Coastal erosion in NW Spain: recent patterns under extreme storm wave events

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ABSTRACT

Coastal dunes are sensitive to both anthropic and natural processes of erosion. In this study, we analyse the geomorphic changes in 15 dune-fringed coastlines of Asturias (NW Spain) for the period 1992 to 2014 to determine specific drivers of erosion. Coastline migration patterns were obtained using geospatial analysis of vertical aerial images and field surveys. The annual and maximum wave energy, maximum significant wave height, duration and number of storm events were determined for each climatic year by using available wave data from both recorded buoy data (1997-2014) and the WAM numerical model (1956-2015). The study shows that since 2006, coastline retreat has significantly accelerated along the Asturias coast. In particular, severe erosion of sandy beaches and dunes occurred in 2013/14, reaching up to 40 m of coastline retreat and destroying numerous ports and seafront promenades. Increased frequency of unusually strong storm waves, with significant wave height (H_s) exceeding 9 m, together with an unusual 5º westward variation from the mode in offshore wave approach direction during these storms, appear to be the main catalysts in heightened erosion capacity of storm waves in the 2013/14 period. This resulted in the removal of small dune areas and a severe recession in the easternmost part of the largest (natural) dune fields in the region. Under these stormy periods, foredunes and climbing dunes developed notably pronounced escarpments and blowouts, with sand subsequently relocated into the foreshore and backshore zones. This study demonstrated that increased frequency in powerful storm events (H_s > 9 m) and an alteration in storm approach direction, can lead to significantly enhanced erosion of dune coastlines, even along those that are modally-attuned to high energy events.

Keywords: coastal dunes, coastline retreat, climate change, storm frequency, storm approach angle.

1- INTRODUCTION

Morphological changes in the coastal zone are the result of complex interactions between natural and anthropogenic processes, operating over various spatial and temporal scales (Ruggiero et al., 2005; Crapoulet et al., 2015, Jackson and Short, 2020, Short and Jackson, 2021). These processes can act within short (event) time scales, such as storm wave events (Castelle and Harley, 2020), or longer cyclical periods, such as tidal forcing, seasonal variations in wave climate (Senechal and Ruiz de Alegría-Arzaburub, 2020), and inter-annual to decadal-scale variations in the ocean-atmosphere system (Nordstrom, 1980; Aubrey and Ross, 1985; Zoulas, 2008; Yates et al., 2009b). They can also exist over even longer timelines as with Relative Sea Levels (Trindade and Ramos-Pereira, 2013).

Over short time-scales, beach morphodynamics are typically controlled through seasonal weather patterns (Fontán-Bouzas et al., 2009; 2019; Senechal and Ruiz de Alegría-Arzaburub, 2020). In these scenarios, a close relationship usually exists between morpho-sedimentary changes and the energy of the incident waves, with storm waves normally inducing rapid coastal erosion, while beach rebuilding during calm weather is much slower (Davis and Fox, 1972; Wright and Short, 1984, Castelle and Harley, 2020). Storm waves can also exhibit pseudo-cyclical patterns of change over shorter intervals, varying from a few days to over several weeks (Nordstrom, 1980).

Sandy beaches can be particularly vulnerable to storm wave events (Fenster et al., 2001; Fontán-Bouzas et al., 2009; Cid et al., 2016, Castelle and Harley, 2020) and many studies have attempted to model the impact of coastal storm events, with a focus largely on the response of sand beaches to storms (Lee et al., 1998; Dail et al., 2000; Hill et al., 2004; Cooper et al., 2004; Von Storch and Woth, 2008; Yates et al., 2009a, Guisado-Pintado and Jackson, 2018; 2019, Anfuso et al. 2020). Within the embayed Asturian coast (NW Spain), sediment supply is not provided from longshore drift sources, and instead largely originates from local riverine sources (Fig.1).

INSERT FIGURE 1

Coastal dunes play a key role in stabilising the coast, acting as an essential sedimentary reserve for beaches, particularly during intense storms and very high tides. Dunes are therefore an important source of sediments with which to regenerate beaches from (Hesp, 2002, 2011; Hesp and Smyth, 2016). The sedimentary thickness of coastal dunes is strongly related to sand availability on beaches (Fontán Bouzas et al., 2013) and the evolution of beaches and dunes is therefore strongly inter-related (Short and Hesp, 1982; Hesp, 2011), with dune behaviour directly forced by storm wave events.

