0	0	0	0	0	0	0	0	0	0	0,00	Low	
	JC2	0	0	0	0	0	0	0	0	0	0	0	0,00	Low	
	JC3	0	0	0	0	0	0	0	0	0	0	0	0,00	Low	
	JC4	0	0	0	0	0	0	0	0	0	0	0	0,00	Low	
	JC5	0	0	0	0	0	0	0	0	0	0	0	0,00	Low	
	JC6	0	0	0	0	0	0	0	0	0	0	0	0,00	Low	
	JC7	3	1	2	1	1	3	1	2	4	0	0	0,41	Medium	
	JC8	3	2	3	2	1	4	1	2	4	0	0	0,50	Medium	
Eraclea	EC1	3	3	4	0	0	4	0	2	4	0	0	0,45	Medium	
	EC2	3	1	3	0	0	4	0	2	4	0	1	0,41	Medium	
	EC3	0	0	0	0	0	0	0	0	0	0	0	0,00	Low	
	EC4	0	0	0	0	0	0	0	0	0	0	0	0,00	Low	
	EC6	3	1	2	0	2	3	1	0	2	0	3	0,39	Medium	
	EC7	3	3	2	1	0	1	1	0	2	0	3	0,36	Medium	
	EC8	3	3	2	2	2	1	1	0	2	0	3	0,43	Medium	
	Duna Verde	DVC9	3	1	1	0	0	1	2	0	2	0	3	0,30	Low
Porto S. Margherita	SMC10	0	0	0	0	0	0	0	0	0	0	0	0,00	Low	
	SMC11	0	0	0	0	0	0	0	0	0	0	0	0,00	Low	
	SMC12	0	0	0	0	0	0	0	0	0	0	0	0,00	Low	
	SMC13	3	1	1	2	0	3	4	0	2	0	3	0,43	Medium	
Caorle	CC1	0	0	0	0	0	0	0	0	0	0	0	0,00	Low	
	CC2	0	0	0	0	0	0	0	0	0	0	0	0,00	Low	
	CC3	0	0	0	0	0	0	0	0	0	0	0	0,00	Low	
Valle vecchia	VC1	3	4	4	1	0	4	4	0	2	3	4	0,66	Medium	
	VC2	3	4	4	1	0	4	2	2	4	0	0	0,55	Medium	
	VC3	3	4	4	1	1	4	3	2	4	0	0	0,59	Medium	
Bibione	BC1	3	3	2	1	1	4	3	2	4	0	0	0,52	Medium	
	BC2	3	3	2	3	1	3	1	0	4	0	1	0,48	Medium	
	BC3	0	0	0	0	0	0	0	0	0	0	0	0,00	Low	
	BC4	2	1	1	1	2	3	1	0	4	2	3	0,45	Medium	
	BC5	3	4	4	2	1	1	2	0	4	0	2	0,52	Medium	

Table A3.2: Values assigned to each indicator of BeaPot index in each analysed cell and relative mean and class rating associated.

Physiographic unit	Cell	BeaPot indicator									Mean value	BeaPot class
		1	2	3	4	5	6	7	8	9		
Isola Verde	IVC1	4	0	4	2	4	4	4	2	4	0,78	High
	IVC2	4	3	4	2	4	4	4	1	1	0,75	High
	IVC3	4	2	4	2	4	4	4	2	1	0,75	High
	IVC4	4	3	4	2	4	4	4	1	1	0,75	High
	IVC5	4	1	4	2	4	4	4	1	1	0,69	High
	IVC6	4	1	4	2	4	4	4	1	1	0,69	High
	IVC7	4	2	4	2	4	4	4	1	3	0,78	High
	IVC8	4	4	4	2	4	4	4	2	4	0,89	High
Sottomarina	SC1	4	3	4	2	4	4	4	2	4	0,86	High
	SC2	4	1	4	2	4	4	4	1	4	0,78	High
	SC3	4	4	4	2	4	4	4	2	4	0,89	High
	SC4	4	3	3	2	4	4	4	0	4	0,78	High
	SC5	4	4	3	2	4	4	4	4	4	0,92	High
Pellestrina	PC1	4	4	3	2	4	4	4	3	4	0,89	High
	PC2	2	3	3	2	4	4	4	1	0	0,64	Medium
	PC3	2	1	3	2	4	4	4	1	4	0,69	High
	PC4	2	3	3	2	4	4	4	2	3	0,75	High
	PC5	4	3	3	2	4	4	4	2	3	0,81	High
	PC6	4	3	3	2	4	4	4	2	3	0,81	High
	PC7	2	1	3	2	4	4	4	2	1	0,64	Medium
Lido Venezia	LC1	4	4	3	2	4	4	4	2	1	0,78	High
	LC2	4	4	3	2	4	4	4	2	0	0,75	High
	LC3	4	3	3	2	4	4	4	2	1	0,75	High
	LC4	4	4	3	2	4	4	4	1	3	0,81	High
	LC5	4	4	3	2	4	4	4	1	3	0,81	High
	LC6	4	4	3	2	4	4	4	2	4	0,86	High
Cavallino	CVC1	4	4	2	2	4	4	4	2	4	0,83	High
	CVC2	4	2	2	2	4	4	4	2	3	0,75	High
	CVC3	4	4	2	2	4	4	4	2	3	0,81	High
	CVC4	4	3	2	2	4	4	4	2	3	0,78	High
	CVC5	4	4	2	2	4	4	4	2	4	0,83	High
	CVC6	4	4	2	2	4	4	4	2	4	0,83	High
	CVC7	4	3	2	2	4	4	4	1	3	0,75	High
	CVC8	4	3	2	2	4	4	4	2	4	0,81	High
Jesolo	JC1	4	3	2	2	4	4	4	2	4	0,81	High
	JC2	4	4	2	2	4	4	4	2	4	0,83	High
	JC3	4	4	2	2	4	4	4	2	4	0,83	High
	JC4	4	4	2	2	4	4	4	2	4	0,83	High
	JC5	4	0	2	2	4	4	4	1	3	0,67	High
	JC6	4	0	2	2	4	4	4	1	3	0,67	High
	JC7	4	4	2	2	4	4	4	2	4	0,83	High
	JC8	4	0	2	2	4	4	4	0	1	0,58	Medium
Eraclea	EC1	4	3	2	2	4	4	4	1	1	0,69	High
	EC2	4	3	2	2	4	4	4	1	0	0,67	High
	EC3	0	3	2	2	4	4	4	2	0	0,58	Medium
	EC4	0	3	2	2	4	4	4	2	0	0,58	Medium
	EC6	4	4	2	2	4	4	4	1	4	0,81	High
	EC7	4	4	2	2	4	4	4	1	3	0,78	High
	EC8	4	2	2	2	4	4	4	2	1	0,69	High
	Duna Verde	DVC9	2	2	2	2	4	4	4	2	3	0,69
Porto S. Margherita	SMC10	2	2	2	2	4	4	4	1	0	0,58	Medium
	SMC11	2	2	2	2	4	4	4	1	0	0,58	Medium
	SMC12	2	0	2	2	4	4	4	2	1	0,58	Medium
	SMC13	4	0	2	2	4	4	4	2	4	0,72	High
Caorle	CC1	4	2	2	2	4	4	4	2	4	0,78	High
	CC2	0	0	0	0	0	0	0	0	0	0,00	Low
	CC3	4	0	2	2	4	4	4	2	4	0,72	High
Valle vecchia	VC1	4	2	1	2	4	4	4	2	1	0,67	High
	VC2	4	1	1	2	4	4	4	1	1	0,61	Medium
	VC3	4	2	1	2	4	4	4	3	1	0,69	High
Bibione	BC1	4	4	1	2	4	4	4	2	3	0,78	High
	BC2	4	2	1	2	4	4	4	2	4	0,75	High
	BC3	4	4	1	2	4	4	4	3	4	0,83	High
	BC4	4	0	1	2	4	4	4	1	4	0,67	High
	BC5	4	0	1	2	4	4	4	2	3	0,67	High

Table A3.3: Values assigned to each indicator of CoMan index in each analysed cell and relative mean and class rating associated.

Physiographic unit	Cell	CoMan indicator									Mean value	CoMan class
		1	2	3	4	5	6	7	8	9		
Isola Verde	IVC1	0	4	2	4	2	3	3	1	4	0,64	Medium
	IVC2	1	4	2	4	2	3	1	2	4	0,64	Medium
	IVC3	1	4	2	0	4	3	2	1	4	0,58	Medium
	IVC4	1	4	2	0	4	3	4	1	4	0,64	Medium
	IVC5	1	4	2	0	4	3	4	1	4	0,64	Medium
	IVC6	0	4	4	4	0	3	2	1	4	0,61	Medium
	IVC7	0	4	4	4	0	3	0	0	4	0,53	Medium
	IVC8	0	4	2	4	0	3	2	1	4	0,56	Medium
Sottomarina	SC1	0	4	2	4	0	3	4	1	4	0,61	Medium
	SC2	1	4	2	4	0	3	4	1	4	0,64	Medium
	SC3	1	4	2	4	4	3	4	1	4	0,75	High
	SC4	1	4	2	4	4	3	4	1	4	0,75	High
	SC5	1	4	2	4	4	3	4	2	4	0,78	High
Pellestrina	PC1	0	0	2	4	0	0	0	1	4	0,31	Low
	PC2	1	4	3	4	4	1	1	1	4	0,53	Medium
	PC3	1	4	3	4	4	0	1	0	4	0,56	Medium
	PC4	0	4	3	4	4	0	1	0	4	0,56	Medium
	PC5	0	4	3	4	4	0	0	0	4	0,53	Medium
	PC6	0	4	3	4	4	0	0	0	4	0,53	Medium
	PC7	0	4	3	4	4	0	0	0	4	0,53	Medium
Lido Venezia	LC1	0	4	4	3	0	1	1	1	4	0,50	Medium
	LC2	0	4	4	4	4	0	0	0	4	0,56	Medium
	LC3	0	4	4	4	4	0	0	0	4	0,56	Medium
	LC4	0	4	4	4	4	3	4	2	4	0,81	High
	LC5	0	4	4	4	4	3	3	1	4	0,75	High
	LC6	0	4	2	4	0	1	3	1	4	0,53	Medium
Cavallino	CVC1	1	4	2	1	0	3	1	2	4	0,50	Medium
	CVC2	1	0	2	1	0	3	1	3	4	0,42	Medium
	CVC3	1	4	2	4	4	3	1	4	4	0,75	High
	CVC4	1	4	2	4	0	3	0	2	4	0,56	Medium
	CVC5	1	4	2	4	4	3	1	3	4	0,72	High
	CVC6	1	4	2	4	2	3	1	2	4	0,64	Medium
	CVC7	4	4	2	4	2	3	3	1	4	0,75	High
	CVC8	4	4	2	4	4	3	3	1	4	0,81	High
Jesolo	JC1	4	4	2	4	4	3	4	1	4	0,83	High
	JC2	4	4	2	4	4	3	4	1	4	0,83	High
	JC3	4	4	2	4	4	3	4	1	4	0,83	High
	JC4	4	4	2	4	4	3	4	1	4	0,83	High
	JC5	4	4	2	4	4	3	4	2	4	0,86	High
	JC6	4	4	2	4	4	3	1	2	4	0,78	High
	JC7	1	4	2	4	4	3	2	4	4	0,78	High
	JC8	1	4	2	4	0	3	1	3	4	0,61	Medium
Eraclea	EC1	0	4	2	4	0	0	0	0	4	0,39	Medium
	EC2	0	4	2	4	0	0	0	0	4	0,39	Medium
	EC3	0	4	4	4	4	0	0	0	4	0,56	Medium
	EC4	0	4	4	4	4	0	0	0	4	0,56	Medium
	EC6	4	4	2	3	4	3	1	2	4	0,75	High
	EC7	4	0	2	4	4	3	2	2	4	0,69	High
	EC8	1	0	2	4	4	3	0	1	4	0,53	Medium
	Duna Verde	DVC9	4	4	2	4	4	3	3	1	4	0,81
Porto S. Margherita	SMC10	1	4	2	4	4	3	3	1	4	0,72	High
	SMC11	1	4	2	4	4	3	2	1	4	0,69	High
	SMC12	4	4	2	4	4	3	4	1	4	0,83	High
	SMC13	4	4	2	4	4	3	4	1	4	0,83	High
Caorle	CC1	4	4	2	4	4	3	4	1	4	0,83	High
	CC2	0	4	4	4	4	0	0	0	4	0,56	Medium
	CC3	1	4	2	4	4	3	4	1	4	0,75	High
Valle vecchia	VC1	0	0	2	4	0	1	0	0	4	0,31	Low
	VC2	0	0	2	4	0	1	0	0	4	0,31	Low
	VC3	0	0	2	4	0	1	0	1	4	0,33	Medium
Bibione	BC1	2	0	2	4	0	1	1	1	4	0,42	Medium
	BC2	4	4	2	4	4	3	3	2	4	0,83	High
	BC3	4	4	2	4	4	3	4	1	4	0,83	High
	BC4	1	4	2	4	2	3	4	1	4	0,69	High
	BC5	0	0	2	2	2	3	0	1	4	0,39	Medium

