Study of Morphological Evolution of Dune Fields in Cantabria (N. Spain) during the Anthropocene

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Abstract

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The beach-dune system constitutes a dynamic system in which several natural processes interact, both at short and long time scale. Beaches are important because are the source of sediment for the dunes that form at the limit of the shore and that create barriers that protect the mainland from the high energy waves and from floods. However dunes are quite fragile features because susceptible to erosion and for this reason they need particular attention and management, tasks not always easy to carry out since the factors involved are numerous.

Along the Cantabrian coast, northern Spain, extended dune fields are present in correspondence with estuarine environments. In the last few decades they have experienced erosion due to natural agents such as winds, superficial water currents and river discharge and due to the anthropogenic influence, which after the Second World War started to increase, until the present. Additionally, intense erosive events such as storms occur seasonally, causing eventually damages to the infrastructures; the last remarkable events happened precisely in January and February 2014.

The objective of this work is the analysis of the evolution of the surface and limits of four representative dune fields in the region of Cantabria in the northern Spain, describing first the main factors involved. The study is based on nine sets of aerial photographs and orthophotos ranging from 1956 to 2014 for each site, overlapped and elaborated through the software ArcGIS; the digital work allowed the calculation of the rates of migration for each interval of time along with the computation of the surface extent of each dune field.

The results indicate that as general trend the coastline has retroceded in the last 58 years at average rates of 0.7m/y, but still exist, even within same dune fields, different behaviors, making of each site a complex dynamic system. The interpretation of the results led to the recognition of a rough conceptual model of evolution for each dune field: three out of four respond mainly to natural forces, while the other one migrates because of the anthropogenic pressure.

The study here presented constitutes a rough attempt to examine the different processes that are implicated in the formation of large dune fields and, even though 58 years are not enough to delineate a precise evolution trend, it can be useful for future researches about coastal management.

Keywords: Dune fields, Cantabrian coast, erosion, ArcGIS, Anthropocene

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Populärvetenskaplig sammanfattning

Studie av morfologisk utveckling av dynfält i Kantabrien (norra Spanien) under Antropocen

Cecilia Borghero

Stranddyner utgör ett dynamiskt geomorfologiskt system där flera naturliga processer samverkar, både på kort och på lång tidsskala. Stranddynerna är viktiga då de skapar barriärer som skyddar fastlandet från hög energi vågor och översvämningar. Men dynerna är utsatta för konstant förändring eftersom de är känsliga för erosion och det är av denna anledning som dynerna behöver särskild uppmärksamhet och förvaltning. Uppgifter som inte alltid lätt att genomföra eftersom faktorerna är många.

Längs den Kantabriska kusten i norra Spanien finns flera dynfält i samband med flodmynningsmiljöer. Under de senaste decennierna har dessa dynkomplex upplevt erosion på grund av naturliga faktorer så som förändringar i vindar, ytliga vattenströmmar och flodmynningar och på grund av antropisk påverkan som började öka efter andra världskriget och fortsatt fram till idag. Många av förändringarna sker i episodiska intensiva händelser, som stormar, vilket kan skada viktig mänsklig infrastruktur i området. De senaste anmärkningsvärda händelserna inträffade just i januari och februari 2014.

Syftet med detta arbete är att analysera utvecklingen av formen och utbredningen av fyra representativa dynfält i regionen Kantabrien i norra Spanien, genom att först beskriva de viktigaste faktorerna som är inblandade. Studien är baserad på nio uppsättningar av flygfoton och ortofoton som sträcker sig från 1956 till 2014 för varje plats. Genom att digitalisera dynernas utbredning i bildmaterialet tillåts beräkning av migrationen av dynfältens gräns och av ytomfattningen för varje tidsintervall.

Resultaten tyder på att som allmän trend så har kusten genomsnittligt gått tillbaka 0,7 m/år under de senaste 58 åren, men variationer förekommer, även inom samma dyn fält, olika beteenden vilket tydliggör att det är ett komplext dynamiskt system. Tolkningen av resultaten har lett till en en grov konceptuell modell av evolution för varje dyn fält där tre av fyra påverkas främst av naturkrafterna, medan den fjärde migrerar på grund av det ökade antropiska trycket.

Studien som presenteras utgör ett första försök att undersöka de inblandade processerna i bildandet och utvecklingen av dynfältet, dock är 58 år är inte tillräckligt för att beskriva en tydlig trend, men det kan vara användbart för framtidiga undersökningar om kustförvaltning.

Nyckelord: Dynfält, Kantabriska kusten, erosion, ArcGIS, Antropocen

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1. Introduction

The coastline is generally sensitive to changes both at local and global scale and the interplay between erosion and sedimentation through fluvial, marine and aeolian processes play an important role in the maintenance of the natural equilibrium (Arteaga, Sanjós & Serrano 2008).

In the last few decades, the attention has shifted to climate change and its long-term consequences that might lead to processes such as beach and dune erosion. Cycles of erosion are natural and make the coast environment a dynamic system (Reinen-Hamill, Hegn & Shand 2008); however, urbanization along the coast however aggravates erosion in some places, in the name of socio-economic development and its effects are visible in relatively short periods of time (Milne, Dong & Davidson 2012). These aspects are being investigated along the European Atlantic coasts, examining in depth dune management in response to changes in climatic conditions, dune and estuary morphologies, as well as ecology (Provoost, Jones & Edmondson 2011; Clarke & Rendell 2006; Flor & Flor-Blanco 2005; Nordstrom 2005).

Nonetheless, making predictions regarding beach recession could be difficult because the magnitude of the forcing conditions involved are variable; although some simplistic models try to estimate the sediment fluxes cross- and alongshore, they do not provide detailed information to delineate coastal hazard zones, or do not suggest correct engineering interventions to compensate the loss of sediment on the beach after storms (Coco et al. 2014).

The areas adjacent to the shoreline, where the sand accumulates and acts as barrier from the high-energy waves, are strongly involved in these mechanisms (Gómez-Pina et al. 2002). These barriers are the dunes which are dynamically coupled with the evolution of the shoreface and their buildup depends on the wind-controlled sediment supply and absence of storm waves (Flor & Flor-Blanco 2014a).

Dunes are considered as a reservoir of sediment, and they could be easily described as a natural defense against high-energy waves, reducing their intensity preventing flooding (Pye, Saye & Blott 2007). Accretion and recession are natural processes which reflect the environmental conditions. Dry sand from the backshore is moved landward carried by wind and accumulates on obstacles, mainly vegetation. During storm events, the wave action subtracts to the dune fields vital sediment which may be transported offshore or redistributed over the beach (Pye, Saye & Blott 2007) , undercutting the dune face and determining their decrease in size. During quiet conditions, the sand will be brought again landward.

Urbanization nevertheless could ruin this equilibrium, causing alterations that can drastically modify the coastal environment (Bruschi et al. 2013). Such scenarios are more evident in oceanic coastal environments, where the wind and the greater tidal range are responsible for moving larger bodies of water and sediment. In particular, the coasts of the northern regions of the Iberian Peninsula
are being affected by relevant morphological changes in the last 50 years, due to both anthropogenic and natural causes. By one side, tourist urbanization, constructions and sand extraction started around the 1960 enhanced dune field degradation (Gómez-Pina et al. 2002). On the other hand, intense events such as the storms occurred in January and February 2014 caused local disasters, especially in the north Atlantic, Galician and Cantabrian coast, and raised concerns regarding the preservation of the natural environment. These worries induce the question if the dune fields has suffered natural phenomena like the last in the past and if yes, with which magnitude.

Although some measures for reconstructing the coasts after the storms have already been taken on by different regional authorities supported by the Spanish government (Ministerio de Agricultura, Alimentación y Medio Ambiente, 2014), the need to detect vulnerable areas should be a priority. Vulnerability to environmental changes, intended as the “the state of susceptibility to harm from exposure to stresses” (Adger 2006, p. 268), can be evaluated through the correlation between the frequencies of the disturbing events with the response time for the dune system to recover; this quantification let a more realistic approach for the coastal sustainability in doing plans (Pethick & Crooks 2000). Each dune field is indeed different morphologically and for the processes involved, so generic management approaches are not always appropriate (Wallingford 2000) and hence solutions suitable to the different eventualities should be found, in order to preserve and protect the environment from the developing urbanization while taking into account the natural adjustments.

Understanding the evolution of the dune fields in the past, together with a better qualitative and quantitative knowledge of the coastal changes would aid to better understand the mechanisms and processes along with their significant variables. Periodical information should be collected in order to identify the coastal evolution through time, to therefore observe how the shoreline would vary in the future.
2. Aim

The variability of morphologies encountered in the dune fields of the northern Spanish coast reflects different evolution patterns through the time. The interaction of the natural sphere and the anthropogenic sphere is a critical aspect regarding the historical changes during the last half century and the study of it could constitute a base for further researches about coastal hazards.

This dissertation is aimed to the analysis of such relationship, looking at how representative dune fields of the northern Spanish coast have evolved through the time. The observations carried out would allow an attempt to identify whether a predominant factor is responsible for the environmental evolution and establish an evolution model for each study site.

The study consists in an updated analysis of the evolution of four aeolian field dunes located along the coast of Cantabria, the administrative region in the north-western part of Spain (Figure 1). This research treats the transformations which the dune fields have undergone through the last 58 years, a time period where the anthropogenic expansion has particularly become more prominent and where strong atmospheric events have dramatically changed the morphology of the coast, as happened in the winter season of 2013-2014.
The methodology comprises, in addition to a literature review of the most relevant aspects of the dune fields, the analysis of orthophotos and photogrammetric flight surveys gathered in different years, starting from 1956 and concluding with 2014.
3. Background

3.1 Coastal dynamics

The dunes are very fragile coastal features (Ley Vega de Seoane, Carlos, Gallego Fernández, Juan Bautista & Vidal Pascual 2009; Wallingford 2000; NSW Department of Land and Water Conservation 2001), subjected to forces that according their intensity and frequency can provoke abrupt modifications. Gradual changes indeed are absent, since the high variability of the processes involved, and episodes of minimum impact alternate with events able to move larger amounts of sediment (Wallingford 2000).

The beach-dune system undergoes cyclic processes, composed by both short-term and long-term fluctuations of the shoreline, and its evolution depends on the sediment budget to which different subsystems contribute (NSW Department of Land and Water Conservation 2001), as seen in the schematic model in Figure 2 which illustrate in simple way how the coastal environment loses and gains material form rivers, cliffs, sea waves and humans. The reduction of sediment supply from rivers, as well as the sea level rising for example, are processes whose erosional effects are visible on a long time period; on the other hand, effects of isolated events e.g. storms are visible over smaller scales.

![Figure 2 Schematic model of inputs (yellow arrows) and outputs (red arrows) of sediment in the beach system. ©NSW Government through the Department of Planning and Environment. Reuse according the policy http://www.planning.nsw.gov.au/copyright.aspx. From NSW Department of Land and Water Conservation (2001)](image-url)
Sporadic and intense events are more concerning when regarding the coastal management, even though dunes can preserve and recover naturally from the waves if provided with sediments and with protective vegetation (Wallingford 2000).

Used restoration techniques aimed to mitigate the erosion are multiple in the European North Atlantic areas, and they are studied in all their complexities with more emphasis to the long-term “soft engineering” approaches (e.g. beach nourishment), which provide the harmonization with the natural processes reducing the impact on the landscape (Gómez-Pina et al. 2002; Hamm et al. 2002; Flor, Martínez Cedrún & Flor Blanco 2012).

An optimal restoration work should be decided after a deep analysis of the site in all its morphological and physical aspects, according to the objectives planned and considering the risks and impacts that they could have on the population and natural environment. Availability of materials and costs should be taken in consideration as well. In generic situations the simple acceptance of the natural course is preferred so that the natural equilibrium is maintained, limiting any kind of intervention to the monitoring of the coastline, which includes analysis of historical investigations and collection of data of different aspects such as weather records, bathymetric surveys and topographical measurements (Wallingford 2000).