Human activities also modify the evolution of coastal areas (Alonso et al., 2002; Augustinus, 2003), often triggering significant changes (Rodríguez-Ramírez et al., 2008; Flor-Blanco et al., 2015a; Flor et al., 2015, Hernández-Cordero et al., 2018), which ultimately affect coastal retreat dynamics (Ruz et al., 2005). The Intergovernmental Panel on Climate Change (IPCC) predicts that climate change will magnify extreme events (Church et al., 2013). Vousdoukas et al. (2015) have shown the interaction between storm surge levels and the increases in relative sea level, while Plomaritis et al. (2015) purport that large-scale atmospheric phenomena are the main cause of diversity in recent storm patterns.

Sea-level also plays an important role in promoting the retreat of most of the world's shorelines, particularly along dune-fringed coasts (Carter et al., 1990, Carter, 1991). Between 1961 and 2008, secular sea level rose by 1.8 ± 0.4 mm yr^{-1}, and is expected to continue to rise (0.5 to 1.0 m) until 2100 and beyond (Church et al., 2013). The global trend published by IPCC (2014) shows projected rates of around 3.2 and 3.4 ±0.4 mm y^{-1} and Vousdoukas et al (2017) reforced this idea which consider that future extreme levels along Europe's coastlines is on average projected to increase by 57 cm, taking into account to the changes in storm surges and waves enhance the effects of relative sea level rise along the majority of northern European coasts and lees in the south. Moreover, different effects of climate change, such as the global sea level rise and the changes in the regional storm climate and the atmospheric circulation patterns are expected to increase in the future in the Spanish coast (Rasilla et al., 2018)

Exceptionally intense storm wave events in recent years have increased awareness of the frequency, impact, and roles of storms in the European Union (Cooper et al., 2004; Ciavola et al., 2011; Rangel-Buitrago and Anfuso, 2013; Loureiro et al., 2014; Guisado-Pintado and Jackson, 2018; 2019; Anfuso et al., 2020), the barrier islands of the Eastern United States (US) (Anthony, 2013), and in East Asia (An et al, 2018).

Strong winter storms in February and March 2014 adversely affected European Atlantic shorelines, causing significant impacts on economies, society and the environment, with recent research on this focusing mostly on the north Atlantic coast (Carretero et al., 1998; Goldenberg et al., 2001; Komar and Allan, 2008; Chaaban et al., 2012; Rangel-Buitrago et al., 2016; Masselink et al., 2016; Castelle et al., 2017), and on the Iberian Peninsula

(Rasilla et al., 2014; Flor et al., 2014; Plomaritis, et al., 2015; Cid et al., 2015; Flor et al., 2019).

The current study analyses the geomorphological evolution of 15 dune-fringed coastal stretches of Asturias between 1992 and 2014 (Fig. 1), and the relationship between this evolution and the regional storm wave pattern. The work centres on the exceptionally large storm waves of the 2013/14 climatic year, in order to examine the severe erosion patterns that resulted.

2- REGIONAL SETTING

The Asturian coast, located on the NW Iberian Peninsula, is a mostly cliff-type coast. Its geomorphologic evolution is controlled by both the lithology and its structural arrangement, with a general West to East alignment, although various sections are oriented NW-SE and NE-SW (Flor and Flor-Blanco, 2014a). The coastal hinterland has a relatively smooth relief due to several old erosive flat surfaces that are positioned at various heights (Flor and Flor-Blanco, 2014a; Domínguez-Cuesta et al., 2015, López-Fernández et al., 2020). In addition, it is one of the most natural coasts of the Iberian Peninsula and has been afforded several conservation protections including Sites of Community Interest (SCI), as well as many wetlands and estuaries classed as Special Protection Areas (SPA).

The most frequent wave approach directions on the inner continental shelf are from the first and fourth quadrants, with waves coming from the NE in fair weather and waves from the NW during storm events. Offshore significant height (H_s) is usually greater than 1.7 m, with the highest H_s recorded at the Peñas buoy since 1998 being 23.3 m (Flor et al., 2014a). The tides affecting the Cantabrian coast (Bay of Biscay) are semi-diurnal, and average ranges are generally meso-tidal (2-4m) for 68.52% of the year.

Sandy, embayed beaches are prevalent, with their siliciclastic sediments originating from the mountain and lowland coastal rivers, but bioclastic carbonate fractions also appear in many coastal sectors (Flor et al., 1982). Many Asturian beaches are sheltered and generally protected from the NW waves, such as those generated east of Peñas Cape (Flor, 1978) or locally bounded by large headlands and high cliffs slopes.