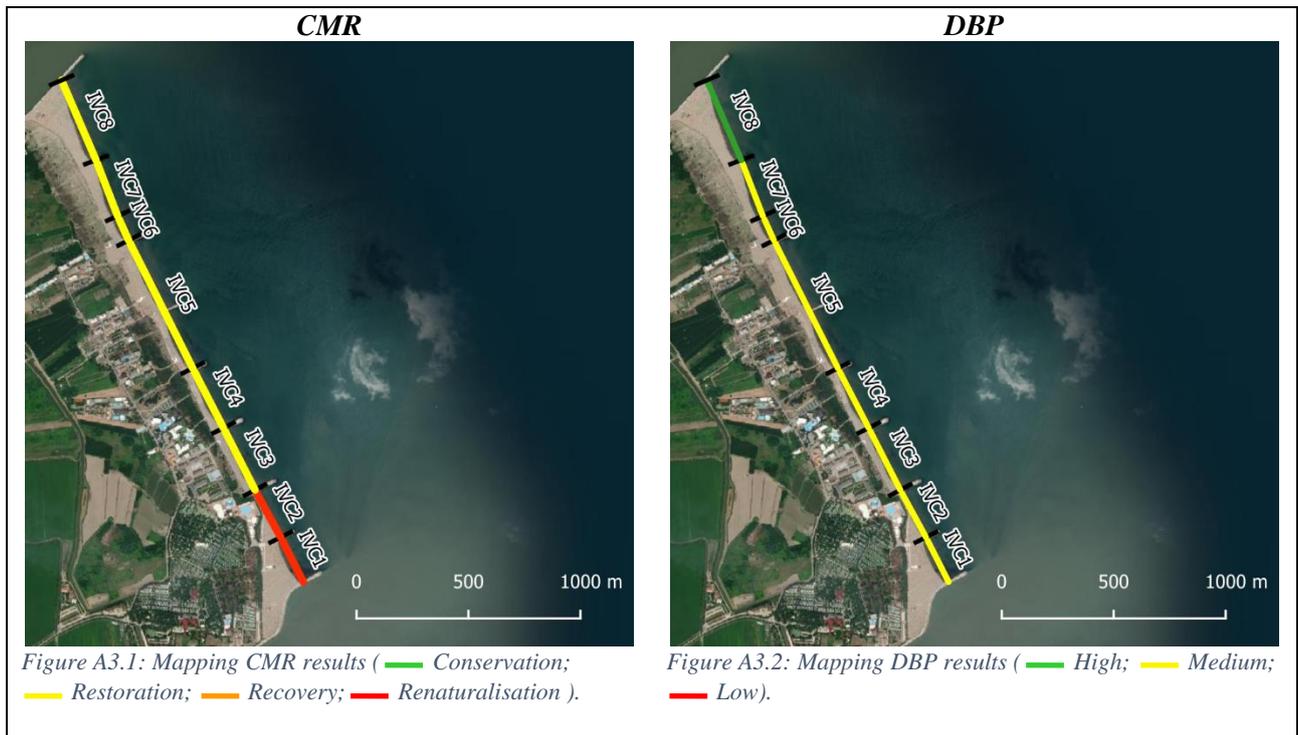
Table A3.4: Values assigned to each indicator of SurLan index in each analysed cell and relative mean and class rating associated.

Physiographic unit	Cell	SurLan indicator I	Mean value	SurLan class
Isola Verde	IVC1	1	0,25	Low
	IVC2	1	0,25	Low
	IVC3	1	0,25	Low
	IVC4	1	0,25	Low
	IVC5	1	0,25	Low
	IVC6	2	0,50	Medium
	IVC7	3	0,75	High
	IVC8	2	0,50	Medium
Sottomarina	SC1	3	0,75	High
	SC2	1	0,25	Low
	SC3	0	0,00	Low
	SC4	0	0,00	Low
	SC5	0	0,00	Low
Pellestrina	PC1	4	1,00	High
	PC2	0	0,00	Low
	PC3	0	0,00	Low
	PC4	1	0,25	Low
	PC5	2	0,50	Medium
	PC6	2	0,50	Medium
	PC7	1	0,25	Low
Lido Venezia	LC1	2	0,50	Medium
	LC2	2	0,50	Medium
	LC3	2	0,50	Medium
	LC4	0	0,00	Low
	LC5	0	0,00	Low
	LC6	0	0,00	Low
Cavallino	CVC1	2	0,50	Medium
	CVC2	2	0,50	Medium
	CVC3	2	0,50	Medium
	CVC4	2	0,50	Medium
	CVC5	2	0,50	Medium
	CVC6	2	0,50	Medium
	CVC7	2	0,50	Medium
	CVC8	2	0,50	Medium
Jesolo	JC1	1	0,25	Low
	JC2	0	0,00	Low
	JC3	0	0,00	Low
	JC4	0	0,00	Low
	JC5	1	0,25	Low
	JC6	1	0,25	Low
	JC7	2	0,50	Medium
	JC8	2	0,50	Medium
Eraclea	EC1	3	0,75	High
	EC2	3	0,75	High
	EC3	4	1,00	High
	EC4	4	1,00	High
	EC6	2	0,50	Medium
	EC7	2	0,50	Medium
	EC8	3	0,75	High
	Duna Verde	DVC9	2	0,50
Porto S. Margherita	SMC10	2	0,50	Medium
	SMC11	3	0,75	High
	SMC12	0	0,00	Low
	SMC13	0	0,00	Low
Caorle	CC1	0	0,00	Low
	CC2	0	0,00	Low
	CC3	0	0,00	Low
Valle vecchia	VC1	3	0,75	High
	VC2	3	0,75	High
	VC3	3	0,75	High
Bibione	BC1	2	0,50	Medium
	BC2	1	0,25	Low
	BC3	0	0,00	Low
	BC4	0	0,00	Low
	BC5	3	0,75	High

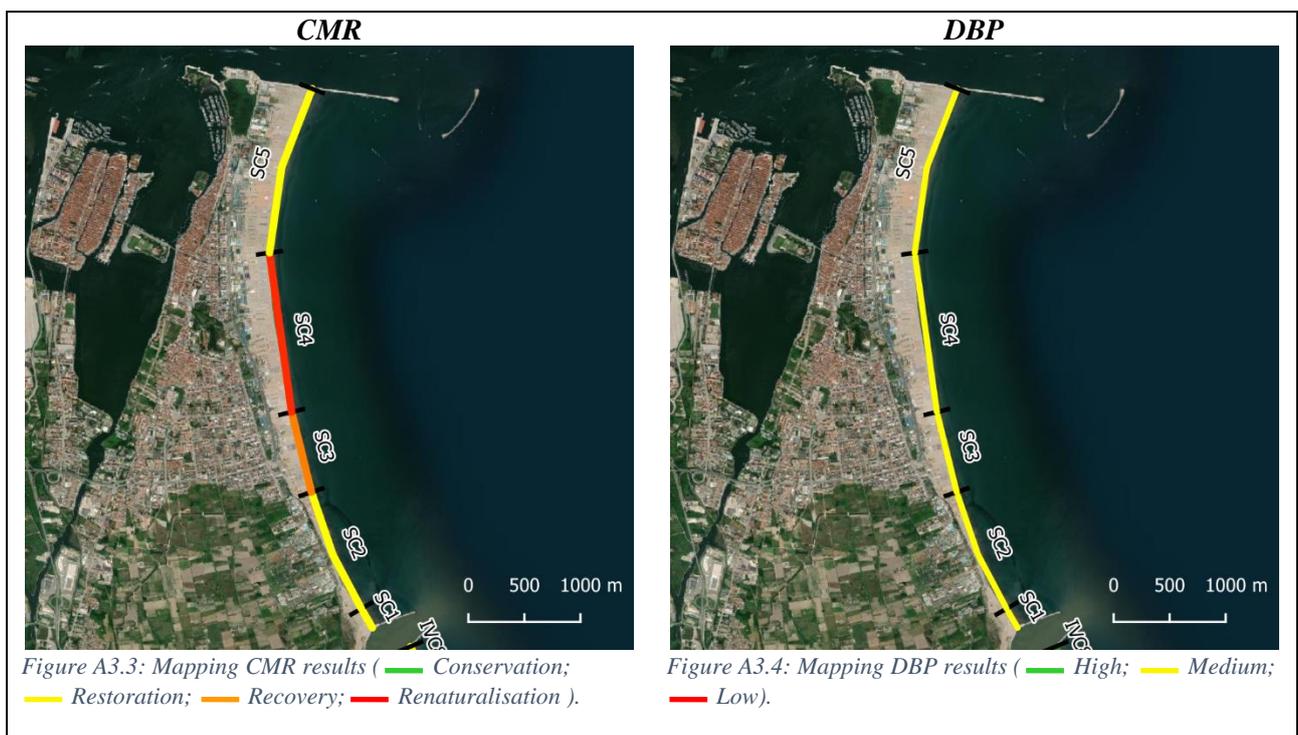
Table A3.5: Sub-indices and indices values obtained for each analysed cell of the Venetian coast.