Examples of most practiced interventions are sand trapping with geotextile sheets, transplanting vegetation (*Amophilla Arenaria*), fencing, reducing number of dune walkover and beach nourishment (Hamm et al. 2002; Flor & Flor-Blanco 2005). The first methods for avoiding coastal deterioration are improving environmental awareness in the population, while limiting excessive exploitations by human activities.

Coastal dunes located on Spanish shorelines for example were totally unprotected until 1988, when the Government edited the Spanish Shore Act with the purpose of regulating some destructive coastal activities such as sand mining (Gómez-Pina et al. 2002).

Spanish dune fields that are more affected by changes are being periodically surveilled, as past researches demonstrate (Rodríguez-Ramírez et al. 2003; Arteaga & González 2005; Arteaga, Sanjosé & Serrano 2008; Flor, Martínez Cedrún & Flor Blanco 2012), and the historical regression and progression are studied in parallel with the developing urbanization to discuss the policies, economic resources and strategies pointing at an improved coastal management (Muñoz, Juan M. Barragán 2003).

### 3.2 The Cantabrian region

Cantabria is one of the administrative regions located in the north-western part of the Iberian Peninsula. It is bordered by the Basque Autonomous Community to the east, Principality of Asturias to the west and Castile and León to the south. The coastline oriented W-E is facing the Cantabrian Sea to the north (Figure 1).
3.2.1 Geological settings

The region could be ideally divided in three zones going from north to south according the topography (Figure 3): the coast, the valleys, and the less populated Campoo area, in the south (Barba Regidor 2004).

The littoral fringe, known as La Marina, extends for 10-15 km width until a small mountain range (Sierra de El Escudo de Cabuérniga) oriented W-E where elevations reached range from 600m to 1000m (Flor Blanco et al. 2012). Within 35-50km from the coast there is the Peaks of Europe Massif, southwestern part of the Cantabrian Range, whose axis is oriented parallel to the coastline and with altitudes of 2000-2600 m (Fischer, Rivas & Cendrero 1995). The Cantabrian Range, which is the western continuation of the Pyrenees, extends from the region of Galicia to the Basque Countries.

The bedrock in Cantabria is composed mostly by sedimentary rocks, such as shales limestone and sandstones, whose age goes from the Precambrian to the Cenozoic (Jiménez-Sánchez et al. 2014) and the oldest rocks, more visible in the western area (Barba Regidor 2004), are quartz-arenites with shales and siltstones interbedded, dated back to the Cambrian-Lower Ordovician (approx.541-470 Ma), after which a lack of deposition occurs (Alonso 1998).

Figure 3 Physical map of Cantabria. “Physical map of Cantabria (Spain)” by Emilio Gómez Fernández, File licensed under Creative Commons Attribution-Share Alike 3.0 Unported license. Slightly modified. From http://commons.wikimedia.org
Piles more than 3000m thick of limestone dated back to the Carboniferous Period (approx. 360-290 Ma) were uplifted during the Hercynian Orogeny that occurred in the Late Paleozoic, resulting in the present Picos de Europa Massif (Jiménez-Sánchez et al. 2014).

The Mesozoic is the most represented ensemble of the region through the presence of limestones, sandstones and clays well stratified from the Triassic (approx. 252-201 Ma) and Jurassic (approx. 201-145 Ma), period in which the marine invasion started (Maroto, Álvarez & Suárez del Río 2004).

The Upper Triassic Keuper facies, composed by clays, evaporites and salts, intruded through diapirs in the more recent rocks and now outcropping along the coast and in other sites. These structures are an important factor in the genesis of some Cantabrian estuaries due to their lithological tendency to be eroded (González Diez et al. 2012). At the end of the Jurassic and during the Lower Cretaceous Period (approx. 145-100 Ma) the sea was regressing and deltaic sedimentation led to deposition of facies of continental origins (conglomerates, sandstones); the Upper Cretaceous (approx. 100-65 Ma) is characterized by periods of regression and transgression represented by limestones and marlstones with terrigenous materials interbedded (Barba Regidor 2004).

The Alpine Orogeny, started in the Late Mesozoic, determined definitely the continental setting of the region and caused south-verging thrusts and faults that influenced the topography, creating an asymmetrical profile: northern valley sides are steep and narrow, meanwhile the southern side has been gentle slopes; the modelling of the landscape has then carried forward by Quaternary glaciers, rivers and gravitational and karst processes (Jiménez-Sánchez et al. 2014). Extended uplift, after the N-S compression in the Eocene, generated the Cantabrian Range and the regional topography, allowing the formation of the cliff coast and flat surfaces.

3.2.2. Coastal morphology

The coastal landscape is shaped by an ensemble of processes, which include waves, climate, rivers and environmental characteristics (Monge-Ganuzas, Evans & Cearreta 2015).

The Cantabrian littoral fringe is characterized by a smooth relief where it is noticeable a characteristic features of this region, the “rasas”, a series of Late Miocene or Early Pliocene to Holocene continental and marine erosional surfaces positioned at several heights along the coastline characterized by gentle slopes toward the sea (Flor-Blanco et al. 2014b). These terraces started to form in correspondence with the Late Paleozoic tectonic uplift, while the most recent ones, covered by sand and gravel deposits, reflect the last Holocenic eustatic cycle. (Flor & Flor-Blanco 2014b).

The coast is mainly represented by rocky littorals interrupted by sandy, gravelly and mixed pocket beaches often associated with river mouths, in areas where urbanization and frequently port activities are settled (Flor-Blanco et al. 2015; Lechuga et al. 2012).
The rivers, influenced by the sea level fluctuations and the human activities, represent an important factor in the coastal dynamics and ecosystems because they are one of the most important way of transportation of the terrestrial constituents toward the ocean (Prego, Boi & Cobelo-García 2008; Garrote, Page & Garzon 2001).

The streams and rivers flowing in this region are generally short and with seasonal character and according to the geographic position of their origin, can be either cordilleran or coastal (Martínez-Cedrún et al. 2014); the major part of them follow an orientation N-S, crossing geological structures and showing steep slopes, whereas the rivers with orientation W-E are more likely to follow geological structures (González Díez et al. 2012).

Along the coast the outlet of rivers forms an estuary, which can be defined as semi closed coastal environments influenced by the tides where waters from the rivers and from the sea meet (Pritchard 1967). The estuaries have often a spit that is likely to close it (Lechuga et al. 2012) and that forms in the eastern side of the mouth due to longitudinal littoral drift eastward created by the local refraction of waves of the Cantabrian Sea (Flor-Blanco et al. 2015). From a geological point of view the estuaries are hence depositional environments subjected to fluvial and tidal processes and whose morphological characteristics develop according to the size of the basin and the river discharge, which in turn depends on the bedrock (Flor-Blanco et al. 2015).

It can occur that coastal rivers, despite the small hydrographic basin and lacking large water discharge, form estuaries with larger surface than the ones made by cordilleran rivers. This happens when the coastal area exhibits Triassic bedrock, characterized by soft materials that are easily eroded (Flor Blanco et al. 2012).

The nature of the estuaries determines how the sediment is distributed and which morphological features there would be present along the Cantabrian coast they are generically regarded as wave-dominated with an average tidal range of 2-4m (mesotidal regime) (Flor 1997). These types of estuaries are characterized by a stronger influence of the sea waves in building the sand barriers if compared to tidal currents, pushing the sandy sediment along stream. The weaker tidal currents are more evident in the inner part of the valley, where fluvial discharge is enriched of angular pebbles and cobbles.

Where a rocky headland shelters the estuary mouth, the different current directions create a cyclical transport of the sediment within the estuary: on one side the sand is carried by the fluvial flow outside on the continental shelf, forming eventually beach-dune systems; on the other side the refracted waves by the headland transport the sediment toward the inner areas, creating mudflats and saltmarshes (Monge-Ganuzas, Evans & Cearreta 2015).
3.2.3. Dune morphology

Dune fields develop under control of several factors (Short & Hesp 1982; Aagaard, Orford & Murray 2007): they are mainly the direction and the velocity of the winds from the sea to the land, the availability of the sand on the beach and its size, the orientation of the beach in respect to the winds, the vegetation and the grade of humidity, which enhance the cohesion of the sand grains; according to their intensity and predominance different dune geometries will form.

The shapes and sizes of the dunes observed in Cantabria are various and amply studied (González Diez et al. 2012; Flor et al. 2012; Flor Rodríguez, Martínez Cedrún & Flor Blanco 2011; Sanjaume Saumell, Gracia & Flor 2011). During this work some particular ones up to decametric scale have been studied and they can be categorized and described according to their geometry (Figure 4) following as example scheme the one of Sanjaume Saumell, Gracia & Flor (2011) and of Flor (1998), who in turn follow the classification of littoral dunes made by Cooper (1958) and Goldsmith (1985).

The first important categorization is between depositional dunes controlled by the relief, uncontrolled and mixed, as explained below:

- **Uncontrolled by the relief**

  - Tabular forms or sand sheets: form when wind blows from the sea and they are characterized by a subhorizontal cover of sand with meter scale dimensions, and they could be considered as incipient foredunes (Hesp 2002). They usually are found at the border of the dune field, signing the transition zone between the upper beach and the major dune field.

  - Longitudinal dunes: they form following the direction of wind either as ridges not controlled by the vegetation or as tongue-like shape, also called lee-projection dunes (Cooper 1958), which consist of lobular-shaped sand accumulations and originate from the foredune crest growing over the lee side and even beyond the swales. The interplay between sedimentation and deflation at times create erosive residual mounds or knobs (Hesp & Thom 1990).

  - Transversal dunes or foredunes (Hesp 2002): they form perpendicular to the direction of the wind and develop as ridges more or less parallel to the beach at the rear of the backshore. The side facing upwind is steepest, because more exposed to the erosion of the waves during the storms; it derives an asymmetric cross section. These dunes are the most represented in the Cantabrian coast (Flor et al. 2012).

- **Controlled by the relief**

  The climbing dunes (Tsoar 1983) are tabular forms characterized by the ability to adapt to the topography, which means that sand moved by the wind can move uphill. They are generally found as fossil dunes in the inner part of the dune field, fixed to the soil through vegetation (either natural or...
artificially planted). They can cover either an extended area, as it is the case of one of the study sites, or a small one.

- **Mixed**
  - The parabolic dunes (Hack 1941) are a type of transversal dunes, with a U-shape. The arms are pointing upwind, that is toward the beach. The gentler slope is on the windward side; the leeward side instead is steepest. The part surrounded by the arms is subjected to intense wind flow, creating eventually an erosional depression, called blowout (Hesp 2002).
  - The blowouts are depressions with an ellipsoid plant originated by the deflation of sand over a preexisting sand cover; accumulations of sand mark the culmination of the bowl-shaped structure.
Figure 4 Some typologies of coastal dunes, according to the classification of Flor (1998); most of these geometries represented are seen in the study area. From Flor (1998). Reuse authorized by the author.
3.2.4. Climate

Globally temperatures and precipitations are driven by the atmospheric circulation, which is generated by pressure differences due to unequal heating of the Earth. Natural fluctuations in the pressure pattern lead to variations in the climatic ranges; in the Northern Hemisphere the variability mechanism that most affect the Iberian Peninsula is the North Atlantic Oscillation (NAO), which is responsible interannual and decadal variations mostly in precipitations and to less extent in temperatures (Bladé & Castro-Diez 2010).

The Iberian Peninsula is located in a climatic zone between the temperate and tropical latitudes. In particular the Cantabrian area is characterized by oceanic conditions, categorized as Cfb (temperate oceanic climate) according to the Köppen-Geiger classification, with warm summers and cool winters and precipitations quite evenly distributed throughout the year.