Sandy beaches with abundant sand sources have formed large dune fields close to wide estuaries or those linked to the eastern side of the mouths of the major (Eo, Navia, Nalón, and Sella) and minor (Aboño, Piles, Linares, Libardón, and Espasa) river systems (Fig. 1; Flor and Flor-Blanco, 2014b). The orientation of the dunes is associated with the NW and NE prevailing wind directions, although the SW winds are dominant (Flor and Flor-Blanco, 2014b).

3- METHODOLOGY

3.1. Wave data analysis

The local wave regime data was derived from both offshore buoys and the WAM numerical prediction model (Puertos del Estado. Government of Spain). Wave data from Estaca de Bares (44.12°N, 7.67°W; 1800 m water-column depth, 41 kilometres from the coast, 01/01/1996 to 02/02/2015) and Cabo de Peñas (43.75°N, 6.16°W, 615 m water-column depth, 20 kilometres from the coast, 06/09/1997 to 30/01/2015) buoys (Deepwater Buoy Network) were examined (Fig 1). These wave data were initially recorded in 3-hours intervals, but have been recorded in 1-hour intervals since January 1998. Secondly, the wave database (1958-2015) from the offshore 1052075 SIMAR point was obtained by the WAM wave prediction model in 1-hour intervals. Significant wave height (H_s), maximum wave height (H_{max}), peak period (Tp) and wave approach direction were considered from both wave databases. Additionally, for 2014, tidal records from Musel Port (Gijón) and wave records from a buoy located at Cudillero (43.60°N, 6.13°W) were also obtained.

The beginning of a storm event was considered when offshore Hs overtopped 3 m and its duration determined by the successive hours over this critical value. Based in the Airy

Theory, the total energy (J m^{-2}) for each storm event was determined after the n successive Hs_o (m) values during the event, and in consideration of the number of waves that occurred each hour after the Tp (s). This is expressed in the following equation:

$$E_T = \frac{1}{2}\rho g \sum_{i=0}^{n} Hs_{o_i}^2 \left(\frac{60}{Tp_i}\right) \qquad (1)$$

Where E_T is the total energy of the storm event, ρ is seawater density, g is gravity acceleration, H_{si} is the offshore significant wave height for the i hour, with a total duration of the storm event of n hours, and T_{pi} is the associated peak period for the hour i.

Sea state curves were plotted for each buoy, but statistical analyses of these data series were not used because they contained too many gaps. In contrast, the wave database obtained from the numerical model allowed the determination of seven parameters for each climatic year (beginning July 1st and ending the following June 30th): i) maximum H_s; ii) maximum energy of a storm event; iii) number of storm events; iv) total duration of the storm events; v) maximum duration of a storm event; vi) average duration of storm events; and vii) total annual energy. Finally, directional histograms were plotted using Grapher of Golden Software Package for all storm wave events (Hs>3m) and only for extreme storm wave events (Hs>7m), considering both the entire study period (1958-2015) and only the climatic year 2013-2014.

3.2. Coastline evolution pattern

The recent coastline evolution patterns (1992 to 2014) of 15 dune fields in the Asturian coast (Fig. 1) were assessed through the analysis of vertical aerial images (1992 and 2001), ortho-photographs (2006, 2009, 2011 and 2014) and field measurements in Spring 2015.

Google Earth and Bing Maps images were used for reviewing satellite photographs. The images were included in a Geographic Information System (GIS) and georeferenced by rectification with a rubber-sheeting process using checkpoints on vector topographic maps with the ArcGIS (ESRI) software tools. To calculate RMS error, each image was independently georeferenced based on the 2014 orthophoto mosaic and ground control points derived from buildings and parcel boundaries. The RMS error achieved was less than 0.5 m.

Recent frontal limits of all dune fields were measured during the spring and summer of 2014 using a Leica Disto D5 laser distance meter and a GPS to validate the progradation or erosion rates from contemporaneous orthophotographs and to assess the effects of the exceptionally strong storm waves of February and March 2014.

Finally, the effects of storm waves in the geomorphological evolution of the Asturian coastal dune over a period of more than two decades were obtained by combining the analysis of the shoreline changes with corresponding wave patterns. For this analysis, net seaward advance and landward retreat of the frontal dune line were calculated by considering three cross-shore profiles for each dune field (WP= Western profile, CP= Central profile, EP= Eastern profile), by comparing aerial photographs/orthophotographs and field measurements since the last decade of the 20th century with field measurements during 2014. All profiles were selected from locations where information on their historical evolution was known, avoiding heavily modified/managed areas.