<i>Physiographic unit</i>	<i>Cell</i>	<i>StaDun</i>	<i>BeaPot</i>	<i>CoMan</i>	<i>SurLan</i>	<i>CMR</i>	<i>DBP</i>
<i>Isola Verde</i>	IVC1	0,00	0,78	0,64	0,25	Renaturalisation	Medium
	IVC2	0,00	0,75	0,64	0,25	Renaturalisation	Medium
	IVC3	0,36	0,75	0,58	0,25	Restoration	Medium
	IVC4	0,34	0,75	0,64	0,25	Restoration	Medium
	IVC5	0,36	0,69	0,64	0,25	Restoration	Medium
	IVC6	0,48	0,69	0,61	0,50	Restoration	Medium
	IVC7	0,48	0,78	0,53	0,75	Restoration	Medium
	IVC8	0,48	0,89	0,56	0,50	Restoration	High
<i>Soittomarina</i>	SC1	0,41	0,86	0,61	0,75	Restoration	Medium
	SC2	0,43	0,78	0,64	0,25	Restoration	Medium
	SC3	0,00	0,89	0,75	0,00	Recovery	Medium
	SC4	0,00	0,78	0,75	0,00	Renaturalisation	Medium
	SC5	0,45	0,92	0,78	0,00	Restoration	Medium
<i>Pellestrina</i>	PC1	0,66	0,89	0,31	1,00	Conservation	High
	PC2	0,43	0,64	0,53	0,00	Restoration	Medium
	PC3	0,39	0,69	0,56	0,00	Restoration	Medium
	PC4	0,41	0,75	0,56	0,25	Restoration	Medium
	PC5	0,41	0,81	0,53	0,50	Restoration	Medium
	PC6	0,43	0,81	0,53	0,50	Restoration	Medium
	PC7	0,41	0,64	0,53	0,25	Restoration	Medium
<i>Lido Venezia</i>	LC1	0,64	0,78	0,50	0,50	Restoration	Medium
	LC2	0,00	0,75	0,56	0,50	Renaturalisation	Medium
	LC3	0,00	0,75	0,56	0,50	Renaturalisation	Medium
	LC4	0,00	0,81	0,81	0,00	Renaturalisation	Medium
	LC5	0,00	0,81	0,75	0,00	Renaturalisation	Medium
	LC6	0,57	0,86	0,53	0,00	Restoration	High
<i>Cavallino</i>	CVC1	0,73	0,83	0,50	0,50	Conservation	High
	CVC2	0,66	0,75	0,42	0,50	Conservation	High
	CVC3	0,00	0,81	0,75	0,50	Renaturalisation	Medium
	CVC4	0,66	0,78	0,56	0,50	Restoration	Medium
	CVC5	0,48	0,83	0,72	0,50	Restoration	Medium
	CVC6	0,52	0,83	0,64	0,50	Restoration	Medium
	CVC7	0,52	0,75	0,75	0,50	Restoration	Medium
	CVC8	0,61	0,81	0,81	0,50	Restoration	Medium
<i>Jesolo</i>	JC1	0,00	0,81	0,83	0,25	Recovery	Low
	JC2	0,00	0,83	0,83	0,00	Recovery	Medium
	JC3	0,00	0,83	0,83	0,00	Recovery	Medium
	JC4	0,00	0,83	0,83	0,00	Recovery	Medium
	JC5	0,00	0,67	0,86	0,25	Renaturalisation	Low
	JC6	0,00	0,67	0,78	0,25	Renaturalisation	Low
	JC7	0,41	0,83	0,78	0,50	Restoration	Medium
	JC8	0,50	0,58	0,61	0,50	Restoration	Low
<i>Eraclea</i>	EC1	0,45	0,69	0,39	0,75	Conservation	Medium
	EC2	0,41	0,67	0,39	0,75	Conservation	Medium
	EC3	0,00	0,58	0,56	1,00	Renaturalisation	Medium
	EC4	0,00	0,58	0,56	1,00	Renaturalisation	Medium
	EC6	0,39	0,81	0,75	0,50	Restoration	Medium
	EC7	0,36	0,78	0,69	0,50	Restoration	Medium
	EC8	0,43	0,69	0,53	0,75	Restoration	Medium
	<i>Duna Verde</i>	DVC9	0,30	0,69	0,81	0,50	Renaturalisation
<i>Porto S. Margherita</i>	SMC10	0,00	0,58	0,72	0,50	Renaturalisation	Low
	SMC11	0,00	0,58	0,69	0,75	Renaturalisation	Low
	SMC12	0,00	0,58	0,83	0,00	Renaturalisation	Low
	SMC13	0,43	0,72	0,83	0,00	Restoration	Low
<i>Caorle</i>	CC1	0,00	0,78	0,83	0,00	Renaturalisation	Low
	CC2	0,00	0,00	0,56	0,00	Renaturalisation	Low
	CC3	0,00	0,72	0,75	0,00	Renaturalisation	Low
<i>Valle vecchia</i>	VC1	0,66	0,67	0,31	0,75	Conservation	High
	VC2	0,55	0,61	0,31	0,75	Conservation	Medium
	VC3	0,59	0,69	0,33	0,75	Conservation	High
<i>Bibione</i>	BC1	0,52	0,78	0,42	0,50	Conservation	High
	BC2	0,48	0,75	0,83	0,25	Restoration	Low
	BC3	0,00	0,83	0,83	0,00	Recovery	Medium
	BC4	0,45	0,67	0,69	0,00	Restoration	Low
	BC5	0,52	0,67	0,39	0,75	Conservation	Medium