As reported by the Meteorological Agency of Spain (Agencia Estatal de Meteorologia, AEMET), in Cantabria temperatures in the period 1951-1980 the average annual temperature was 12.4°C, whereas in the period 1981-2010 it was 12.9°C, indicating a regional increase of the temperatures (Ancell trueba & Célis Díaz 2010). Concerning the precipitation, in Cantabria the distribution varies in time and space. Regarding the temporal aspect, the cold season is the wettest and in particular the highest peak of precipitation occurs be usually in November (averages considered over the period 1981-2010). The precipitations exceeding of 1000 mm per year interest over 80% of the surface but the wettest areas are the central, occupied by the Picos de Europa Massif, and the littoral fringe (Ancell trueba & Célis Díaz 2010). The monthly temperatures and precipitations recorded in the city of Santander in the period 1981-2010 are the ones indicated in Table 1.

The seasonal character is related to the geographical position of the region, which implies perturbations generated from atmospheric circulation systems linked associated with the polar jet stream during the autumn and winter, and convective rainfall during the summer, when the Polar Front moves northward (Serrano et al. 1999). The spatial distribution of the climate is due to the topographical settings of the region, since the mountain range blocks the air masses coming from North or South (Fernandez & Rasilla 1993). The migration of the Azores High leads to extreme storm events to occur in the coldest season: in 2014 the Galician and Cantabrian coast suffered storms driven by western winds with velocities of 174 km/h that were associated with waves that caused erosion of the coast and damages to the infrastructures (Flor Blanco, Flor Rodriguez & Flores Soriano 2014).
Table 1 Average values for precipitations, temperatures and wind (direction and maximum velocity reached) over the period 1981-2010. Data from the airport of Santander. Modified from Ancell trueba & Célis Díaz (2010)

<table>
<thead>
<tr>
<th>Month</th>
<th>Temperature average (°C)</th>
<th>Prec. average (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>January</td>
<td>9.7</td>
<td>106.2</td>
</tr>
<tr>
<td>February</td>
<td>9.8</td>
<td>92.2</td>
</tr>
<tr>
<td>March</td>
<td>11.3</td>
<td>87.9</td>
</tr>
<tr>
<td>April</td>
<td>12.4</td>
<td>102.2</td>
</tr>
<tr>
<td>May</td>
<td>15.1</td>
<td>78.0</td>
</tr>
<tr>
<td>June</td>
<td>17.8</td>
<td>58.2</td>
</tr>
<tr>
<td>July</td>
<td>19.8</td>
<td>52.4</td>
</tr>
<tr>
<td>August</td>
<td>20.3</td>
<td>73.4</td>
</tr>
<tr>
<td>September</td>
<td>18.6</td>
<td>83.1</td>
</tr>
<tr>
<td>October</td>
<td>16.1</td>
<td>119.8</td>
</tr>
<tr>
<td>November</td>
<td>12.5</td>
<td>157.1</td>
</tr>
<tr>
<td>December</td>
<td>10.5</td>
<td>118.4</td>
</tr>
<tr>
<td>Year</td>
<td>14.5</td>
<td>1129.0</td>
</tr>
</tbody>
</table>

As stated in the IPCC report (2014) it is quite clear that the global temperature will increase furthermore over the next century (Stocker, Alexander & Allen 2013) and for the coastal areas global warming could constitute a problem in terms of storms frequency/intensity and sea level rise (Castro, Martín-Vide & Alonso 2005).

A recent investigation (Lechuga et al. 2012) tried to study the behavior of the Spanish northern beaches to the storms (considered such when the significant height of the waves exceed 4m) in the period 1995-2010 from buoy data, in order to find a relationship between the climate change and the storm intensity. The researchers considered storm intensities in terms of annual average energy (function of number of storms and height of the waves) and return period (recurrence interval) and they discovered that in Cantabria beaches exposed to NW waves have suffered more intense storms in the period 2006-2010 than the previous years but looking at the entire time interval it is increasing neither the number of coastal storms nor their intensity. However, the number of years considered was not enough to detect a certain influence of climate change (Lechuga et al. 2012).

3.3 Study area

The study area consists of four representative dune fields which develop in the internal fringe of the beaches in correspondence with estuarine environment along the coast of Cantabria (Figure 1). From west to east they are located in the municipalities of: Valdáliga (the dune field of Oyambre-La Rabia), Piélagos (Lierres), Santander and Ribontán al Mar (Somo-Santander) and Laredo. Associated river systems and estuaries, some of them constituted by two subsystems, wind directions and dune morphologies for the study sites are summarized in Table 2.
### DUNE FIELD | ESTUARY/ SUBSYSTEMS | TYPE OF RIVERS | DUNE TYPOLOGIES | MAIN WINDS
---|---|---|---|---
Oyambre | La Rabia (Zapedo and Capitán) | Coastal | Foredunes; tabular | NW |
Lieneres | Pas or Mogro | Cordilleran | Foredunes; parabolic; tongue-like; climbing | NW and SW |
Somo | Santander bay (Santander and Cubas) | Coastal and cordilleran | Tabular; foredunes; tongue-like; blowouts; climbing | NW and SSW |
Laredo | Asón | Cordilleran | Tabular; foredunes; tongue-like; blowouts | NE and NW |

**Table 2** Resuming table for each dune field, showing the estuary associated, the dune types and the predominant winds involved in the dune formation. Modified from Flor Rodríguez, Martínez Cedrún & Flor Blanco (2011)

#### 3.3.1. The dune field of Oyambre–La Rabia (Valdáliga)

The beach of Oyambre is located between the cities of Comillas and San Vicente de la Barquera (western Cantabria) and is long approximately 3.5 km. It extends in the northwestern side of the estuary of the coastal river La Rabia, which is constituted by two arms, Zapedo at east and Capitán at west (Figure 5).

The two estuarine subsystems are confined by a spit, where a dune field has generated thanks to the interplay between sedimentation supply coming from NW and coming from the river (Martínez Cedrún 2009). The estuary of La Rabia River has a total perimeter of 13.6 km and a drainage basin of 40 km² and it carries autochthonous sediments that are almost nonexistent (Garrote, Page & Garzon 2001).
The beach lies upon turbidite facies dated back to Eocene and Oligocene, meanwhile more resistant calcareous rocks are exposed in Cabo Oyambre and Peña de la Barra, in the western and eastern side of the beach/river zone respectively (Garrote Revilla & Garzón Heydt 2004).

Today the spit is hosting a golf club, but still the morphologies are recognizable despite the continuous adjustment for the sporting events, and in particular foredunes develop in a series of ridges sub-parallel to the coastline (foredunes), and tabular dunes formed in the northeastern part as well as the side toward the estuary. The dune field has been suffering erosion in the last half century (Garrote Revilla & Garzón Heydt 2004; Martínez Cedrún 2009) and after the storms of 2014 in particular (Figure 6).

**Figure 5** Satellite view of the estuarine environment of La Rabia River and the associated dune field of Oyambre (yellow box). From Esri's ArcGIS Online based on TerraColor® images (2015) Available online via http://www.flashearth.com/ [Accessed 10 May 2015]
3.3.2. The dune field of Liencres (Piélagos)

This field dune is located approximately 15 km west of Santander. It is part of the Regional Natural Park, created in 1986 and with extent of approximately 200,000 m².

Winds are mostly from NW and affect the orientation of the dunes; winds from NE are blowing as well even if with less frequency (Sanjosé & Arteaga 2004).

The dune field is placed in the eastern side of the mouth of the Pas River, 57 km long, which has origin in the Cantabrian Range and has formed a mesotidal estuary confined by a sandy barrier that is oriented NE-SW (Figure 7). This barrier, represented by the Valdearenas Beach, culminates with some of the dunes. The beach continues toward NE until a rocky outcrop, where now is hosting a parking; from here the beach is flanked by low cliffs, on top of which fossil climbing dunes have developed and that extend in the eastern and southern zone of the Park (in correspondence of the dark green areas in Figure 7).

Analyses demonstrate that the dune sand is quartz dominant, whereas the outcrops in this area are made of limestone belonging to the Jurassic and Cretaceous (Arteaga & González 2005), indicating that it is the river discharge that contributes to the sediment supply of the beach-dune system.

The Pas River is not the only supplier of sediment to the system, indeed also some solid load from the close estuary of San Martín de la Arena (5 km at west) reaches the shore, thanks to the littoral drift (Barba Regidor 2004).

Figure 6 Exposed side of the dune field (photo taken in March 2015 from the northwestern corner by C.Borghero)
An active dune system can be recognized, where heights can reach also 30-40 m, with embryonal tabular dunes easily destroyed by the storm waves, foredunes, parabolic dunes and blowouts (Flor Rodríguez, Martínez Cedrún & Flor Blanco 2011; Arteaga, Sanjosé & Serrano 2008). Footpaths have been created by humans (Figure 8), letting the aeolian sand to enter from the foredunes, creating tongue-like dunes (Barba Regidor 2004). Inactive dunes are represented by an aforesaid extended field of climbing dunes in the eastern inner side, originated because of the winds coming from NW and SW and now fixed thanks to pine trees (*Pinus pinaster*) planted in the middle of the last century (Martínez Cedrún 2009).

**Figure 7** Satellite view of the estuarine environment of the Pas River and the associated active dune field of Liencres (yellow box) and the fossil climbing dunes (dashed yellow box). From Esri's ArcGIS Online based on TerraColor® images (2015) Available online via http://www.flashearth.com [Accessed 10 May 2015]
3.3.3. The dune field of Somo and the eastern dune-beach system (Santander-Ribamontan al Mar)

This dune field is located in the vicinities of the biggest city of Cantabria, in the bay of Santander, the largest in the Cantabrian coast (Flor & Flor-Blanco 2014c), which is generated by the confluence of two estuarine subsystems: the Santander properly said and the Cubas. The first one, which is located in a faulted valley of clays and evaporites, is fed by coastal rivers with ephemeral flow; the second one, smaller, is drained by the cordilleran Miera River (Flor Blanco et al. 2012).

The NE oriented inlet, which has an extension of 23.5 km² (Flor Blanco et al. 2012), is closed at north by La Magdalena peninsula and at south-east by a sandy barrier oriented W-E (the spit of Somo), where a dune field developed (Figure 9).

The spit is 2.5 km long and 100-250 m wide and its evolution has been hypothesized by Losada et al. (1991) to be depending on the presence offshore of the Las Quebrantas shoal that is breaking the waves. The barrier is therefore divided in two morphodynamic subsystems, where the middle and eastern part are exposed to the waves of NW; the western part due to the shoal and the additional protective action of the peninsula, receives refracted and diffracted waves from NE, letting the sediment therefore to enter in the bay, where tides prevail, creating accumulation of sand and bars in the intertidal zone (Flor Blanco et al. 2012).

In the spit two major foredunes, one on the northern side and one in the southern, are interposed by blowouts and tongue-type dunes; bigger structures such as washover fans occur periodically,
breaking the foredunes and creating gaps, as seen in Figure 10a and 10b (Martínez Cedrún 2009). In the eastern part of the dune field, where the spit is connected with the mainland (location Loredo), the plantations of pines supported the formation of climbing dunes.

These morphological features are suffering erosion because of the natural and human agents and since 1992 when reinforcement works have been carried out to protect them, including setting up willow sand trappers, fences, transplanting vegetation (*Ammophila Arenaria*) and reducing the number of footpaths (Gómez-Pina et al. 2002).

**Figure 9** Satellite view of the estuarine environment of Santander and Cubas of the Miera riverand the associated dune field of Somo and Somo-Loredo (yellow box). From Esri's ArcGIS Online based on TerraColor® images (2015) Available online via http://www.flashearth.com [Accessed 10 May 2015]
The dune field of La Salvé- El Puntal- Regatón (Laredo)

The dune field develops in the proximities of the bay of Santoña, whose brackish water is mainly supplied by the cordilleran 50 km long Asón River, and it is located in the eastern part of Cantabria (Figure 11).