4. RESULTS

4.1. Wave and tidal forcings

The wave databases recorded by the Estaca de Bares and Cabo de Peñas buoys (Fig. 1) show that the winter of 2013-2014 had the highest number of extreme storm wave events (Hs>7m) of the entire 22-year study period, although some small differences between both wave records were observed (Fig. I, supplementary material). Nevertheless, the data series presented gaps of 30.99% and 17.37% at Estaca de Bares and Cabo Peñas, respectively. Therefore, results from these buoys were considered unreliable.

The analysis of the wave database from the WAM model, without gaps, shows that compared with previous decades, the period 2000-2005 corresponded to a low energy phase. Subsequently, since 2006, storm wave events again became more energetic and recurrent (Fig. 2).

INSERT FIGURE 2

A window of low energy was identified in the period 2000-2005, particularly for the climatic year 2004-2005, with a decrease in the total number of storm events, total duration, maximum duration, total annual energy and maximum energy of the storms. These fair weather conditions were in consonance with storm conditions in previous decades, and since 2006 storm energy increased again (Fig. 2; Fig. I, supplementary material).

The wave database from the WAM model also confirms that the period 2013-2014 was particularly energetic. However, it was not overly different to some previous years for some parameters. Thus, considering all storm wave events (H_s> 3m), similar values of total annual energy occurred in 1959-1960, 1976-77, and 1994-95, and the total annual energy was clearly highest in the years 1960-1961, 1971-72, 1977-78, 1982-83, 1983-84, and 1993-94. 2013-14 did not represent a year with the strongest storm event nor the maximum H_s. The average energy was not any higher in this year in comparison to other years, and neither the average duration of storms and maximum duration of a storm was especially higher compared to all other years in the study period (Fig. 2).

Considering the storm frequency after Hs intervals however, it can be observed that 2013/14 had an unusual abundance of storm waves with a H_s > 9 m, only surpassed by 1982/83 (Table 1). Therefore, 2013/14 was in the top 5% of all years recorded after the occurrence of extreme storm waves (H_s > 9 m), i.e. the key to the erosional power of

2013/2014 was not the occurrence of storm events with H_s>3m, but the high number of *extreme* storm events with H_s > 9 m.

Range of Hs (m)	1958-2015	1960-1961	1971-1972	1977-1978	1982-1983	1983-1984	1993-1994	1994-1995	2013-2014
3.1-4.9	81.14	84.01	78.52	71.49	80.13	70.43	77.99	74.76	81.94
5.0-6.9	15.25	14.80	17.15	21.19	14.98	26.18	19.23	22.39	15.65
7.0-8.9	3.22	1.12	3.97	7.33	3.94	3.20	2.78	2.85	1.91
9.0-10.9	0.35	0	0.36	0	0.79	0.19	0	0	0.50
11.0-12.9	0.04	0	0	0	0.15	0	0	0	0

Table 1. Percentage distribution of storm wave events obtained from the WAM numerical model for the whole period (1st July 1958 - 30th June 2015), and for the nine climatic years with highest total annual energy.

Another noteworthy observation is that the typical wave approach direction for storm events was on most occasions from the north-west for the entire study period, however during 2013/14, a small change (5º westward from the mode) occurred. This change in wave approach direction is much more evident only during extreme storm waves (Fig. 3). Buoy data also picks up this directional change in wave approach angle, previously undetected for this period. This change in offshore approach direction under storm wave scenarios implicates variations in the wave propagation patterns and incidence angle as being more impactful for coastal dune-beach systems.

INSERT FIGURE 3

The storm surges (meteorological tides), associated with low atmospheric pressure systems and astronomical tides had an adversely effect, increasing the destructive effect of storm waves. Indeed, the storm wave events on February 1-2 and March 3-4, when the State Port buoys detected H_s> 11m, coincided with high spring tides, reaching up to 4.61 m of tidal range (Table 2).

The recurrence of this type of strong storms over the last 20 years is remarkable, as between 1998 and 2015 there have been up to 36 storm events of Hs>7m, while between 1956 and 1998 there were only 2 (Source: Buoys-Puertos del estado. Ministerio de Fomento). This trend has continued until 2020.