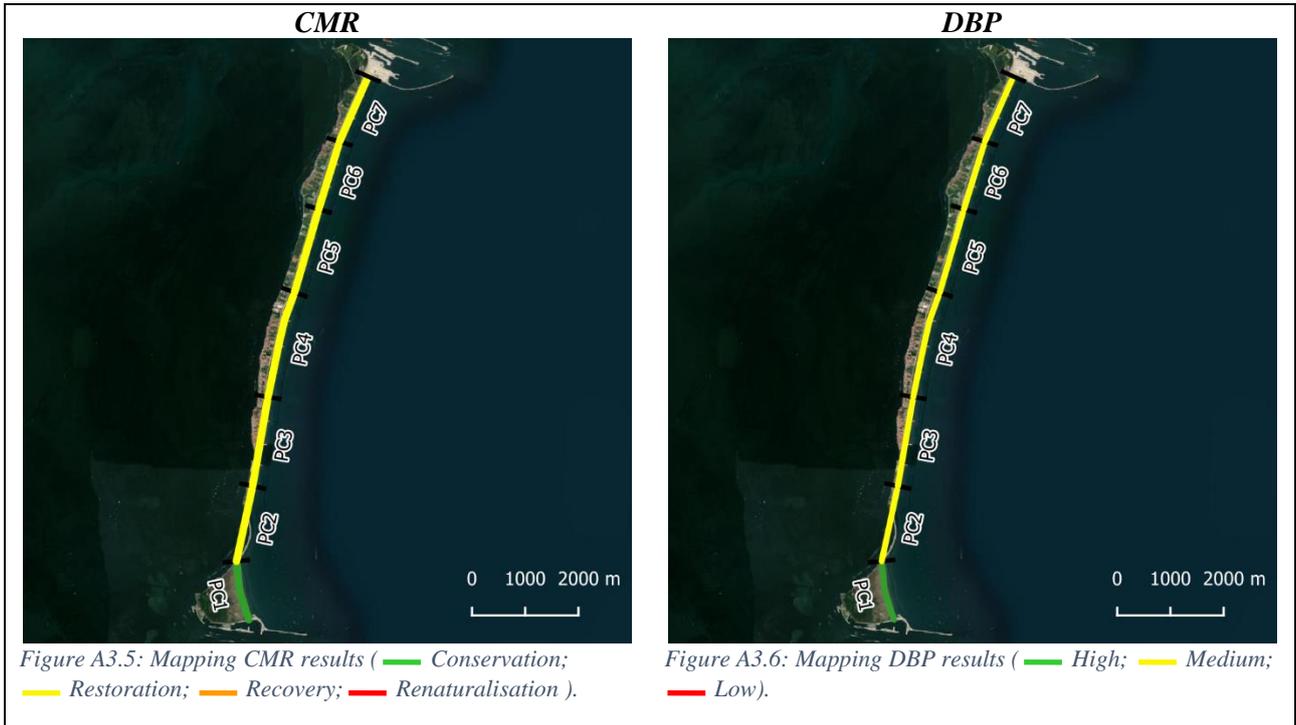
Physiographic unit of Isola Verde



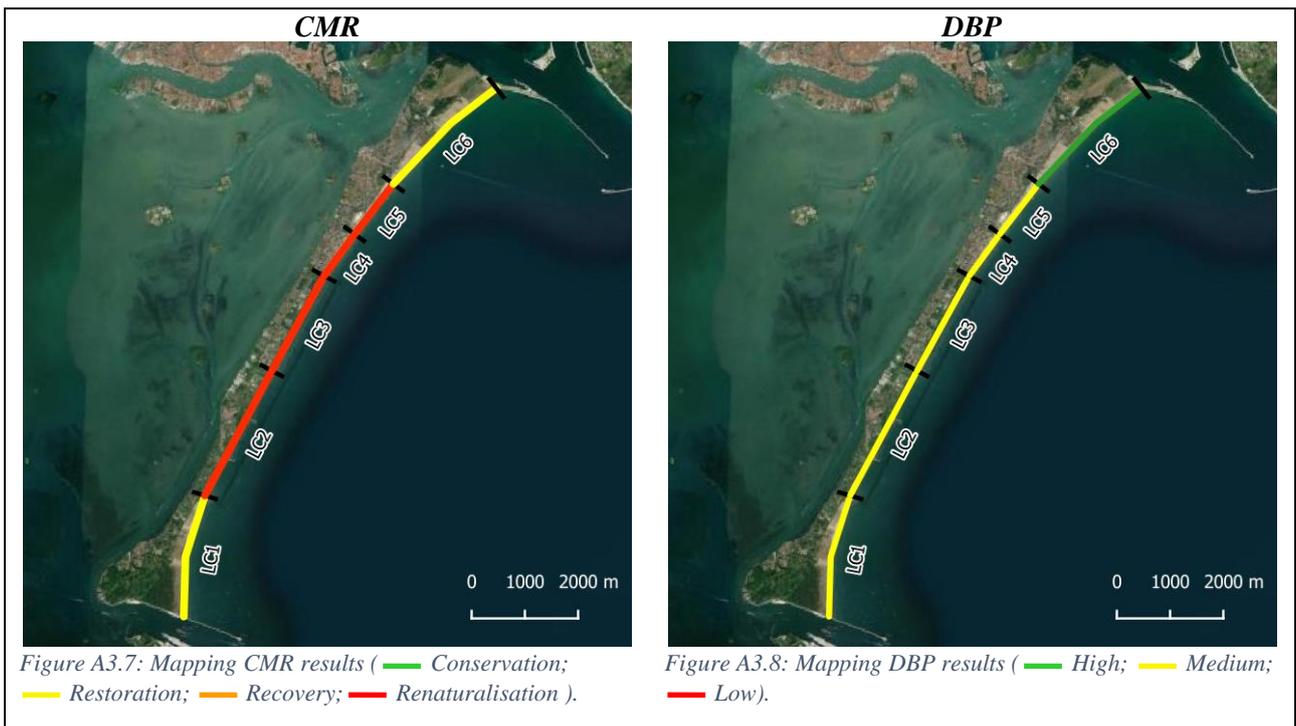
Physiographic unit of Sottomarina



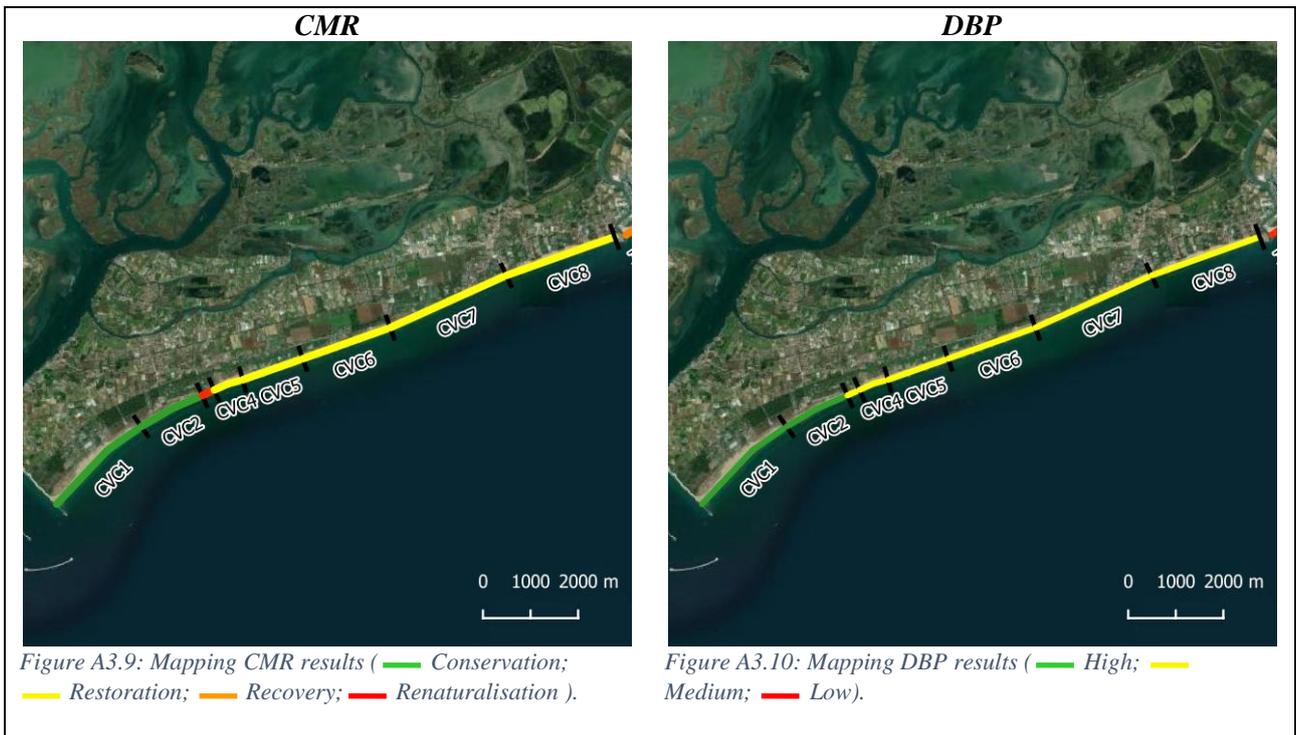
Physiographic unit of Pellestrina



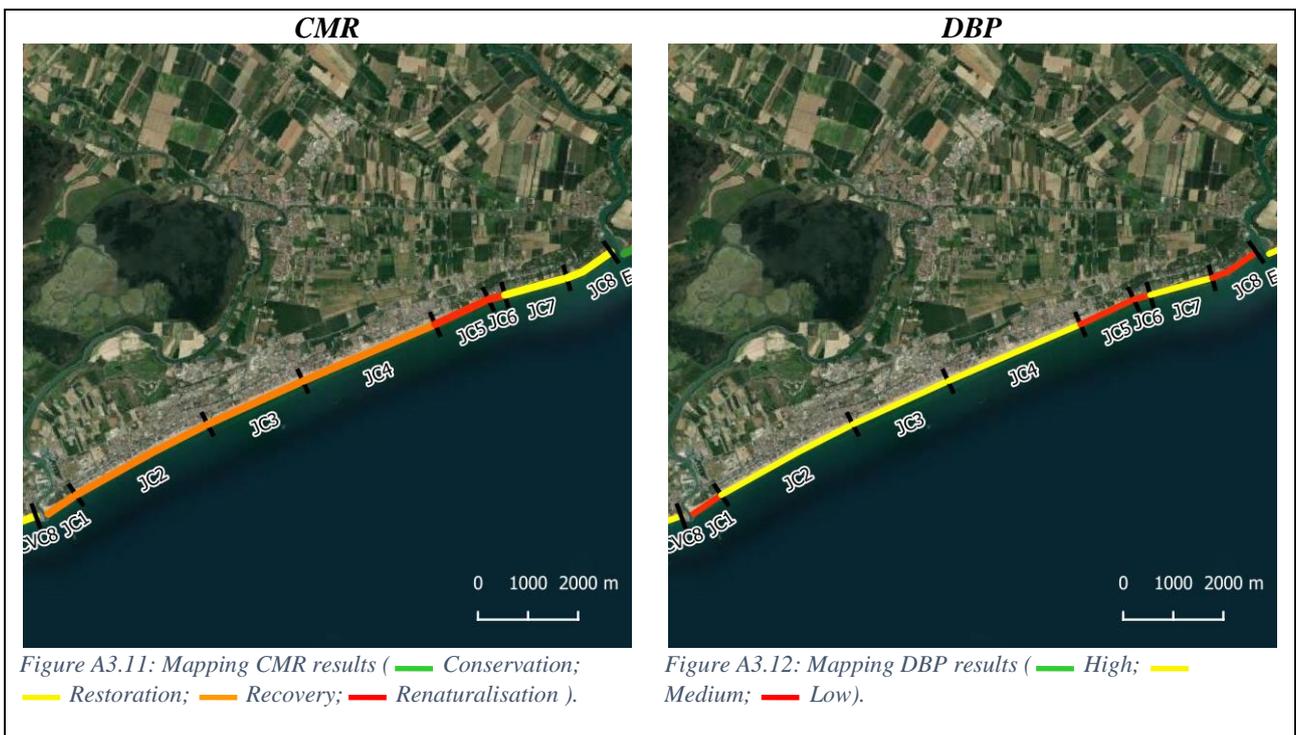
Physiographic unit of Lido di Venezia



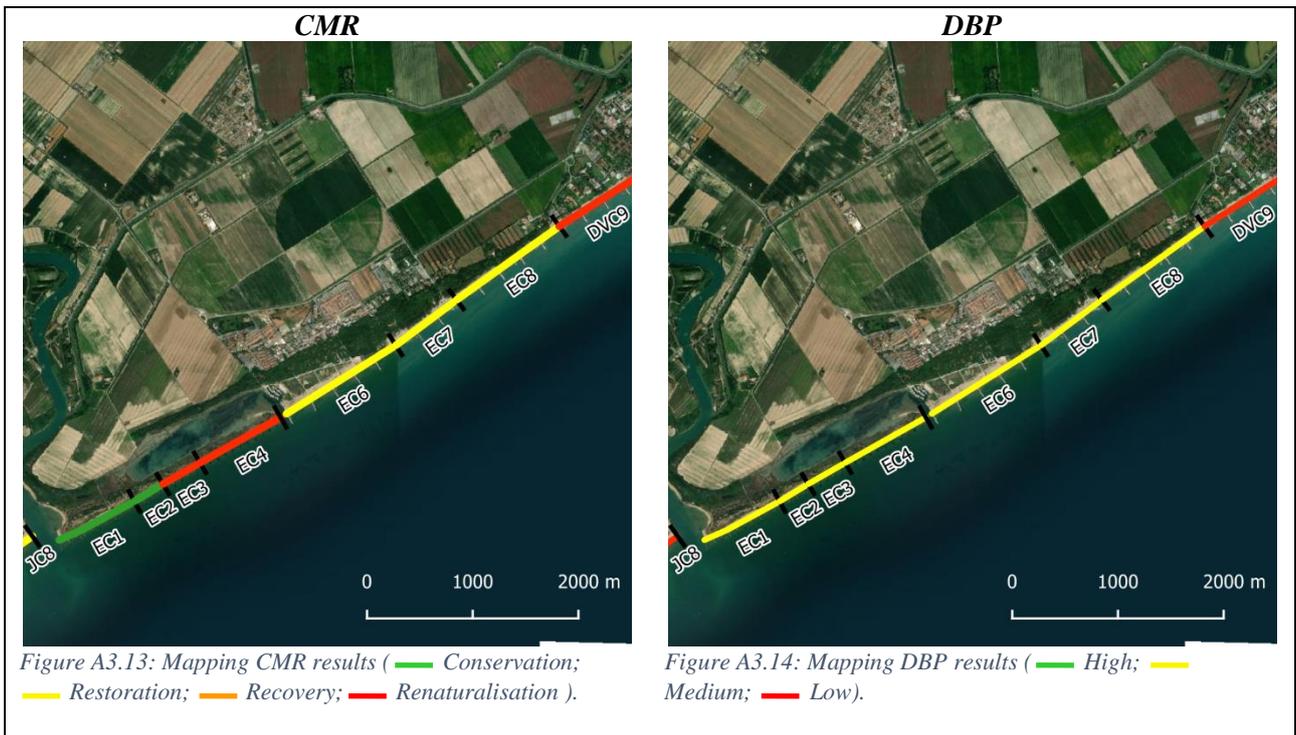
Physiographic unit of Cavallino



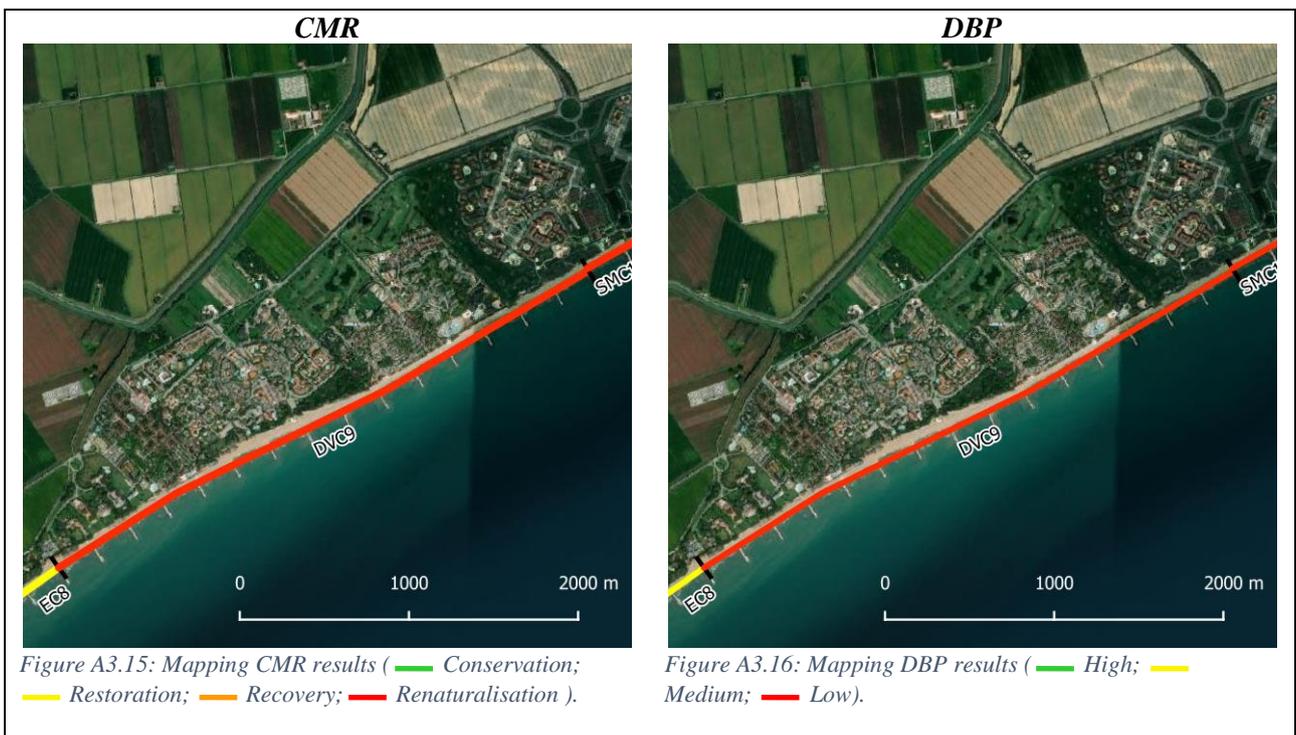
Physiographic unit of Jesolo



Physiographic unit of Eraclea



Physiographic unit of Duna Verde



Physiographic unit of Porto Santa Margherita