From a geological point of view, in the estuary are exposed rocks from Mesozoic to the Cenozoic: old layers of clay with volcanic materials are overlaid by younger limestones, sandstones and marlstones (Martínez Cedrún 1984).

The estuary, characterized by a mesotidal regime, is limited to the North by the tombolo of Santoña and at South-East by a sandy barrier of which both sides present sandy beaches, which feed the aeolian dunes that develop over the backshore in the inner part of this tongue. The eastern side, called La Salvé, is exposed to the Sea and to the dry winds from NE. The waves from NW and NE are

![Image](image.jpg)

**Figure 10** In the spit the foredunes are interrupted by washover fans, usually formed during storms. a) aerial view of the spit where these structures are visible (examples in the red circle). From Bing Maps. b) closer look to the gaps in the foredunes. The photo was taken in the northeastern by C. Borghero.
refracted by the tombolo, letting the sand to deposit mostly on the south-eastern part (Martínez Cedrún 1984). Foredunes, longitudinal dunes oriented ENE-WSW and tongue-like dunes are the most developed in this area, with blowouts that periodically occur (Flor-Blanco et al. 2004). The beach on the western side of the barrier, called El Regatón, has N-S orientation and it is facing the estuary and suffers winds from NW and W, which generate foredunes of small dimensions (Flor Blanco, Flor Rodríguez & Martínez Francisco 2004).

Degradation in Laredo is quite significant (Flor & Flor-Blanco 2005) and urbanization and tourism are a significant force in the morphological changes that has lead to the conservation of the dunes only in the proximities of the beaches. After the storm of 2014, from which the northern parts of the field dune (El Puntal) have particularly suffered as it is visible from the aerial photographs and as demonstrated by the infrastructure damages (Figure 12). To protect the area an artificial dune 5-7m high was built in the tip zone (Ministerio de Agricultura, Alimentación y MedioAmbiente 2014).

![Figure 11 Satellite view of the estuarine environment of the Asón River and the associated dune field of Laredo (yellow box). From Esri's ArcGIS Online based on TerraColor® images (2015) Available online via http://www.flashearth.com/ [Accessed 10 May 2015]](image-url)
3.4 Dynamic agents

There are a series of different factors that are shaping each morphological feature present in the study area and in the whole region. In this work it will be briefly illustrated the most important ones: winds, tides, sea level, river discharge as well as the anthropogenic force.

3.4.1. Winds

Winds form at global scale in response to pressure differences around the planet and contribute along with the terrestrial rotation at the formation of the oceanic superficial currents. Aeolian processes moreover are responsible for the mobilization of sand and dust particles, and the direction of the wind and its strength affect the availability of sediment, playing an important role in determining the shapes of the dunes (Lancaster 2009). The particles move according to their size and to the wind intensity, which means that they move when their weight and the cohesion between adjacent particles are exceeded by the fluid force (Lancaster 2009). The relationship between the sand dune development and the wind regime, in terms of distribution of the direction and the velocity, anyway is not simple, since low velocity winds are not able to move the sand and high velocity winds may damage the dunes (Goldsmith 1985).

The northern peninsular regions are mainly affected by cold either dry or moist winds, depending on the air mass origin; they are controlled indeed by the subtropical high pressure center (Prieto et al. 2013) over the Atlantic Azores Islands (located 907 miles western of Lisbon). Therefore
the wind directions along the Cantabrian coast have a seasonal variability due to the cyclonic movements in the atmosphere. In autumn and winter the prevailing trends are from SSW to NW, which origin in the Atlantic and carrying humidity that drive the storms. During springtime and summer instead dry and cold winds from E and NE are dominant, which create a cooling effect on the coastal waters if persistent (Flor & Flor-Blanco 2013). In its entirety, the winds from NE are the most frequent during the year, followed by the component SSW, as seen in Figure 13.
Figure 13 Wind directions and frequency (in %) based on data retrieved from the airport of Santander. a) Annual average (period 10/2000 - 03/2015 with data daily taken). Image reused according the license policies of the company Windfinder.com. From http://es.windfinder.com/windstatistics/santander_parayas; b) Average of the central month of each season (over approx. 3797 observations during the period 1983-1992). It is appreciable the change of the wind direction through the year. The numbers around the rose indicate the direction of the wind (example 35-36-01 is the N, 2-3-4 is the NNE etc.); the variable value indicate the frequency of wind with different direction from those shown in gray and that could not be represented; the calm value indicate the frequency of quite conditions ©AEMET. Image reused according the policy. From AEMET (2012)
3.4.2. Waves and tides

The superficial currents have the biggest role in sediment distribution along the coastline. The ocean waves directed to the Cantabrian coast come mainly from the NW as they are part of the Gulf Stream (Figure 14), creating a littoral drift toward East carrying water masses, sediments and nutrients (Flor Rodríguez, Martínez Cedrún & Flor Blanco 2011), but currents from NE occur as well when intense winds blow during anticyclonic conditions.

The average height (distances between crest and the following trough) of the waves is 1 m, but during the storms it can exceed 4 m; the period (time between two consecutives crest or trough) ranges mostly between 8 and 12 seconds (Berenguer et al. 2004).

Tides in this coastal frame are characterized by mesotidal (waves range from 2m to 4m) and semidiurnal (a cycle of high and low tide lasts 12 hours) regime, with strong fluctuations within it (minimum of 1 m and maximum of 4.6 m) (Martínez-Cedrún et al. 2014; Blanco & Flor 2008). Tidal data were recorded by the tide gauge of the port of Santander as example of mesotidal regime (Figure 15).

**Figure 14** Annual preferential direction of the waves recorded by the Buoy Bilbao-Vizcaya (600m depth) in the period 1990-2014. From Puertos del Estado (2015). Reuse of image licensed http://www.puertos.es/es/Paginas/Aviso-Legal.aspx

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When the sea water enters into the bay, the waves have to adapt to the new settings of the estuary, and they lose height. Currents develop driven by the winds and related to the mixing of salty and fresh water and to tide changes. On the shore facing the sea, the waves start to break in the zone with maximum of the energy moving the sediment present at the bottom and then it is transported toward the land or in the other way. The littoral drift then causes the longshore movement, creating a zig-zag pattern (Keener-Chavis & Sautter 2000). In Cantabria these periodical movements allow the sand to move and accumulate in the eastern corners, creating dune fields of big extension.

In addition to having a sediment transport function, the waves are capable of physical and chemical erosion, both when they break against the cliffs and when they invade the land during the storms. In general storm events in Cantabria occur in autumn and winter and the biggest wave storm registered by the oceanographic buoy of Santander was in January 2009 with a significant height (the average of the top one-third of the wave heights) of 14.88m, which indicates a maximum wave height (which usually is 1.5-1.9 times the significant height) of approximately 26m (Instituto Español de Oceanografía [IEO] 2015). The significant heights of the storms of 2014 instead were smaller in compare to 2009 but the peculiarity that made these events unique is the frequency with which they occured (Conde Criado 2014). As the experts from the Environmental Hydraulic Institute of Cantabria (IH Cantabria) state, this anomaly has been related with the overlapping of condition of high tide, strong winds and a special atmospheric setting of the North Atlantic, in which the perturbation trajectories shifted toward lower latitudes in compare with last years (IH Cantabria 2014).
3.4.3. Sea level

It is clear the relationship between sea level rise and long term beach change (Leatherman, Zhang & Douglas 2000). Eustatic fluctuation of the sea level indeed influence the coast morphology as when the sea level is low, as it happened during the last glaciation, the estuaries experience an infilling process and the beach and the all dune system tend to migrate toward the continent border.

Sea level rises because of different factors at different time scale, such as atmospheric perturbations and tectonic activities, and it increases due to both the thermal expansion of the water after the ocean warming and the melting of the glaciers (Nicholls & Cazenave 2010; IPCC 2014).

The immediate impacts of such processes on coastal zones involve low lying areas and beaches implying more floods and saltwater intrusion into the land, followed by wetlands deterioration and erosion of the sandy barriers and coastlines (Cendrero, Sánchez-Arcilla Conejo & ZazoCardeña 2005; Chust et al. 2010). The redistribution of the morphological features provokes continuous changes in the associated habitats an in the degree of vulnerability of the wildlife and the human society (Crooks 2004).

As reported by the fifth assessment by IPCC the global mean sea level increased at rates of $1.7\pm0.2$ mm yr$^{-1}$ in the 20th century and it will rise up to 0.98 m by the end of 2100, but there will be some regional variations and the rate will not be constant (IPCC 2014). In the Bay of Biscay for example studies based on gauge records and global coverage of satellite altimetry in open oceans showed a rate of 2.12 mm yr$^{-1}$ over the period 1943-2001 (gauge from Santander, Marcos 2005) and 3.09 mm yr$^{-1}$ between 1993 and 2002 (Chust et al. 2010) respectively, signifying that there has been a significant acceleration in this area over the current century.

However, according to García-Artola, Cearreta & Leorri (2015) global instruments such as tide-gauge are sparse and not always enough to appreciate accelerations in the sea level rise over more centuries since they cover limited periods of time, and consequently not exact predictions nor estimation of the economic repercussions on the coastal environment are not possible. As attempt to fill the lack of information foraminifera from an estuary in the Basque coast (Bay of Biscay) have been studied by the same authors: the rate obtained for the last century is approximately 1.7 mm yr$^{-1}$, in line with the Santander gauges trend (Figure 16), showing that the estuarine records can be considered valid and able to improve the quality of the data sedimentary records.
Figure 16 Relative sea levels in the Bay of Biscay. A. Data obtained from the foraminifera records in the estuary of Guernica (Basque Country) located about 100 km east of Santander. B. Data obtained from the tide gauge of Santander. From García-Artola, Cearreta & Leorri (2015). Reuse of the image licensed by Elsevier.

3.4.4. River solid transport

River basins are characterized by dissolved and solid transport and both of them contribute at the coastal dynamics and sedimentation in dunes, beaches and estuaries.

The discharge is forced by precipitations, which are predicted to decrease in the total annual amount but to increase in intensity enhancing flood events with the global warming (IPCC 2014); the amount of solid yield is difficult to quantify due the high degree of uncertainty but is quite clear that it is worldwide related to changes in rainfall regime and to human activities (Cendrero, Sánchez-Arcilla Conejo & ZazoCardeña 2005; Syvitski et al. 2005).

Along the Cantabrian cordilleran rivers there are only few gauging stations for measuring water discharges, but not stations recording solid transport. In general, the sediment supply by the rivers is quite absent due to the tectonic settings, the scarce removal eroding the valley heads and the small size of the river basins (Diez 1999; Flor-Blanco et al. 2015) but still along the coast it exists a variation in
the mineralogical and textural characteristics of the sediments carried by the rivers (Martínez-Cedrún et al. 2014).

The larger part of the rivers transport siliciclastic sands toward the sea where carbonate fractions coming from the organisms living on the rocky coastal are added and transported toward east because of the littoral drift (Flor & Flor-Blanco 2013).

3.4.5. Anthropogenic factor

Human interventions can influence either directly or indirectly the coastal recession, according to the type of interventions and where it is done (Martínez Cedrún 2009). The Spanish coasts have experienced crescent urban pressure in the last century and the landscape has been modified mainly through agriculture, grazing, residential and commercial development and tourism (Ley Vega de Seoane, Carlos, Gallego Fernández, Juan Bautista & Vidal Pascual 2009; Gallego-Fernández, Sánchez & Ley 2011; Micallef & Williams 2002).

Here below examples of human impacts on the coastal environment are briefly resumed, following the lines illustrated in the dissertation of Ley Vega de Seoane et al. (2009).

Regarding the urban development of constructions of infrastructures and buildings (roads, parking places and bars are just few examples) perturb the ecosystems and the loss of natural environments and some ordinary practices related to recreational activities such as cleaning the beach enhance the removal of vegetation and destruction of the small features.