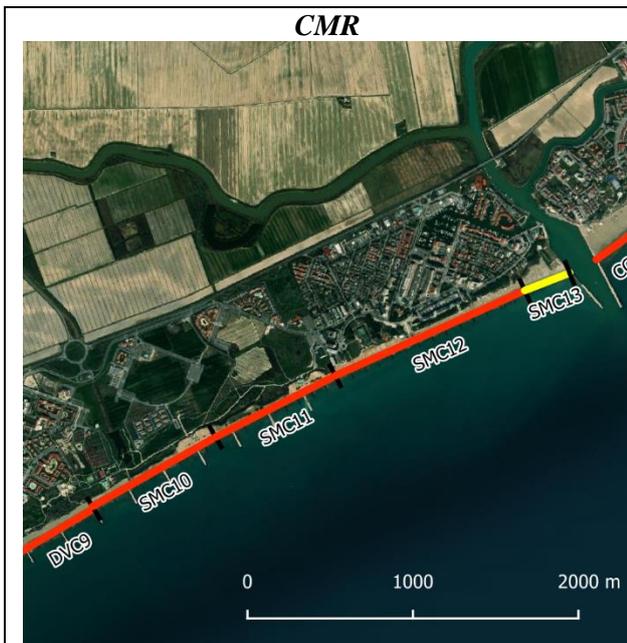


Figure A3.17: Mapping CMR results (— Conservation; — Restoration; — Recovery; — Renaturalisation).

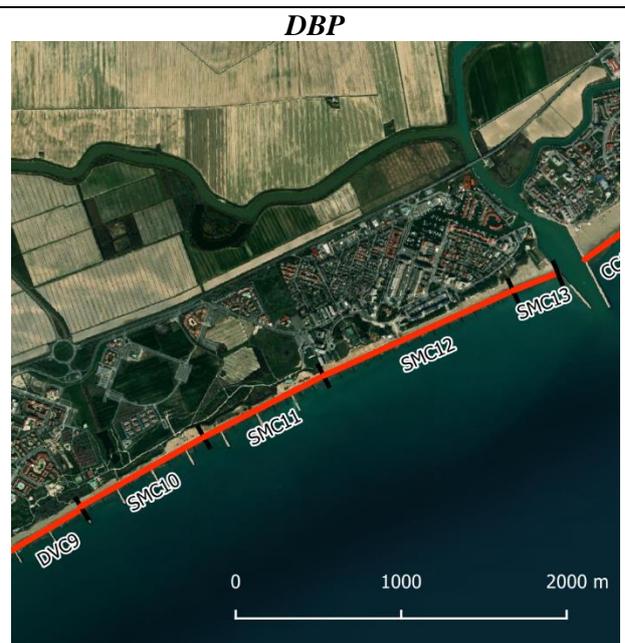


Figure A3.18: Mapping DBP results (— High; — Medium; — Low).

Physiographic unit of Caorle

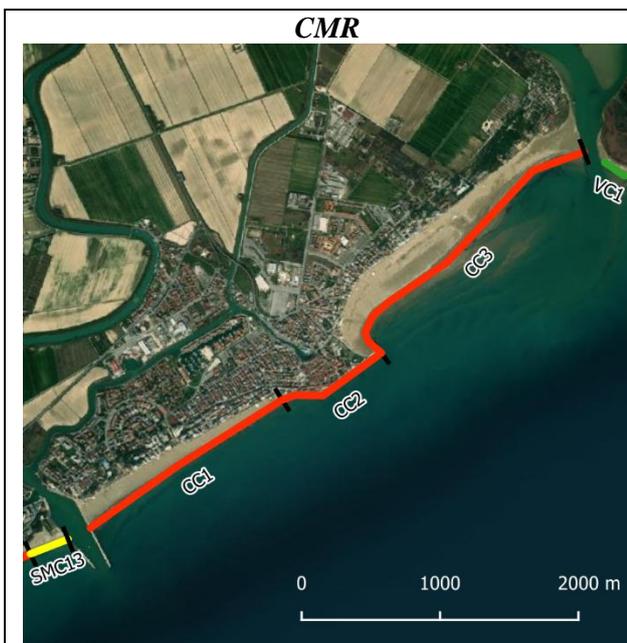


Figure A3.19: Mapping CMR results (— Conservation; — Restoration; — Recovery; — Renaturalisation).

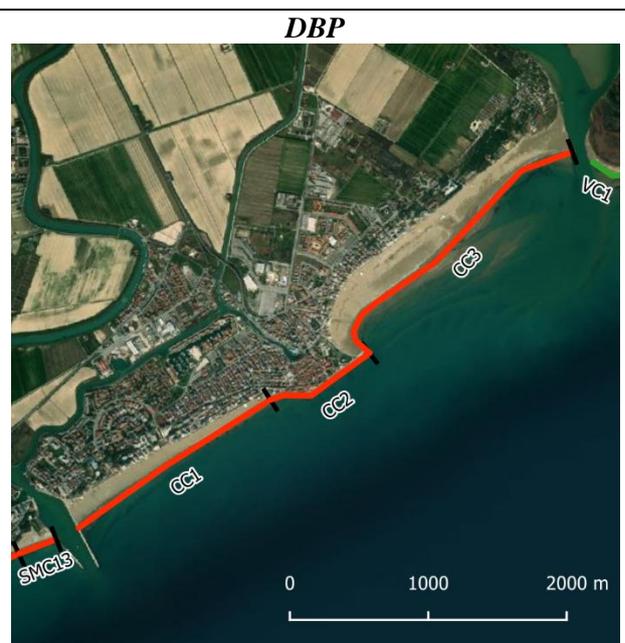
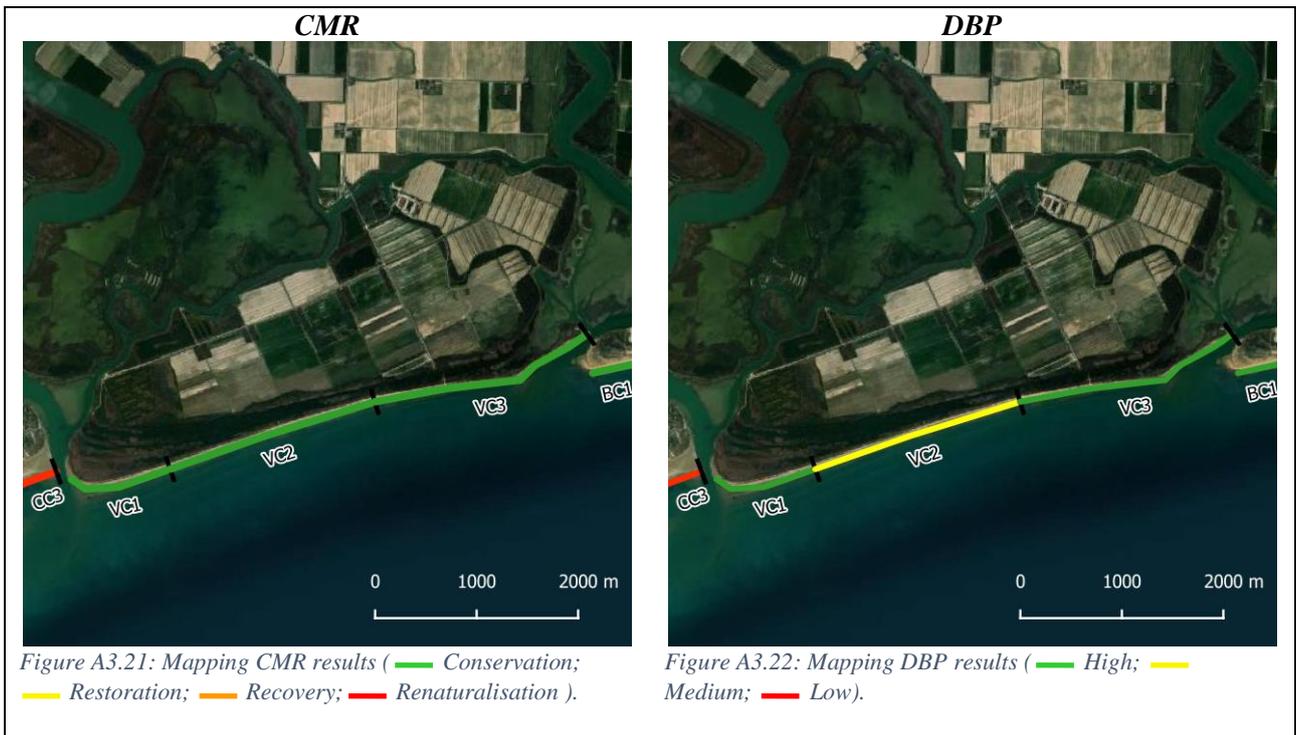
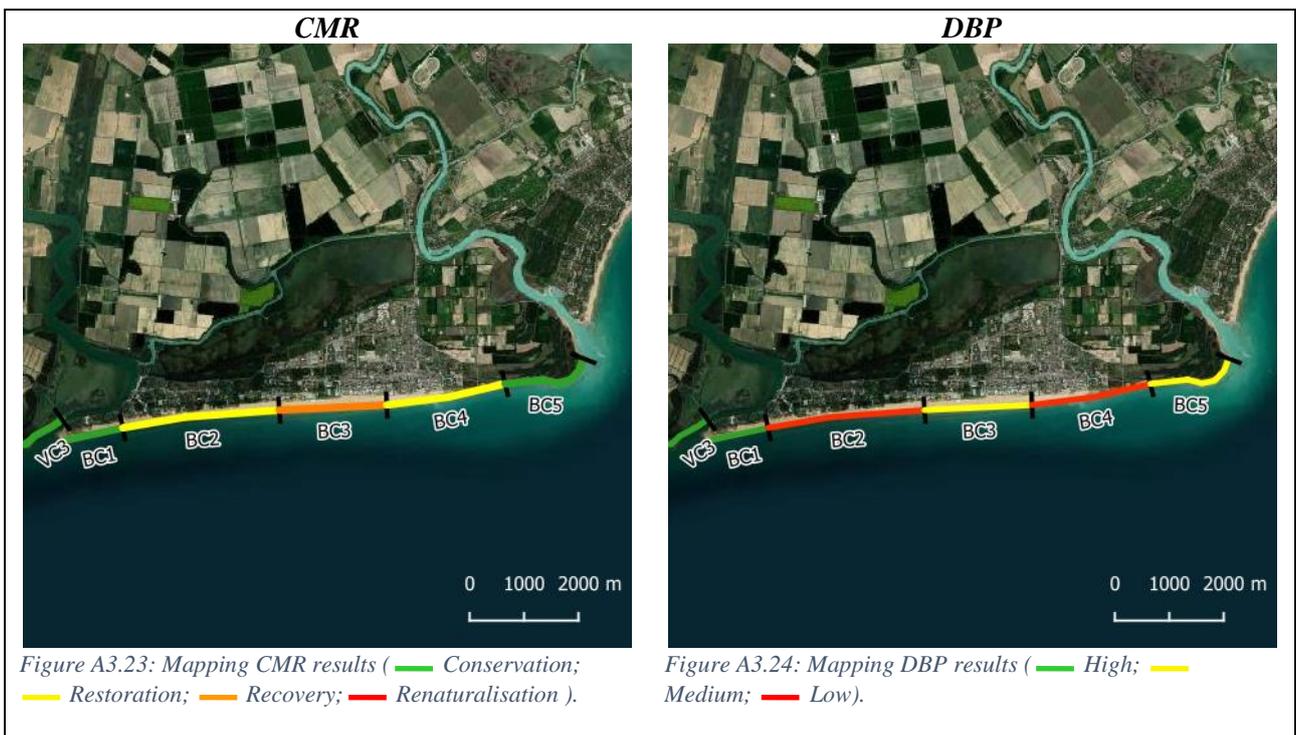


Figure A3.20: Mapping DBP results (— High; — Medium; — Low).

Physiographic unit of Vallevecchia



Physiographic unit of Bibione



Annex IV

Table A4.1: List of changed CoMan indicators. 'Score shift' represents the number of classes that were shifted to simulate lower impact achieved by improving the management actions (e.g., '-1' represents one-class shift, while '-2' represent a "two-classes" shift). 'Least management upgrade achieved' represents the maximum impact found along the Venetian coast after the application of the modification to the considered indicator.

CoMan Indicator	Score shift	Least management upgrade achieved
Managed paths	-1	All the beaches have at least regulated accesses
Managed paths	-2	All the beaches have at least delimited accesses
Dune area with restricted access	-1	At least a quarter of dune systems fenced
Dune area with restricted access	-2	At least half of dune systems fenced
Dune area with restricted access	-3	At least three a quarter of dune systems fenced
Dune area with restricted access	-4	All the beaches have fully fenced dune systems
Sand traps	-2	Installing sand traps that guarantee at least the stability of the dune
Mechanical cleaning/levelling	-1	Maximum frequency of beach cleaning: weekly
Mechanical cleaning/levelling	-2	Maximum frequency of beach cleaning: occasionally
Surface area occupied by seasonal services on beach-dune system	-1	Portion of temporary structures reduced by 5% of the beach-dune system
Surface area occupied by seasonal services on beach-dune system	-2	Portion of temporary structures reduced by 10% of the beach-dune system
Surface area occupied by permanent services on beach-dune system	-1	Portion of permanent structures reduced by 25% of the beach-dune system
Protection of the system and the immediate environment	-2	Surveillance of at least 50% of the dune system
Protection of the system and the immediate environment	-4	Surveillance of the entire dune system

Table A4.2: List of modified CoMan indicators for each hypothesis considered (1-35, first column). The hypotheses have been grouped according to increasing effort (— 'low effort actions'; — 'medium effort actions'; — 'high effort actions'). Hypothesis 0 represents the current CoMan status (i.e., the starting situation).

CoMan Indicator	Managed paths		Dune area with restricted access				Sand traps	Mechanical cleaning/levelling	Surface area occupied by seasonal services on beach-dune system		Surface area occupied by permanent services on beach-dune system		Protection of the system and the immediate environment	
	-1	-2	-1	-2	-3	-4			-2	-4	-1	-2	-1	-2
Score upgrade	-1	-2	-1	-2	-3	-4	-2	-1	-2	-1	-2	-1	-2	-4
Hypothesis														
0														
1	X													
2							X							
3								X						
4		X												
5								X						
6	X						X							
7	X						X	X						
8							X	X						
9	X						X	X						
10	X						X	X						
11		X					X	X						
12		X					X	X						
13			X											
14				X										
15					X									
16						X								
17	X		X				X	X						
18	X			X			X	X						
19	X				X		X	X						
20	X					X	X	X						
21	X						X	X	X					
22	X						X	X						
23	X						X	X						
24	X			X			X	X	X			X		
25	X			X			X	X	X			X		
26	X						X	X					X	
27	X						X	X					X	
28	X			X			X	X					X	
29	X					X	X	X					X	
30	X			X			X	X					X	
31	X					X	X	X					X	
32													X	
33													X	
34													X	
35						X							X	

Table A4.3: DBP results for each site ("cell") after applying the changes related to each hypothesis. The hypotheses are sorted from the lowest to the most demanding effort (from green to orange).

ID	Hypothesis Cell	0	1	2	3	4	5	6	7	8	9	10	11
		DBP											
1	IVC1	0,139	0,167	0,194	0,167	0,194	0,194	0,222	0,194	0,222	0,250	0,278	0,278
2	IVC2	0,111	0,139	0,167	0,139	0,167	0,167	0,194	0,167	0,194	0,222	0,250	0,250
3	IVC3	0,167	0,194	0,222	0,194	0,222	0,222	0,250	0,222	0,250	0,278	0,306	0,306
4	IVC4	0,111	0,139	0,167	0,139	0,167	0,167	0,194	0,167	0,194	0,222	0,250	0,250
5	IVC5	0,056	0,083	0,111	0,083	0,111	0,111	0,139	0,111	0,139	0,167	0,194	0,194
6	IVC6	0,083	0,111	0,083	0,111	0,139	0,139	0,111	0,139	0,111	0,139	0,167	0,222
7	IVC7	0,250	0,278	0,250	0,278	0,306	0,306	0,278	0,306	0,278	0,306	0,333	0,389
8	IVC8	0,333	0,361	0,333	0,361	0,389	0,389	0,361	0,389	0,361	0,389	0,417	0,417
9	SC1	0,250	0,278	0,250	0,278	0,306	0,306	0,278	0,306	0,278	0,306	0,333	0,333
10	SC2	0,139	0,167	0,139	0,167	0,194	0,194	0,167	0,194	0,167	0,194	0,222	0,222
11	SC3	0,139	0,167	0,194	0,167	0,194	0,194	0,222	0,194	0,222	0,250	0,278	0,278
12	SC4	0,028	0,056	0,083	0,056	0,083	0,083	0,111	0,083	0,111	0,139	0,167	0,167
13	SC5	0,139	0,167	0,194	0,167	0,194	0,194	0,222	0,194	0,222	0,250	0,278	0,278
14	PC1	0,583	0,611	0,583	0,583	0,639	0,583	0,611	0,611	0,583	0,611	0,611	0,639
15	PC2	0,111	0,028	0,056	0,028	0,056	0,028	0,083	0,056	0,083	0,111	0,111	0,167
16	PC3	0,139	0,139	0,167	0,111	0,167	0,111	0,194	0,139	0,167	0,194	0,194	0,250
17	PC4	0,194	0,222	0,250	0,194	0,250	0,194	0,278	0,222	0,250	0,278	0,278	0,333
18	PC5	0,278	0,306	0,333	0,278	0,333	0,278	0,361	0,306	0,333	0,361	0,361	0,417
19	PC6	0,278	0,306	0,333	0,278	0,333	0,278	0,361	0,306	0,333	0,361	0,361	0,417
20	PC7	0,111	0,139	0,167	0,111	0,167	0,111	0,194	0,139	0,167	0,194	0,194	0,250
21	LC1	0,278	0,306	0,278	0,306	0,333	0,306	0,306	0,333	0,306	0,333	0,333	0,417
22	LC2	0,194	0,222	0,250	0,194	0,250	0,194	0,278	0,222	0,250	0,278	0,278	0,361
23	LC3	0,194	0,222	0,250	0,194	0,250	0,194	0,278	0,222	0,250	0,278	0,278	0,361
24	LC4	0,000	0,028	0,056	0,028	0,056	0,056	0,083	0,056	0,083	0,111	0,139	0,194
25	LC5	0,056	0,083	0,111	0,083	0,111	0,111	0,139	0,111	0,139	0,167	0,194	0,250
26	LC6	0,333	0,361	0,333	0,361	0,389	0,361	0,361	0,389	0,361	0,389	0,389	0,417
27	CVC1	0,333	0,361	0,333	0,361	0,389	0,389	0,361	0,389	0,361	0,389	0,417	0,417
28	CVC2	0,333	0,361	0,333	0,361	0,389	0,389	0,361	0,389	0,361	0,389	0,417	0,417
29	CVC3	0,056	0,083	0,111	0,083	0,111	0,111	0,139	0,111	0,139	0,167	0,194	0,194
30	CVC4	0,222	0,250	0,222	0,250	0,278	0,278	0,250	0,278	0,250	0,278	0,306	0,306
31	CVC5	0,111	0,139	0,167	0,139	0,167	0,167	0,194	0,167	0,194	0,222	0,250	0,250
32	CVC6	0,194	0,222	0,250	0,222	0,250	0,250	0,278	0,250	0,278	0,306	0,333	0,333
33	CVC7	0,000	0,028	0,056	0,028	0,056	0,056	0,083	0,056	0,083	0,111	0,139	0,083
34	CVC8	0,000	0,028	0,056	0,028	0,056	0,056	0,083	0,056	0,083	0,111	0,139	0,083
35	JC1	-0,028	0,000	0,028	0,000	0,028	0,028	0,056	0,028	0,056	0,083	0,111	0,056
36	JC2	0,000	0,028	0,056	0,028	0,056	0,056	0,083	0,056	0,083	0,111	0,139	0,083
37	JC3	0,000	0,028	0,056	0,028	0,056	0,056	0,083	0,056	0,083	0,111	0,139	0,083
38	JC4	0,000	0,028	0,056	0,028	0,056	0,056	0,083	0,056	0,083	0,111	0,139	0,083
39	JC5	-0,194	-0,167	-0,139	-0,167	-0,139	-0,139	-0,111	-0,139	-0,111	-0,083	-0,056	-0,111
40	JC6	-0,111	-0,083	-0,056	-0,083	-0,056	-0,056	-0,028	-0,056	-0,028	0,000	0,028	-0,028
41	JC7	0,056	0,083	0,111	0,083	0,111	0,111	0,139	0,111	0,139	0,167	0,194	0,194
42	JC8	-0,028	0,000	-0,028	0,000	0,028	0,028	0,000	0,028	0,000	0,028	0,056	0,056
43	EC1	0,306	0,333	0,306	0,306	0,361	0,306	0,333	0,333	0,306	0,333	0,333	0,361
44	EC2	0,278	0,306	0,278	0,278	0,333	0,278	0,306	0,306	0,278	0,306	0,306	0,333
45	EC3	0,028	0,056	0,083	0,028	0,083	0,028	0,111	0,056	0,083	0,111	0,111	0,194
46	EC4	0,028	0,056	0,083	0,028	0,083	0,028	0,111	0,056	0,083	0,111	0,111	0,194
47	EC6	0,056	0,083	0,111	0,083	0,111	0,111	0,139	0,111	0,139	0,167	0,194	0,139
48	EC7	0,083	0,111	0,139	0,111	0,139	0,139	0,167	0,139	0,167	0,194	0,222	0,167
49	EC8	0,167	0,194	0,222	0,194	0,222	0,222	0,250	0,222	0,250	0,278	0,306	0,306
50	DVC9	-0,111	-0,083	-0,056	-0,083	-0,056	-0,056	-0,028	-0,056	-0,028	0,000	0,028	-0,028
51	SMC10	-0,139	-0,111	-0,083	-0,111	-0,083	-0,083	-0,056	-0,083	-0,056	-0,028	0,000	0,000
52	SMC11	-0,111	-0,083	-0,056	-0,083	-0,056	-0,056	-0,028	-0,056	-0,028	0,000	0,028	0,028
53	SMC12	-0,250	-0,222	-0,194	-0,222	-0,194	-0,194	-0,167	-0,194	-0,167	-0,139	-0,111	-0,167
54	SMC13	-0,111	-0,083	-0,056	-0,083	-0,056	-0,056	-0,028	-0,056	-0,028	0,000	0,028	-0,028
55	CC1	-0,056	-0,028	0,000	-0,028	0,000	0,000	0,028	0,000	0,028	0,056	0,083	0,028
56	CC2	-0,556	-0,528	-0,500	-0,556	-0,500	-0,556	-0,472	-0,528	-0,500	-0,472	-0,472	-0,389
57	CC3	-0,028	0,000	0,028	0,000	0,028	0,028	0,056	0,028	0,056	0,083	0,111	0,111
58	VC1	0,361	0,389	0,361	0,389	0,417	0,389	0,389	0,417	0,389	0,417	0,417	0,444
59	VC2	0,306	0,333	0,306	0,333	0,361	0,333	0,333	0,361	0,333	0,361	0,361	0,389
60	VC3	0,361	0,389	0,361	0,389	0,417	0,389	0,389	0,417	0,389	0,417	0,417	0,444
61	BC1	0,361	0,389	0,361	0,389	0,417	0,389	0,389	0,417	0,389	0,417	0,417	0,444
62	BC2	-0,083	-0,056	-0,028	-0,056	-0,028	-0,028	0,000	-0,028	0,000	0,028	0,056	0,000
63	BC3	0,000	0,028	0,056	0,028	0,056	0,056	0,083	0,056	0,083	0,111	0,139	0,083
64	BC4	-0,028	0,000	0,028	0,000	0,028	0,028	0,056	0,028	0,056	0,083	0,111	0,111
65	BC5	0,278	0,306	0,333	0,306	0,333	0,333	0,361	0,333	0,361	0,389	0,417	0,417