Recreational use of the beach and/or walk upon the aeolian dunes facilitates the fragmentation of the dune ridges enhancing the erosional action of the wind. The authorities take actions against this with the technique of plantation of trees; it helps because it limits the erosion of the dunes, but it has the intrinsic effect of inducing the autochthonous plant communities to disappear.

Sand extraction is performed either in the coastal dunes (now prohibited according the Spanish Coastal Law, 1988 and its modification of 2014) or in the adjacent marine zone, through dredging, and causes mobilization of the morphologies toward new equilibriums. In the bay of Santander, for example, the dredging in the estuary creates an imbalance which the natural processes try to compensate through migration of the sand spit.

Actions directed to the saltmarshes and intertidal areas, like artificial desiccation and refilling, and disposition of jetties in the estuaries near the harbors aimed at the control of the flow direction to facilitate the navigation, change the dynamics of the sediment distribution in the basin and in the beach-dune system associated, leading indirectly to degradation of the environment (Cendrero, Sánchez-Arcilla Conejo & Zazo Cardeña 2005; Flor-Blanco et al. 2015).
4. Methods

This research has been investigated through office work supplemented at the end by field work. The study consisted of the analysis of digital aerial vertical photographs (stereoscopic vision) and orthophotos provided by the Regional Ministry of Presidency and Justice of the Government of Cantabria and the measurement of distances and surfaces through the Geographical Information System (ESRI Inc.) platform using the software ArcGIS® version 9.3.

The method is based on the concept that the best way to get an idea of the changes of the dunes at the limit of the shore through the years is mapping the extension of the dune field from several aerial photographs taken over time. The mapped coastline migration is therefore considered obtaining a profile of the dune evolution. Additionally, in order to evaluate the artificial impact in the dune fields and in the surroundings, changes in the settled areas are also mapped and evaluated.

The area of each type of surface has been determined, always through ArcGIS measurement tools, to quantify the dune field evolutionary process. Elaboration of the data obtained has been done using both ArcGIS tools and spreadsheets to get resuming graphs.

The material examined are aerial photographs of the years 1956 (flight from the US Air Force, scale approx. 1:33000), 1970 (flight made by the Headquarters of the Coasts and Ports of the region of Cantabria (scale 1:20000), 1988 (flight from the Regional Council of Cantabria scale 1:15000) and set of orthophotos made by the Autonomous Community of Cantabria under the Nation Plan of Aerial Orthophotography (except 2001 and 2002) of the years 2001 (project Regional Cartographic Base at scale 1:10000), 2002 (at scale 1:50000), 2005 (at scale 1:10000), 2007 (at scale 1:50000), 2010 (at scale 1:5000), 2014 (at scale 1:5000). This latter set was realized during the summer of 2014, some months after the storms and even though the estimation of the erosion caused by the single event is not achievable, it is still possible to notice some of the damages.

The first step has been the georeferencing according the reference system ETRS89/ UTM zone 30N of the aerial photographs using the tools offered by the software ArcGIS 9.3 on the base of the 2010 topography (scale 1:5000) furnished by the Cantabrian Government.

Given the variety of scales, the georeferencing process has been made focusing on the shoreline area, to minimize as much as possible errors afterwards; the control points as consequence were in positions very close to or within the area of interest, so that the overlapping of the entire set would have been more accurate. The procedure has been considered successful when the entire mosaic georeferenced exhibited a Root Mean Square Error (RMSE) less than 3 m.

The orthophotos properties instead displayed a RMSE value between 0.5 m and 1 m. The digital mapping of the extent of the dune fields was then made on the georeferenced images with the support of online maps (Google Earth and Bing Maps).
During the digitalization some simplified criteria were used (Martínez Cedrún 2009):

- Natural areas were defined as active environments that despite human footpaths conserve the natural morphology and vegetation eventually protected by fences.

- Developed areas were defined as buildings, infrastructures and activities (e.g. sand mining) that have occupied or at least influenced the original dune fields; the artificial plantations of trees are included in this category as well. The eventual expansion of these features in the inner land has been considered only within the limits of the original dune field of 1956.

The temporal evolution for each dune field has been estimated by drawing shore-normal transects and measuring the lengths between the mapped contours starting from the 1956 limit. The profiles have been placed where the dune migration could have been appreciable and their number varies according the size of the dune fields: five in Oyambre, three in Liencres, nine in Somo and ten in Laredo.

Finally, the rate of accumulation or erosion for each interval of time has been calculated to have an idea of the magnitude of the dune migration. In this step the year 2002 has not been considered because the contours were overlapping with the ones of 2001, indicating no movement.

Despite the attractiveness of the process in terms of the low cost and large availability of the materials, there are some uncertainties involved. The usage of techniques that comprise photogrammetry indeed implies errors, whose sources are the original data, the interpretation during the digitizing (due to both the software and the operator) and therefore the computation of surfaces, distances and rates (Moore 2000).

The geometry of aerial photographs taken by aircrafts constitutes the first source of error, since distortions and displacement take place due to disadvantages encountered during the flights, such as camera tilts and changes of altitude of the aircraft (Gorman, Morang & Larson 1998). In some cases, different scales exist between the images, making more laborious and less accurate the process of orthorectification. Interpretation errors arise mainly from the bad contrast of the images, that does not make enough evident the contours of the dunes (Del Rio & Gracia 2013).

In this thesis errors relative to the final calculations of the rates and the areas have been estimated through analytical approaches.

Regarding the rates, the main factor involved is the digitized position of the dune limits on the base of aerial photographs and orthophotos. This is affected by errors both made by the operator and intrinsic to the instruments/processes. The elements taken into account are the image resolution or cell size ($\epsilon_{\text{res}}$), and the orthorectification error, represented by the RMSE ($\epsilon_{\text{geo}}$) from the georeferencing.

The error linked to the position of the dune field limit on a given photograph ($\epsilon_P$) is therefore the quadratic sum of each element, expressed as seen in Eq.1.
\[ \varepsilon_p = \sqrt{\varepsilon_{res}^2 + \varepsilon_{geo}^2} \quad (1) \]

The uncertainty then related to the rate of change of position of the dune field contours (\(\varepsilon_{rate}\)), which implies a different photograph source, and hence different position error, is given by the quadratic sum of the errors divided by the time interval (\(dt\)) (Eq.2).

\[ \varepsilon_{rate} = \frac{\sqrt{\varepsilon_{P1}^2 + \varepsilon_{P2}^2}}{dt} \quad (2) \]

Given the amount of aerial photographs and orthophotos with different resolution, in this dissertation only the maximum and the minimum rate errors have been estimated for each time interval, using the maximum and the minimum value encountered of the cell (or pixel) size (2.65 and 0.25 m respectively) and the RMSE (3 and 0.5 m respectively). In the calculation of the rate error, the position error then was considered the same (\(\varepsilon_{P1} = \varepsilon_{P2}\)). As result, the rates obtained during this study include uncertainties that range between ±0.014 m yr\(^{-1}\) (\(\varepsilon_{rate} \) min) and ±0.098 m yr\(^{-1}\) (\(\varepsilon_{rate} \) max).

Regarding the surfaces, once again the main factor involved is the position of the points drawn to create the polygons from which the surfaces have been calculated. To calculate the range of uncertainty it has been used the Buffer tool of the software ArcGIS, a geoprocessing tool that allows creating polygons whose points are at specific distance from the original polygon. In this way, selecting as distance as the position error calculated in the previous step, it will be obtained a polygon whose area would be subtracted from the original one and as result it will be estimated the maximum and minimum span of uncertainty for the area calculations. Through this process it has been evaluated that the area errors space among percentages of 0.35% and 10.92% relative to the area considered.

The research has been complemented by observations in situ, to look at both the dune morphologies and the integrity of the dune fields one year after the storms.
5. Results

In this section the main results obtained in this investigation will be presented for the different study sites. It will be shown maps with the contours of the dune field through the years (higher resolution images in Appendix 1) and they will be accompanied by graphs of the profiles and tables of both the rates of dune migration and the natural and anthropogenic areas for each study site. The areas of Somo and Laredo, due to their large extent, have been divided in smaller areas to better appreciate the contours. The dune field maps, from which the areas have been calculated for each year are available in the Appendix section (Appendix 2).

5.1 Evolution of Oyambre-La Rabia

The dune field of Oyambre, at the mouth of La Rabia River, is today hosting a golf club. The human interventions however are not limited to the transformation of the dunes into a game field. Indeed the hydrodynamic and the sedimentation process has been modified indirectly in the last decades (Belmonte et al. 1987), especially in the Capitán River were two dykes were controlling the water flux and the former wetland was occupied by a plantation of eucalyptus; between the years 1988 and 2001 one of the dyke has been opened, letting the salty water to enter and inundating the wetland, transforming the plantation in a dead forest.

Oyambre in 1956 was entirely natural, with a surface of 91,662 m² and now the natural area is less than the 5% of the original, after the inauguration of the golf club and after the last period including the storm event in 2014 in which almost 6200 m² have been lost (Table 3).

Between the 1970 and the 1988 the dune field has been subjected to continuous transformations in order to make the soil adapted for the golf and a parking has been built nearby, but after that it had not undergone further significant artificial changes. The dune field reached the maximum extension just in 1988, with over 100,000 m².

In this dune field have been studied five profiles (Figures 17 and 18), three in the northern part (N1, N2 and N3) and two in the South (S1 and S2), and they do not show always similar trends, although some similarities occur especially in the last 10 years.

In the period 1956-1970 the dune fields lose area, but the eastern part represented by profiles N3 and S1 prograde since 1956 of 16.55m and 9.4m, respectively.

In the following interval of time accretion prevail everywhere, with a peak of 24.33 m in N3.

From 1988 the whole zone started to be subject to erosion until nowadays with periods of small accretions in some sectors, a part in the western part in correspondence with the profile N1 that keeps the positive trend started in 1970 until 2005.

However there have been some remarkable events that are worth mentioning. For example, in N3, the eastern part, from 2005 and 2007 the already negative trend is deepened by an “abrupt”
recession of 3.8 m followed by small accretion and then again recession (26 m). A similar pattern, but less clearly, occurs in the other profiles (N1, S1 that loses 12 m). N2 instead in the same period displays an advance, even though at relatively low rates.

After 2010 the dune field is dominated by erosion in all the sectors and the northern profiles display an increase of the amount toward East, ranging from 9.89 m (N1) to 26.04 m (N3); the southern part suffered less.

In the complex, different sectors of this dune field have not reacted in the same way through the years (Figure 18): the part that has undergone more modifications is the eastern part, that started to expand toward north but now is regressing toward the inner part of the estuary. The strongest retreat measured for this dune field takes place in the vicinities of the dyke, represented by S1, with a span of 26.57 m in 2001. In the southern part the dune field recession is accompanied by the formation of a beach.

The average rates of erosion for the period 1956-2014 in this dune field are greater for the side facing the small estuarine bay, but in general they have not exceeded the 0.55 m yr\(^{-1}\) (Table 4), despite some intervals of time exhibit relatively higher values (retreat of 6.51 m yr\(^{-1}\) in the period 2010-2014 for the northern part (N3)).
Figure 17 The dune field contours over the years 1956-2014 with the profiles considered. Orthophoto of the year 2014. To notice how much the northeastern part changed through the time.
<table>
<thead>
<tr>
<th>Year</th>
<th>Natural</th>
<th>Anthropogenic</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>1956</td>
<td>91,662.50</td>
<td>-</td>
<td>91,662.50</td>
</tr>
<tr>
<td>1970</td>
<td>89,955.44</td>
<td>-</td>
<td>89,955.44</td>
</tr>
<tr>
<td>1988</td>
<td>94,120.12</td>
<td>13,312.58</td>
<td>107,432.70</td>
</tr>
<tr>
<td>2001</td>
<td>17,176.06</td>
<td>81,644.58</td>
<td>98,820.64</td>
</tr>
<tr>
<td>2002</td>
<td>14,638.51</td>
<td>81,335.51</td>
<td>95,974.02</td>
</tr>
<tr>
<td>2005</td>
<td>14,025.66</td>
<td>82,449.93</td>
<td>96,475.59</td>
</tr>
<tr>
<td>2007</td>
<td>12,782.20</td>
<td>81,560.68</td>
<td>94,342.88</td>
</tr>
<tr>
<td>2010</td>
<td>10,371.05</td>
<td>81,213.65</td>
<td>91,584.70</td>
</tr>
<tr>
<td>2014</td>
<td>3,852.01</td>
<td>73,473.58</td>
<td>77,325.59</td>
</tr>
</tbody>
</table>

**Table 3** Natural and anthropogenic areas calculated for the dune field of Oyambre-La Rabia

<table>
<thead>
<tr>
<th>Time interval</th>
<th>N1</th>
<th>N2</th>
<th>N3</th>
<th>S1</th>
<th>S2</th>
</tr>
</thead>
<tbody>
<tr>
<td>1956-1970</td>
<td>-1.00</td>
<td>-0.31</td>
<td>1.18</td>
<td>0.67</td>
<td>-0.24</td>
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<td>1970-1988</td>
<td>0.35</td>
<td>1.14</td>
<td>1.35</td>
<td>0.73</td>
<td>0.20</td>
</tr>
<tr>
<td>1988-2001</td>
<td>0.46</td>
<td>-0.31</td>
<td>-0.63</td>
<td>-2.04</td>
<td>-1.12</td>
</tr>
<tr>
<td>2001-2005</td>
<td>0.18</td>
<td>-0.58</td>
<td>-0.28</td>
<td>-1.68</td>
<td>0.13</td>
</tr>
<tr>
<td>2005-2007</td>
<td>-1.31</td>
<td>0.37</td>
<td>-1.93</td>
<td>-6.16</td>
<td>-2.39</td>
</tr>
<tr>
<td>2007-2010</td>
<td>-1.13</td>
<td>-1.93</td>
<td>0.37</td>
<td>-1.16</td>
<td>-0.84</td>
</tr>
<tr>
<td>2010-2014</td>
<td>-2.47</td>
<td>-4.24</td>
<td>-6.51</td>
<td>-1.29</td>
<td>-1.10</td>
</tr>
<tr>
<td>1956-2014</td>
<td>-0.29</td>
<td>-0.21</td>
<td>-0.05</td>
<td>-0.55</td>
<td>-0.44</td>
</tr>
</tbody>
</table>

**Table 4** Rates calculated along the profiles for each interval of time

**Figure 18** Evolution of the dune field of Oyambre-La Rabia for the period 1956-2014. The continuous lines represent the profiles, the dotted lines the anthropogenic and the natural surfaces. The value 0 in the y-axis on the left corresponds to the 1956 contour line and constitutes the starting point for the measurements of accretion (positive, the line goes up) and erosion (negative, the line goes down).
5.2 Evolution of Liencres

The dunes of Liencres at the mouth of the Pas River constitute, along with the estuarine environment in which they are comprised, a matter of scientific interest for their morphologies and for their fragilities and they are part of the Natural Park of the Dunes of Liencres.

At the beginning was a completely natural environment, counting 1,688.481m², but in the 1960’s pine trees were planted in the inner and eastern part of the area and a car parking built, occupying in 1970 73% of the total surface (Table 5). After these interventions the developed area remains pretty the same, with some small variations. The natural area variations instead have a wider spectrum, and this is attributable to the continuous ruptures and reconstructions of the spit for the exposition to storm waves. For this morphological temporal variability, no evolution study has been carried out in this extremity in this dissertation. Three profiles approximately 350 m distant from each other have been studied, all of them in the Valdearenas Beach (Figure 19).

Despite that the profiles are closely located they do not show always the same behavior through the time (Figure 20). In the period 1956-1970 the dune field was eroding in all the sectors, and in particular the western profile (W) indicates a retreat of 44.12 m, against the 35.78 m of the eastern one (E).

The recession continues until the 1988, and at this time, the central part (profile C) shows the highest erosion rate, retroceding of 17.82 m. However, during this period the rate of erosion has decreased of the order of 2-3 m yr⁻¹ respect to the previous one (Table 6).

From 1988 the process inverted and the dunes started to advance until 2005, even though the eastern sector at a slower rate. One of the most significant erosive events occurred in February 1995, when a storm from NW with winds blowing from South hit the coast: the spit broke, causing a gap in the dune system that later recovered.

Between 2005 and 2007 another recession takes place, leading the coast to recede of 24m and 48m in the W and C profile respectively. On the contrary, the E profile shows a gain of sediment. After a period of recover between 2007 and 2010, the dune system keeps receding even if not at high rates as happened in 2005-07. Finally, in 2014 the dune field has migrated landward respect to 1956, and the total net displacement is around of 35-40 m.

To sum up it is possible to see that not all the sectors of the dune system moved in the same way (Figure 20), but still the tendency is clearly toward erosion; despite the plantation of vegetation, construction of fences and sand trapping, dunes are migrating toward the inner land and so far human interventions such as walls, sand extraction performed in the seventies, roads and salt marsh filling have intensified the degradation of the dune field (Arteaga, Sanjosé & Serrano 2008).
Figure 19 The dune field contours over the years 1956-2014 with the profiles considered. Orthophoto of the year 2014. To notice how the spit geometry varied, in which years of small dune cover (for example 1988) alternate with years of larger dune cover (for example 2001)
Table 5 Natural and Anthroogenic areas calculated for the dune field of Liencres.

<table>
<thead>
<tr>
<th>Year</th>
<th>Natural</th>
<th>Anthropogenic</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>1956</td>
<td>1,688,481.42</td>
<td>-</td>
<td>1,688,481.42</td>
</tr>
<tr>
<td>1970</td>
<td>444,735.79</td>
<td>1,257,066.37</td>
<td>1,701,802.16</td>
</tr>
<tr>
<td>1988</td>
<td>414,777.72</td>
<td>1,283,185.27</td>
<td>1,697,963</td>
</tr>
<tr>
<td>2001</td>
<td>465,538.58</td>
<td>1,291,971.47</td>
<td>1,757,510.05</td>
</tr>
<tr>
<td>2002</td>
<td>453,226.65</td>
<td>1,292,096.4</td>
<td>1,745,323.05</td>
</tr>
<tr>
<td>2005</td>
<td>378,646.67</td>
<td>1,288,907.37</td>
<td>1,667,554.05</td>
</tr>
<tr>
<td>2007</td>
<td>417,836.15</td>
<td>1,291,761.12</td>
<td>1,709,597.28</td>
</tr>
<tr>
<td>2010</td>
<td>446,003.36</td>
<td>1,303,056.3</td>
<td>1,749,059.67</td>
</tr>
<tr>
<td>2014</td>
<td>445,521.74</td>
<td>1,280,012.92</td>
<td>1,725,534.67</td>
</tr>
</tbody>
</table>

Table 5 Natural and Anthroogenic areas calculated for the dune field of Liencres.

<table>
<thead>
<tr>
<th>Year</th>
<th>W</th>
<th>C</th>
<th>E</th>
</tr>
</thead>
<tbody>
<tr>
<td>1956-1970</td>
<td>-3.15</td>
<td>-2.96</td>
<td>-2.56</td>
</tr>
<tr>
<td>1970-1988</td>
<td>-0.23</td>
<td>-0.99</td>
<td>-0.43</td>
</tr>
<tr>
<td>1988-2001</td>
<td>0.44</td>
<td>1.77</td>
<td>-0.45</td>
</tr>
<tr>
<td>2001-2005</td>
<td>1.51</td>
<td>1.49</td>
<td>1.00</td>
</tr>
<tr>
<td>2005-2007</td>
<td>-12.95</td>
<td>-24.51</td>
<td>2.89</td>
</tr>
<tr>
<td>2007-2010</td>
<td>14.09</td>
<td>17.82</td>
<td>1.45</td>
</tr>
<tr>
<td>2010-2014</td>
<td>-5.40</td>
<td>-4.43</td>
<td>-0.09</td>
</tr>
<tr>
<td>1956-2014</td>
<td>-0.72</td>
<td>-0.75</td>
<td>-0.61</td>
</tr>
</tbody>
</table>

Table 6 Rates calculated along the profiles for each interval of time

Figure 20 Evolution of the dune field of Liencres for the period 1956-2014. The continuous lines represent the profiles, the dotted lines the anthropogenic and the natural surfaces. The value 0 in the y-axis on the left correspond to the 1956 contour line and constitutes the starting point for the measurement of accretion (the line goes up) and erosion (the line goes down). Here is detectable the “abrupt” erosional event of the period 2005-2007.
5.3 Evolution of Somo

Unlike Liencres and Oyambre, the coastal fringe in the proximities of the main city of Cantabria is affected by the human presence since the beginning of the time considered in this project, counting an area of approximately 588,000 m² against the natural 1,350,000 m² (Table 7). The urban development advanced at constant rates until the present, due to the city expansion, plantation of trees and sand extraction both from the dunes and from the fluvial channel.

The first decrease corresponds to an aggressive urbanization explaining a large retreat of the dune contours from 1956 to 1970 (Figure 21 and 22). In fact, in all the profiles it has been calculated a recession of more than 35 m, reaching 30 m in the central part of the spit. The nine profiles are all made along the part of the coast exposed to the sea, since the side facing the bay has not been affected significantly through the time; from the analysis of these three different zones have been distinguished.

The western part represented by W1 is the sector affected by the recent formation of the sand dunes, due the migration of the spit. This segment did not exist until 1988, after which it gets eroded (except in the extent of time 2005-2007) at low but constant rates (Table 8).

The central part is the longest and here represented by six profiles (from C1 to C6, going from West to East); despite the similar pattern, erosion and/or accretion are not evenly distributed within one period, making this area highly unstable illustrated by C6, where rates of variations are usually larger compare to the others. Besides the initial regression, other significant migrations happen in the periods 2005-2007 and 2010-2014. In the first interval of time C1, C2 and C3 recede of 5.11 m, 5.97 m and 3.46 m respectively and C4 C5 and C6 advance of 6.15 m, 4.09 m and 9.77 m respectively; between 2010 and 2014 the recession is wherever, ranging from 7.47 m (C5) to 20.05 m (C3).

The eastern part of the active dune field, represented by E1 and E2, encountered a more fluctuant evolution and it advanced in comparison to the limit of 1956, despite the negative trend of the last years; the largest accretion occurred between 1988 and 2001.

In summary, dune field evolution is highly variable (Figure 21), starting from its western extremity, which is getting thinner and migrating toward the inner bay. The central and the eastern part (E1 and E2) seem to follow two distinct trends when looking at Figure 22: from C1 to C6 the tendency is generally negative but variable; for E1 and E2 the trendline is inclined toward a net relative gain of sediment.
Figure 21. Dune field contours over the years 1956-2014 with the profiles considered in the Somo spit. Orthophoto of the year 2014. To notice the extreme western part migration toward the inner bay.
Figure 21 (continues) The dune field contours of Somo –Loredo over the years 1956-2014 with the profiles considered. Orthophoto of the year 2014.
Table 7 Natural and Anthropogenic areas calculated for the dune field of Somo and Somo-Loredo.