DBP	Number of cells											
Low	14	10	10	10	9	9	8	9	8	4	3	6
Medium	43	45	44	46	41	46	44	44	45	47	45	38
High	8	10	11	9	15	10	13	12	12	14	17	21

Percentage of decrease in the number of low DBP sites from hypothesis 0 (current state)												
0	28,57	28,57	28,57	35,71	35,71	42,86	35,71	42,86	42,86	71,43	78,57	57,14

(continued)

ID	Hypothesis Cell	12	13	14	15	16	17	18	19	20	21	22	23
		DBP											
1	IVC1	0,306	0,167	0,194	0,222	0,250	0,278	0,306	0,333	0,361	0,278	0,306	0,278
2	IVC2	0,278	0,139	0,167	0,194	0,222	0,250	0,278	0,306	0,333	0,250	0,250	0,250
3	IVC3	0,333	0,167	0,167	0,167	0,167	0,278	0,278	0,278	0,278	0,306	0,333	0,306
4	IVC4	0,278	0,111	0,111	0,111	0,111	0,222	0,222	0,222	0,222	0,250	0,278	0,250
5	IVC5	0,222	0,056	0,056	0,056	0,056	0,167	0,167	0,167	0,167	0,194	0,222	0,194
6	IVC6	0,194	0,111	0,139	0,167	0,194	0,167	0,194	0,222	0,250	0,167	0,194	0,167
7	IVC7	0,361	0,278	0,306	0,333	0,361	0,333	0,361	0,389	0,417	0,306	0,306	0,306
8	IVC8	0,444	0,361	0,389	0,417	0,444	0,417	0,444	0,472	0,500	0,417	0,444	0,417
9	SC1	0,361	0,278	0,306	0,333	0,361	0,333	0,361	0,389	0,417	0,333	0,361	0,333
10	SC2	0,250	0,167	0,194	0,222	0,250	0,222	0,250	0,278	0,306	0,222	0,250	0,222
11	SC3	0,306	0,167	0,194	0,222	0,250	0,278	0,306	0,333	0,361	0,278	0,306	0,278
12	SC4	0,194	0,056	0,083	0,111	0,139	0,167	0,194	0,222	0,250	0,167	0,194	0,167
13	SC5	0,306	0,167	0,194	0,222	0,250	0,278	0,306	0,333	0,361	0,278	0,306	0,278
14	PC1	0,639	0,611	0,639	0,667	0,694	0,639	0,667	0,694	0,722	0,611	0,611	0,639
15	PC2	0,139	0,028	0,056	0,083	0,111	0,139	0,167	0,194	0,222	0,139	0,139	0,139
16	PC3	0,222	0,139	0,167	0,194	0,222	0,222	0,250	0,278	0,306	0,222	0,222	0,194
17	PC4	0,306	0,222	0,250	0,278	0,306	0,306	0,333	0,361	0,389	0,306	0,306	0,278
18	PC5	0,389	0,306	0,333	0,361	0,389	0,389	0,417	0,444	0,472	0,361	0,361	0,361
19	PC6	0,389	0,306	0,333	0,361	0,389	0,389	0,417	0,444	0,472	0,361	0,361	0,361
20	PC7	0,222	0,139	0,167	0,194	0,222	0,222	0,250	0,278	0,306	0,194	0,194	0,194
21	LC1	0,361	0,306	0,333	0,361	0,361	0,361	0,389	0,417	0,417	0,361	0,361	0,361
22	LC2	0,306	0,222	0,250	0,278	0,306	0,306	0,333	0,361	0,389	0,278	0,278	0,278
23	LC3	0,306	0,222	0,250	0,278	0,306	0,306	0,333	0,361	0,389	0,278	0,278	0,278
24	LC4	0,167	0,028	0,056	0,083	0,111	0,139	0,167	0,194	0,222	0,139	0,167	0,139
25	LC5	0,222	0,083	0,111	0,139	0,167	0,194	0,222	0,250	0,278	0,194	0,222	0,194
26	LC6	0,417	0,361	0,389	0,417	0,444	0,417	0,444	0,472	0,500	0,417	0,444	0,417
27	CVC1	0,444	0,361	0,361	0,361	0,361	0,417	0,417	0,417	0,417	0,417	0,417	0,417
28	CVC2	0,444	0,361	0,361	0,361	0,361	0,417	0,417	0,417	0,417	0,417	0,417	0,417
29	CVC3	0,222	0,083	0,111	0,139	0,167	0,194	0,222	0,250	0,278	0,194	0,194	0,194
30	CVC4	0,333	0,250	0,278	0,306	0,333	0,306	0,333	0,361	0,389	0,278	0,278	0,306
31	CVC5	0,278	0,139	0,167	0,194	0,222	0,250	0,278	0,306	0,333	0,250	0,250	0,250
32	CVC6	0,361	0,222	0,250	0,278	0,306	0,333	0,361	0,389	0,417	0,333	0,333	0,333
33	CVC7	0,167	0,028	0,056	0,083	0,111	0,139	0,167	0,194	0,222	0,139	0,167	0,139
34	CVC8	0,167	0,028	0,056	0,083	0,111	0,139	0,167	0,194	0,222	0,139	0,167	0,139
35	JC1	0,139	0,000	0,028	0,056	0,083	0,111	0,139	0,167	0,194	0,111	0,139	0,111
36	JC2	0,167	0,028	0,056	0,083	0,111	0,139	0,167	0,194	0,222	0,139	0,167	0,139
37	JC3	0,167	0,028	0,056	0,083	0,111	0,139	0,167	0,194	0,222	0,139	0,167	0,139
38	JC4	0,167	0,028	0,056	0,083	0,111	0,139	0,167	0,194	0,222	0,139	0,167	0,139
39	JC5	-0,028	-0,167	-0,139	-0,111	-0,083	-0,056	-0,028	0,000	0,028	-0,056	-0,028	-0,056
40	JC6	0,056	-0,083	-0,056	-0,028	0,000	0,028	0,056	0,083	0,111	0,028	0,028	0,028
41	JC7	0,222	0,083	0,111	0,139	0,167	0,194	0,222	0,250	0,278	0,194	0,222	0,194
42	JC8	0,083	0,000	0,028	0,056	0,083	0,056	0,083	0,111	0,139	0,056	0,056	0,056
43	EC1	0,361	0,333	0,361	0,389	0,417	0,361	0,389	0,417	0,444	0,333	0,333	0,333
44	EC2	0,333	0,306	0,333	0,361	0,389	0,333	0,361	0,389	0,417	0,306	0,306	0,306
45	EC3	0,139	0,056	0,083	0,111	0,139	0,139	0,167	0,194	0,222	0,111	0,111	0,111
46	EC4	0,139	0,056	0,083	0,111	0,139	0,139	0,167	0,194	0,222	0,111	0,111	0,111
47	EC6	0,222	0,083	0,111	0,139	0,139	0,194	0,222	0,250	0,250	0,194	0,194	0,194
48	EC7	0,250	0,111	0,139	0,167	0,194	0,222	0,250	0,278	0,306	0,222	0,250	0,222
49	EC8	0,333	0,194	0,222	0,250	0,278	0,306	0,333	0,361	0,389	0,278	0,278	0,306
50	DVC9	0,056	-0,083	-0,056	-0,028	0,000	0,028	0,056	0,083	0,111	0,028	0,056	0,028
51	SMC10	0,028	-0,111	-0,083	-0,056	-0,028	0,000	0,028	0,056	0,083	0,000	0,028	0,000
52	SMC11	0,056	-0,083	-0,056	-0,028	0,000	0,028	0,056	0,083	0,111	0,028	0,056	0,028
53	SMC12	-0,083	-0,222	-0,194	-0,167	-0,139	-0,111	-0,083	-0,056	-0,028	-0,111	-0,083	-0,111
54	SMC13	0,056	-0,083	-0,056	-0,028	0,000	0,028	0,056	0,083	0,111	0,028	0,056	0,028
55	CC1	0,111	-0,028	0,000	0,028	0,056	0,083	0,111	0,139	0,167	0,083	0,111	0,083
56	CC2	-0,444	-0,528	-0,500	-0,472	-0,444	-0,444	-0,417	-0,389	-0,361	-0,472	-0,472	-0,472
57	CC3	0,139	0,000	0,028	0,056	0,083	0,111	0,139	0,167	0,194	0,111	0,139	0,111
58	VC1	0,444	0,389	0,417	0,444	0,472	0,444	0,472	0,500	0,528	0,417	0,417	0,417
59	VC2	0,389	0,333	0,361	0,389	0,417	0,389	0,417	0,444	0,472	0,361	0,361	0,361
60	VC3	0,444	0,389	0,417	0,444	0,472	0,444	0,472	0,500	0,528	0,417	0,417	0,444
61	BC1	0,444	0,389	0,417	0,444	0,472	0,444	0,472	0,500	0,528	0,444	0,444	0,444
62	BC2	0,083	-0,056	-0,028	0,000	0,028	0,056	0,083	0,111	0,139	0,056	0,083	0,056
63	BC3	0,167	0,028	0,056	0,083	0,111	0,139	0,167	0,194	0,222	0,139	0,167	0,139
64	BC4	0,139	0,000	0,028	0,056	0,083	0,111	0,139	0,167	0,194	0,111	0,139	0,111
65	BC5	0,444	0,306	0,333	0,333	0,333	0,417	0,444	0,444	0,444	0,389	0,389	0,417