<table>
<thead>
<tr>
<th>Year</th>
<th>Natural [m²]</th>
<th>Anthropogenic [m²]</th>
<th>Total [m²]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1956</td>
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<td>1,937,992.40</td>
</tr>
<tr>
<td>1970</td>
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<td>746,874.67</td>
<td>1,308,469.61</td>
</tr>
<tr>
<td>1988</td>
<td>489,333.26</td>
<td>813,832.22</td>
<td>1,303,165.48</td>
</tr>
<tr>
<td>2001</td>
<td>535,416.33</td>
<td>903,971.22</td>
<td>1,439,387.55</td>
</tr>
<tr>
<td>2002</td>
<td>527,501.31</td>
<td>913,443.75</td>
<td>1,440,945.06</td>
</tr>
<tr>
<td>2005</td>
<td>488,253.86</td>
<td>963,806.44</td>
<td>1,452,060.30</td>
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<tr>
<td>2007</td>
<td>455,261.65</td>
<td>997,814.37</td>
<td>1,453,076.02</td>
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<tr>
<td>2010</td>
<td>427,833.92</td>
<td>1,024,122.82</td>
<td>1,451,956.74</td>
</tr>
<tr>
<td>2014</td>
<td>374,939.31</td>
<td>1,026,111.44</td>
<td>1,401,050.75</td>
</tr>
</tbody>
</table>

Table 8 Rates calculated along the profiles for each interval of time.
Figure 22 Evolution of the dune field of Somo for the period 1956-2014. The continuous lines represent the profiles, the dotted lines the anthropogenic and the natural surfaces. The value 0 in the y-axis on the left correspond to the 1956 contour line and constitutes the starting point for the measurement of accretion (the line goes up) and erosion (the line goes down).
5.4 Evolution of La Salvé- El Puntal- Regatón

In the eastern part of Cantabria the city of Laredo expands in the estuary of the Asón River. The bay, one of the most economically important of the region, has an area characterized by bedrock easily erodible.

Like in Somo, Laredo was already an urban center in 1956 that kept developing following along the coastline which has continued until the present days. In general anyway the hugest growth of the city occurred in the period 1956-1970, when it doubled its area (Table 9). The total dune field area reached its maximum expansion in 2007, with more than 2743380m².

The dune field, whose evolution through the years is shown in Figure 23 and 24, has been studied in all its three fronts: the beach of Regatón, the beach of La Salvé and the northern extreme sector.

The western side (Regatón), facing the estuary, has been analyzed through three profiles (W1 W2 and W3), two of which located in proximity of the Eucalyptus plantations. The three profiles are characterized by fluctuations but overall show equilibrium or slightly negative trend. W1, the closest to the tip, has suffered constant but never intense erosion (maximum 12m in 1956-1970) as happened in the sectors with W2 and W3, where periods of erosion alternate with accretion, but keeping the balances seen in Table 10, the average rates for the entire time span considered are small (W2 show even accretion since 1956).

On the side of La Salvé, at East, the erosion is more intense in the northern part. At southeast instead the dunes tend to grow. E1 and E2 display a fluctuant tendency, where erosion (largest in 2010-2014 for E1 and in 1988-2001 for E2) alternates with accretion (but never exceeding 7m); the general trend is negative, implying net erosion. E3, E4, E5 and E6 exhibit a positive trendline, since the dunes regularly expand except in the interval 2010-2014 where instead the system start to retrocede (except for E6 that keeps growing).

The profile N at the tip of the spit was expanding toward the sea until 2001, but then it has been affected by erosion mostly in the last four years, in which dunes retreat of more than 130m.

As summary, the sandy barrier of Laredo has two type of evolution: one linked to the estuarine environment, at West, characterized by continuous erosion but rarely intense. The other linked to the sea waves, at East, where the fringe is subdivided in two sector, one toward the spit marked by episodes of severe erosion that alternate with accretion and formation of transgressive dune shapes and the other toward SE experiencing accumulation.
**Figure 23** The dune field contours of La Salvé-El Puntal-Regaton over the years 1956-2014 with the profiles considered. Orthophoto of the year 2014. Here it is detectable the erosion of the northern part after the storm of 2014.
Figure 23 (continue) The dune field contours of La Salvé-El Puntal-Regaton over the years 1956-2014 with the profiles considered. Orthophoto of the year 2014
Figure 23 (continue) The dune field contours of La Salvé-El Puntal-Regaton over the years 1956-2014 with the profiles considered. Orthophoto of the year 2014. To notice that the most eastern part, in correspondence with the profile E6, started to develop after the 1970
<table>
<thead>
<tr>
<th>Year</th>
<th>Natural</th>
<th>Anthropogenic</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>1956</td>
<td>1,565.579.3</td>
<td>1,034.367.07</td>
<td>2,599,946.4</td>
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<td>1970</td>
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</tr>
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<td>1988</td>
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</tr>
<tr>
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</tr>
<tr>
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</tr>
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<td>454,016.87</td>
<td>2,287,496.65</td>
<td>2,741,513.5</td>
</tr>
<tr>
<td>2007</td>
<td>452,958.71</td>
<td>2,290,423.22</td>
<td>2,743,381.9</td>
</tr>
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<td>2010</td>
<td>437,334.66</td>
<td>2,277,336.55</td>
<td>2,714,671.2</td>
</tr>
<tr>
<td>2014</td>
<td>362,318.70</td>
<td>2,296,856.76</td>
<td>2,659,175.5</td>
</tr>
</tbody>
</table>

**Table 9** Natural and anthropogenic areas calculated for the dune field of Laredo

<table>
<thead>
<tr>
<th>Time interval</th>
<th>W1</th>
<th>W2</th>
<th>W3</th>
<th>N</th>
<th>E1</th>
<th>E2</th>
<th>E3</th>
<th>E4</th>
<th>E5</th>
<th>E6</th>
</tr>
</thead>
<tbody>
<tr>
<td>1956-1970</td>
<td>-0.86</td>
<td>-0.86</td>
<td>-2.43</td>
<td>0.34</td>
<td>0.43</td>
<td>-0.42</td>
<td>1.51</td>
<td>0.91</td>
<td>-0.44</td>
<td>-</td>
</tr>
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<td>1970-1988</td>
<td>-0.52</td>
<td>1.45</td>
<td>1.96</td>
<td>0.11</td>
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<td>-0.66</td>
<td>1.25</td>
<td>0.52</td>
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<td>-</td>
</tr>
<tr>
<td>1988-2001</td>
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<td>-1.02</td>
<td>1.30</td>
<td>-1.41</td>
<td>-1.30</td>
<td>0.13</td>
<td>1.19</td>
<td>0.98</td>
<td>0.58</td>
</tr>
<tr>
<td>2001-2005</td>
<td>-0.64</td>
<td>-1.14</td>
<td>2.34</td>
<td>-0.32</td>
<td>-0.30</td>
<td>0.35</td>
<td>0.50</td>
<td>0.59</td>
<td>0.36</td>
<td>0.81</td>
</tr>
<tr>
<td>2005-2007</td>
<td>-0.85</td>
<td>-3.89</td>
<td>-3.79</td>
<td>-0.73</td>
<td>0.63</td>
<td>3.61</td>
<td>0.89</td>
<td>4.37</td>
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<td>2007-2010</td>
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<td>0.00</td>
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<td>-6.17</td>
<td>-2.09</td>
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<td>-1.60</td>
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<tr>
<td>2010-2014</td>
<td>-0.67</td>
<td>1.22</td>
<td>2.45</td>
<td>-33.23</td>
<td>-15.14</td>
<td>-3.86</td>
<td>-6.55</td>
<td>0.41</td>
<td>0.41</td>
<td>0.23</td>
</tr>
<tr>
<td>1956-2014</td>
<td>-0.65</td>
<td>0.05</td>
<td>-0.09</td>
<td>-2.07</td>
<td>-1.50</td>
<td>-0.82</td>
<td>0.26</td>
<td>0.78</td>
<td>0.96</td>
<td>-</td>
</tr>
</tbody>
</table>

**Table 10** Rates of accretion and recession calculated along the profiles for each interval of time
Figure 24 Evolution of the dune field of Laredo for the period 1956-2014. The continuous lines represent the profiles, the dotted lines the anthropogenic and the natural surfaces. The value 0 in the y-axis on the left correspond to the 1956 contour line and constitutes the starting point for the measurement of accretion (the line goes up) and erosion (the line goes down).
6. Discussion

In this study the results revealed that in Cantabria recession rates are quite variable over the time interval considered but in general since the 1956 the dunes have eroded at average rate of 0.7 m yr$^{-1}$. Particular areas instead, such as the tip of Laredo and the central sector of Somo, experienced migration of more than 2 m yr$^{-1}$. The general trend is negative, which means that the coastline in this region is subjected to erosion and the most affected parts are the areas exposed to the strength of waves and winds.

The current spatial extents of the dune fields varies between 77325m$^2$ (the smallest, Oyambre) and 2659175m$^2$ (the largest, Laredo). The mapping of natural and urban areas, with the noticeable presence of human activities, shows that urban development expanded rapidly in the period 1956-1988, affecting the natural environment. In the case of Oyambre, the present natural area constitutes only 4% compared with 1956; the data of the other dune fields instead show an average decrease of 25%.

The obtained results in this analysis show that the four representative dune fields which are located in the confining barrier of estuarine environments at the Cantabrian Coast are affected by changes of both small and large entity.

In Cantabria, García Codrón & Rasilla Álvarez (2005) observed that an intensification of coastal erosion would affect the coastline, also in areas with no apparent impacts related to human action. The evolution of the Cantabrian coast can be related to global change, both in atmospheric circulation and sea level rise. The retreat affects most of the dune areas and coastal lowlands, such as Oyambre, with retreats of decametric magnitudes in less than half century, but also cliff sections without a linear trend which makes it not quantifiable.

Out of Spain, models based on the processes involved (e.g sediment transport and wind and waves intensity) were made to predict changes in the dune/beach systems, even though with some limitations (Dissanayake, Brown, & Karunarathna 2014; Pender & Karunarathna 2013). Alternatively, the best option is to focus on repetitive topographic measurements over time that would show an overview of the changes occurred (Andrews et al., 2002). The GIS technology has enabled data acquisition in a more accessible way (van Heuvel & Hillen, 1995; Anthony et al., 2006; Delgado-Fernandez, 2011; Malavasi et al, 2013); additionally, the LIDAR techniques have demonstrated high accuracy in obtaining horizontal and vertical measures, in both micro and mesoscales (Woolard & Colby, 2002), and were widely applied in the Andalusian coast (Ojeda et al. 2007).

Uncertainties related to repeated mapping consisted of the quality of the aerial photographs that caused misinterpretation of the outlines of the dune field, especially for the series of 1956 and 1970. Additionally, the simple fact that aerial photographs were taken in different months of the same year (is the case of the series 1988 of Laredo, in which three aerial
photographs were necessary to cover the entire study area) was a source of errors in the mapping. Moreover, the dune morphologies were often covered by trees or other vegetation and not clear. These ambiguities were solved by looking at previous studies or, as in the case of the present conditions, by direct observation. An additional source of errors that affected the accuracy of the results resides in the georeferencing process that made the geographical points shifted of ±4m.

The results are different for each study site and it is not easy to delineate a clear and unique cause that is valid for all the areas. Moreover these rates have to be taken with some precautions as the analysis spans 58 years. For a more accurate analysis shoreline position data covering at least a century should be considered (Leatherman et al. 2000).

As described in the background section, the dune fields are affected by natural processes, including in this category sea level fluctuations, winds and wave storms, and by anthropogenic activities, such as sand extraction, tourism and urban development.

The analysis of the evolution of the dune field in this work led to highlight some common patterns. As a general trend, the dune limits exposed to the sea reached the maximum expansion at the end of the last century, in correspondence with the major human development; if there is a relationship or it is just a coincidence is not known. The migration was variable but having a net negative trend, except for some cases (e.g. the southeastern part in Laredo and the eastern part in Somo). Some sectors of the dune fields experienced intense recession at the border of several meters, probably after big storm events which are as in the case of the periods 2005-2007 (evident example in Liencres) as well as 2010-2014, most recent and more widespread. A different case is provided by the segment of Somo where due to the intensive dredging in the Santander Bay for port development (especially during the 1980ies) dune retreat was dramatic. However, beach sand drift towards the ends of El Puntal de Somo and Loredo minimizes the dune retreat. Each dune field develops in an independent way but with a common trend which can be interpreted as linked to global forces combined with local stresses.

Looking at the evolution of each site from both a natural and an anthropogenic processes, it has been possible however to establish a simplified conceptual model of the future evolution according to the predominant forcing factor involved.

In case of Oyambre field, it can be observed that despite of the changes related to anthropogenic effects, the trend has a natural cause. Sea water enters the estuary, following the main direction of the currents, carrying sediment and modifying the extreme eastern part of the dune field. On a long term evolution, these changes might allow the formation of a beach where now is intertidal zone, which would naturally migrate inland; this sector has been affected numerous times in the last decades, even though in minor measure, by the dykes that influenced the river sediment and water supply.

Similarly to the Oyambre, the dune field of Liencres is evolving by natural causes. The most prominent human presence appears in the form of sand extraction and footpaths that
induce wind deflation, but despite these artifacts the dunes are able to recover from the erosion events through an auto-alimenting system (Flor et al. 2011; Martínez Cedrún 2009). The sediment supply coming from the river, even though decreasing (Arteaga & González 2005) is transported by the littoral drift once it exits the estuary and is deposited right after, keeping a sort of equilibrium. However, it is likely that it will continue to undergo erosion if the current trend is maintained.

The Somo field, in Santander, is the part which has suffered most of the human pressure and its evolution is therefore strongly controlled by this factor. The first observation is that the extreme western part is migrating and receding toward the inner bay, as a consequence of the sediment supply pattern disturbed by the exertion of the harbor, located inside the bay and which is known to be active since the 18th century (Losada et al. 1991). Periodical dredging indeed of the main channel, whose average depth is 10-11 m depth (Flor Blanco et al. 2012) is needed to remove the sediments to allow the passage of ships. In Table 11 the data indicate the amount of sediment dredged by the bay of Santander for different periods, showing a very intense activity around the mid-20th century. Nowadays periodically a surface of 59,000 m² is dredged, with a volume ranging from 40,000 to 60,000 m³ (APS 2012). The sediments dredged are deposited then on the shelf in the open sea that later is transported by the currents toward the beach, in the eastern side (the accumulation sector seen in the profiles).

<table>
<thead>
<tr>
<th>Period</th>
<th>(x10⁶ m³)</th>
<th>(m³/yr)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1903-1905</td>
<td>1.54</td>
<td>0.77</td>
</tr>
<tr>
<td>1905-1960</td>
<td>13.85</td>
<td>0.25</td>
</tr>
<tr>
<td>1960-1989</td>
<td>7.60</td>
<td>0.26</td>
</tr>
</tbody>
</table>

*Table 11 Dredging data in the bay of Santander. Modified from CEDEX (2005)*

The Laredo field has dominant natural cause as well, since the estuarine environment has not experienced strong anthropogenic influence. The western portion reflects responses to the currents of the estuarine settings and despite the planted trees field it is not spared by retreating; the eastern side, exposed to the sea, is losing sediment in the northern side, but at the same time is gaining it in the south, due of the littoral drift.

Despite three study sites out of four seem to respond mainly from natural changes, the results indicate that the human presence is an important factor, able not only to change the morphology, but also the dynamic responsible of the formation of the coastal features. Provided that the first rough distinction of the responses of the dune fields described above is correct, the next step forward should be narrowing down which factors the coast is most sensitive to, in
order to have the right perspective in planning any kind of feasible interventions against erosion, but it is not easy task to have precise estimations of long term erosion rates (Galgano et al. 1998). As the factors involved are different and highly variable. Additionally this issue is not restricted to this area and beach erosion is a worldwide phenomenon, and the researches has been quite recently focused on single forces (Cooper & Alonso 2006; Slott et al. 2006; Zhang et al. 2004; Nicholls & Cazenave 2010) to improve the knowledge about their impacts in shoreline retreat.

In these studies globally present agents such as the sea level, variations in storm characteristics related to climate pattern and human pressure have been observed conditioning the evolution of the study areas, as expected. Local factors, that change their peculiarities regionally, such as precipitation amounts and river discharge, have minor impact.

Regarding the analysis carried out in this dissertation, it is hard to find a factor that is more dominant compare to the others.

Looking from a long term point of view, probably the most predominant is the sea level rise (Zhang et al. 2004) that, rather than causing directly coastal retreat, enables the high energy waves created during the occasional storms to reach more elevated heights and to provoke inundations and erosion that would alter the distribution of the sediment across and along the shoreface. An attempt to foresee the behavior of the coastline to the sea level rise in a simplistic way consists of the two dimensional model by Bruun (1962), that returns a scenario where there would be a shift landward and upward of the beach and where the sediment would be deposited offshore; this has been criticized however because of its scarce reliability because as a matter of facts the coastline settings are not homogeneous (Cooper & Pilkey 2004; Leatherman et al. 2000).

Episodic erosional events, such as storms, are affecting retreat rates in the short terms and their magnitudes are spatially and temporally variable (Masselink & Russell 2007); but it is quite clear that there will be a shift in their pattern due to the global warming on a decadal to centennial time scale (Slott et al. 2006), but this varies according the region considered.

The river discharge instead is not a so relevant factor even if usually fluvial processes influence the coastal dynamic as mentioned in the background section. Along the Cantabrian coast the rivers are relatively short and with seasonal character and are not marked by large amounts of solid transport.

Anthropization is mainly driving the dynamics involved in the sediment transport, and in minor part is affecting directly the dunes retreat (for example through sand extraction). Bruschi et al. (2013) brought forward a study about sedimentation rates in the north western area of Spain showing acceleration in the intensity of geomorphological processes, especially after World War II, due to human activities instead of causes driven by climate changes. As
consequence of these morphological changes, a rise in the hazards would occur according to these authors.

In conclusion, there are several factors influencing the evolution of both the dune fields and the coastal-marine environment. However, anthropogenic influence (urbanization, artificial modification of the environment for tourism or leisure activities, sand extraction etc) and sea level fluctuations were proven to be the two most prominent ones, actively affecting the morphology, behavior and evolution of the whole environment.
7. Conclusions

The northern Spanish coast has been affected during the cold season 2013-2014 by several intense storms that caused damages to the infrastructures and to the natural environment.

The gravity of the events raised concerns about future scenarios and it has questioned if the areas hit have already had similar experiences. Another source of discussion is the urban development that in this area started to increase after the Second World War and its relationship with the natural settings.

In this dissertation the Cantabrian coast has been studied and its exposure to different factors that are determining the dynamic and the morphological settings.

The evolution of the four sites associated with estuarine environment (Oyambre, Liencres, Somo and Laredo) considered here, shows that they act quite differently but still there are some common changes. The methodologies used comprise the use of aerial photographs and orthophotos that in total cover a time span of 58 years (from 1956 to 2014) that were handled through ArcGIS.

The results show that maximum expansion of the dune fields occurred toward the end of the 20th century. After that cyclical processes characterize this coast; however as a whole they have a negative trend, with an average recession rate below 1 m yr⁻¹. It is quite clear then that the dune fields are undergoing erosion by either natural or anthropogenic factors, sometimes intensely as happened after the last storm event.

The analysis carried out brought to light the interplay between natural forces and in particular the sea level change, and artificial interventions such as constructions and sand extraction; from the surface data it is clear that in each site the natural area is less than 30% compare to the original state (in Oyambre even 4%). Determining the most important factor however is not easy task. It has been observed two types of response from the dune fields and, in general, of the coastline: natural as it is the case of Oyambre, Liencres and Laredo, where, despite the clear human presence, the coast is shaped in the long term by the sea level rise and by storm waves in the short term; artificial, as it is the case of Somo, where the influence of the anthropogenic activities, especially intensive dredging in Santander Bay, are predominant and responsible for the migration and thinning of the spit.

This rough distinction should be the starting point for a deeper and more spatially extended research about what is really needed in each context. Even though some measures to prevent erosion have already been taken in the last decades, the recent storms highlighted some atmospheric pattern that in the long term would require more knowledge to make more suitable plans in preventing flooding events. A potential sequel for this work could be new research projects for deeper understanding of some mechanisms of these systems or for eventual protection plans.
8. Acknowledgments

This work could not have been accomplished without the help of some precious sources.
In the first place, the academic publishing company Elsevier for the permission of reusing published material in my dissertation.
I would like to thank the Regional Ministry of Presidency and Justice of the Government and the Regional Ministry of Livestock, Fisheries and Rural Development of Cantabria, that furnished with courtesy aerial photographs otherwise not available.
I would like to say thanks to Dr. German Flor Blanco, to his father Prof. German Flor Rodriguez and to the staff of Oviedo University for letting me work with them in the field of the beach erosion in Spain.
I would like to say thanks to Dr. Rickard Pettersson for having the patience at the beginning...and at the end of this work to answer to my mails in which all my fears were expressed.
I would like to say thanks to the persons that, despite the distance, have not forgotten to send me smiles and incitements (and corrections!) or to remind me my similarities with the bees (small but dangerous).
I would like to say thanks to my family that has always encouraged me in all my experiences and all my travels, teaching me that life is a beautiful adventure.
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Appendix 1

Maps of the dune fields, as presented in the Results chapter. The areas of Somo and Laredo, due to their large extent, have been divided in smaller areas, marked by numbers, to better appreciate the lines.

Oyambre-La Rabia
Liencres
Laredo

North (Regatón-El Puntal-La Salvé)

Legend:
- profiles 2002
- 2014
- 2010
- 1988
- 2007
- 1970
- 2005
- 1996
Center (Regatón-La Salvé)
South-East (La Salvé)
Appendix 2

In this section environmental evolution maps of the years 1956, 1970, 1988, 2001, 2002, 2005, 2007, 2010 and 2014 are collected for each study site, following the same order of presentation used in the results chapter.
Oyambre-La Rabia

<table>
<thead>
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<th>Year</th>
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<th>Anthropogenic</th>
<th>Total</th>
</tr>
</thead>
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<td>91,662.50</td>
<td>-</td>
<td>91,662.50</td>
</tr>
<tr>
<td>1970</td>
<td>89,955.44</td>
<td>-</td>
<td>89,955.44</td>
</tr>
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<td>Total [m²]</td>
</tr>
<tr>
<td>------</td>
<td>--------------</td>
<td>--------------------</td>
<td>------------</td>
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</tr>
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<td>17,176.06</td>
<td>81,644.58</td>
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<td>Anthropogenic [m²]</td>
<td>Total [m²]</td>
</tr>
<tr>
<td>------</td>
<td>-------------</td>
<td>-------------------</td>
<td>------------</td>
</tr>
<tr>
<td>2002</td>
<td>14,638.51</td>
<td>81,335.51</td>
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</tr>
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</tr>
<tr>
<td>------</td>
<td>-----------</td>
<td>---------------</td>
<td>----------</td>
</tr>
<tr>
<td>2007</td>
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<tr>
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<td>Natural</td>
<td>Anthropogenic</td>
<td>Total</td>
</tr>
<tr>
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Liencres

<table>
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<td>-</td>
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<td>----------</td>
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</tr>
<tr>
<td>------</td>
<td>-----------</td>
<td>---------------</td>
<td>-----------</td>
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### Areas [m²]

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<td>1,291,761.12</td>
<td>1,709,597.28</td>
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<td>446,003.367</td>
<td>1,303,056.3</td>
<td>1,749,059.67</td>
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<tr>
<td>Year</td>
<td>Natural</td>
<td>Anthropogenic</td>
<td>Total</td>
</tr>
<tr>
<td>------</td>
<td>-----------</td>
<td>---------------</td>
<td>-----------</td>
</tr>
<tr>
<td>2014</td>
<td>445,521.749</td>
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Somo and Somo-Loredo

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</tr>
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La Salvé-El Puntal – Regaton

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