DBP	Number of cells											
Low	3	10	9	8	4	3	3	2	2	3	3	3
Medium	41	45	41	40	43	44	39	37	35	46	45	46
High	21	10	15	17	18	18	23	26	28	16	17	16

Percentage of decrease in the number of low DBP sites from hypothesis 0 (current state)												
78,57	28,57	35,71	42,86	71,43	78,57	78,57	85,71	85,71	78,57	78,57	78,57	78,57

(continued)

ID	Hypothesis Cell	24	25	26	27	28	29	30	31	32	33	34	35
		DBP											
1	IVC1	0,333	0,361	0,306	0,361	0,278	0,333	0,417	0,472	0,194	0,250	0,250	0,361
2	IVC2	0,306	0,306	0,278	0,333	0,278	0,333	0,389	0,444	0,167	0,222	0,222	0,333
3	IVC3	0,306	0,333	0,333	0,389	0,250	0,250	0,389	0,389	0,222	0,278	0,222	0,278
4	IVC4	0,250	0,278	0,278	0,333	0,194	0,194	0,333	0,333	0,167	0,222	0,167	0,222
5	IVC5	0,194	0,222	0,222	0,278	0,139	0,139	0,278	0,278	0,111	0,167	0,111	0,167
6	IVC6	0,222	0,250	0,194	0,250	0,167	0,222	0,306	0,361	0,139	0,194	0,194	0,306
7	IVC7	0,361	0,361	0,361	0,417	0,306	0,361	0,472	0,528	0,306	0,361	0,361	0,472
8	IVC8	0,472	0,500	0,444	0,500	0,417	0,472	0,556	0,611	0,389	0,444	0,444	0,556
9	SC1	0,389	0,417	0,361	0,417	0,333	0,389	0,472	0,528	0,306	0,361	0,361	0,472
10	SC2	0,278	0,306	0,250	0,306	0,222	0,278	0,361	0,417	0,194	0,250	0,250	0,361
11	SC3	0,333	0,361	0,306	0,361	0,278	0,333	0,417	0,472	0,194	0,250	0,250	0,361
12	SC4	0,222	0,250	0,194	0,250	0,167	0,222	0,306	0,361	0,083	0,139	0,139	0,250
13	SC5	0,333	0,361	0,306	0,361	0,306	0,361	0,417	0,472	0,194	0,250	0,250	0,361
14	PC1	0,667	0,667	0,667	0,722	0,639	0,694	0,778	0,833	0,639	0,694	0,694	0,806
15	PC2	0,194	0,194	0,167	0,222	0,139	0,194	0,278	0,333	0,056	0,111	0,111	0,222
16	PC3	0,278	0,278	0,250	0,306	0,194	0,250	0,361	0,417	0,167	0,222	0,222	0,333
17	PC4	0,361	0,361	0,333	0,389	0,278	0,333	0,444	0,500	0,250	0,306	0,306	0,417
18	PC5	0,417	0,417	0,417	0,472	0,361	0,417	0,528	0,583	0,333	0,389	0,389	0,500
19	PC6	0,417	0,417	0,417	0,472	0,361	0,417	0,528	0,583	0,333	0,389	0,389	0,500
20	PC7	0,250	0,250	0,250	0,306	0,194	0,250	0,361	0,417	0,167	0,222	0,222	0,333
21	LC1	0,417	0,417	0,389	0,444	0,361	0,389	0,500	0,528	0,333	0,389	0,389	0,472
22	LC2	0,333	0,333	0,333	0,389	0,278	0,333	0,444	0,500	0,250	0,306	0,306	0,417
23	LC3	0,333	0,333	0,333	0,389	0,278	0,333	0,444	0,500	0,250	0,306	0,306	0,417
24	LC4	0,194	0,222	0,167	0,222	0,167	0,222	0,278	0,333	0,056	0,111	0,111	0,222
25	LC5	0,250	0,278	0,222	0,278	0,194	0,250	0,333	0,389	0,111	0,167	0,167	0,278
26	LC6	0,472	0,500	0,444	0,500	0,417	0,472	0,556	0,611	0,389	0,444	0,444	0,556
27	CVC1	0,444	0,444	0,444	0,500	0,417	0,472	0,528	0,528	0,389	0,444	0,417	0,472
28	CVC2	0,444	0,444	0,444	0,500	0,444	0,444	0,528	0,528	0,389	0,444	0,417	0,472
29	CVC3	0,250	0,250	0,222	0,278	0,278	0,333	0,333	0,389	0,111	0,167	0,167	0,278
30	CVC4	0,333	0,333	0,333	0,389	0,333	0,389	0,444	0,500	0,278	0,333	0,333	0,444
31	CVC5	0,306	0,306	0,278	0,333	0,306	0,361	0,389	0,444	0,167	0,222	0,222	0,333
32	CVC6	0,389	0,389	0,361	0,417	0,361	0,417	0,472	0,528	0,250	0,306	0,306	0,417
33	CVC7	0,194	0,222	0,167	0,222	0,139	0,194	0,278	0,333	0,056	0,111	0,111	0,222
34	CVC8	0,194	0,222	0,167	0,222	0,139	0,194	0,278	0,333	0,056	0,111	0,111	0,222
35	JC1	0,167	0,194	0,139	0,194	0,111	0,167	0,250	0,306	0,028	0,083	0,083	0,194
36	JC2	0,194	0,222	0,167	0,222	0,139	0,194	0,278	0,333	0,056	0,111	0,111	0,222
37	JC3	0,194	0,222	0,167	0,222	0,139	0,194	0,278	0,333	0,056	0,111	0,111	0,222
38	JC4	0,194	0,222	0,167	0,222	0,139	0,194	0,278	0,333	0,056	0,111	0,111	0,222
39	JC5	0,000	0,028	-0,028	0,028	-0,028	0,028	0,083	0,139	-0,139	-0,083	-0,083	0,028
40	JC6	0,083	0,083	0,056	0,111	0,056	0,111	0,167	0,222	-0,056	0,000	0,000	0,111
41	JC7	0,250	0,278	0,222	0,278	0,278	0,333	0,333	0,389	0,111	0,167	0,167	0,278
42	JC8	0,111	0,111	0,083	0,139	0,111	0,167	0,194	0,250	0,028	0,083	0,083	0,194
43	EC1	0,389	0,389	0,389	0,444	0,333	0,389	0,500	0,556	0,361	0,417	0,417	0,528
44	EC2	0,361	0,361	0,361	0,417	0,306	0,361	0,472	0,528	0,333	0,389	0,389	0,500
45	EC3	0,167	0,167	0,167	0,222	0,111	0,167	0,278	0,333	0,083	0,139	0,139	0,250
46	EC4	0,167	0,167	0,167	0,222	0,111	0,167	0,278	0,333	0,083	0,139	0,139	0,250
47	EC6	0,250	0,250	0,222	0,278	0,222	0,250	0,333	0,361	0,111	0,167	0,167	0,250
48	EC7	0,278	0,306	0,250	0,306	0,250	0,306	0,361	0,417	0,139	0,194	0,194	0,306
49	EC8	0,333	0,333	0,333	0,389	0,306	0,361	0,444	0,500	0,222	0,278	0,278	0,389
50	DVC9	0,083	0,111	0,056	0,111	0,028	0,083	0,167	0,222	-0,056	0,000	0,000	0,111
51	SMC10	0,056	0,083	0,028	0,083	0,000	0,056	0,139	0,194	-0,083	-0,028	-0,028	0,083
52	SMC11	0,083	0,111	0,056	0,111	0,028	0,083	0,167	0,222	-0,056	0,000	0,000	0,111
53	SMC12	-0,056	-0,028	-0,083	-0,028	-0,111	-0,056	0,028	0,083	-0,194	-0,139	-0,139	-0,028
54	SMC13	0,083	0,111	0,056	0,111	0,028	0,083	0,167	0,222	-0,056	0,000	0,000	0,111
55	CC1	0,139	0,167	0,111	0,167	0,083	0,139	0,222	0,278	0,000	0,056	0,056	0,167
56	CC2	-0,417	-0,417	-0,417	-0,361	-0,472	-0,417	-0,306	-0,250	-0,500	-0,444	-0,444	-0,333
57	CC3	0,167	0,194	0,139	0,194	0,111	0,167	0,250	0,306	0,028	0,083	0,083	0,194
58	VC1	0,472	0,472	0,472	0,528	0,417	0,472	0,583	0,639	0,417	0,472	0,472	0,583
59	VC2	0,417	0,417	0,417	0,472	0,361	0,417	0,528	0,583	0,361	0,417	0,417	0,528
60	VC3	0,472	0,472	0,472	0,528	0,444	0,500	0,583	0,639	0,417	0,472	0,472	0,583
61	BC1	0,500	0,500	0,472	0,528	0,444	0,500	0,583	0,639	0,417	0,472	0,472	0,583
62	BC2	0,111	0,139	0,083	0,139	0,083	0,139	0,194	0,250	-0,028	0,028	0,028	0,139
63	BC3	0,194	0,222	0,167	0,222	0,139	0,194	0,278	0,333	0,056	0,111	0,111	0,222
64	BC4	0,167	0,194	0,139	0,194	0,111	0,167	0,250	0,306	0,028	0,083	0,083	0,194
65	BC5	0,444	0,444	0,444	0,500	0,417	0,472	0,556	0,611	0,333	0,389	0,389	0,444

DBP	Number of cells											
Low	2	2	3	2	3	2	1	9	4	4	4	2
Medium	37	36	38	33	45	33	26	14	41	43	43	32
High	26	27	24	30	17	30	38	50	15	18	18	31

Percentage of decrease in the number of low DBP sites from hypothesis 0 (current state)											
85,71	85,71	78,57	85,71	78,57	85,71	92,86	92,86	35,71	71,43	71,43	85,71