CABO PEÑAS BUOY (43.75°N, 6.17°W)	
01-02/02/2014	03-04/03/2014
MAXIMUM HEIGHT (m)	
11.3	11.7

01-02/02/2014			
HIGH TIDES		**LOW TIDES**	
(h/m)	(h/m)	(h/m)	(h/m)
04:58/4.79	**17:22/4.40**	**11:07/0.18**	**23:34/0.33**
RANGE: 4.61 m		RANGE: 4.07 m	

02-03/03/2014			
HIGH TIDES		**LOW TIDES**	
(h/m)	(h/m)	(h/m)	(h/m)
04:38/4.70	**16:58/4.40**	**10:44/0.15**	**23:02/0.24**
RANGE: 4.55 m		RANGE: 4.16 m	

Table 2. Maximum significant height (m) recorded in Cape Peñas buoy and tidal ranges (m) recorded in Musel Port (Source: Puertos del estado. Ministerio de Fomento).

4.2. Dune coastline evolution

The Asturian dune fields are characterised by having formed between rocky promontories on a cliffed coast. According to Flor et al. (2011), the predominant morphologies are sand-sheet, climbing, tongue-like, with the most extensive being those associated with estuary spit barriers (Quebrantos, Salinas, Rodiles and Vega) or adjacent to estuary mouths such as Xagó (Fig. 4). In the latter, significant foredune morphologies are clearly evident. In all of the dune coastlines examined, five have been previously altered through anthropogenic activities (jetties or partial occupation), mining activity, and in some cases, dredging and dumping from ports. All other stretches are smaller, except for Vega, and represent natural sites (Fig. 4).

INSERT FIGURE 4

4.2.1. Shoreline behaviour and dune area changes at human impacted sites

In the case of Navia, between 1992 and 2011, during the last decade of the 20th century, dunes were eroded on their western (-3.56 m) and eastern sides (-8.26 m). Shoreline recovery between 2001 and 2006 had rates of 0.70 m yr^{-1} (3.52 m) in West Profile (WP), 1.28 m yr^{-1} (6.39 m) in Central Profile (CP), and 1.57 m yr^{-1} (7.86 m) in East Profile (EP). Since this year, recession was common throughout the dune front until the winter storms of 2014. In 2009, changes were observed in dune front position with recessions of -0.95 m in the west and -0.10 m in the east; nevertheless, the central parts of the dunes prograded (1.41 m). Recession rates between 2011 and 2014 were -1.56 m yr^{-1} in WP and with a maximum of -0.59 m yr^{-1} in CP and EP (Figs. 4 and 5), with a general surface loss of 1,194 m^2 (Fig. 5; Table I, supplementary material).

INSERT FIGURE 5

Similarly, the Quebrantos dune field is part of the confining barrier of the Nalón estuary. Between 1992 and 2001, the system prograded (1 m yr^{-1} in WP, 1.52 m yr^{-1} in CP, and 1.91 m yr^{-1} in EP), but the surface was reduced at the end of the 1990s due to the removal of the eastern sector by the construction of a car park (Flor-Blanco et al., 2015a). The continued progradation occurred until 2006, but to a lesser extent (Fig. 4 and 5; Table I, supplementary material). Since then, recession began with rates of around -0.90 m yr^{-1} (-2.71 m) until 2009 (Table I, supplementary material). In the next photograph (2011), the dune front retreated -3.0 m yr^{-1} (CP), -1.21 m (EP), and recovered 0.38 m (WP). Therefore, in last strongest storms in 2014, the recession was higher than it was in 2011, mainly in the western region with between -16 m and approximately -11 m on the rest of the dune front (Fig. 4 and 5; Table I, supplementary material).

Salinas-El Espartal dune field has been eroding since the 1970s and became more pronounced in the 1990s and in 2014 due to surge events (Fig. 6). The calculated recession for the period 1992 to 2014 is 32.20 m (-1.43 m yr^{-1}) in the western part, 31.57 m (1.43 m yr^{-1}) in central areas, and 10.23 m (-0.46 m yr^{-1}) in the east, with an estimated loss of 121,404.65 m^2 surface area (Table I, supplementary material). This was caused by the growing human occupation and the retreat of the dunes' front (Fig. 4).

Up until 2014, some parts of the Salinas-El Espartal dune field, like in other systems, showed averaged erosion values of 20 m (-1.05 m yr^{-1})(WP), 18.56 m (-0.97 m yr^{-1}) (CP), and 19 m (-0.32 m yr^{-1}) (EP) (Figs. 4 and 5; Table I, supplementary material). However, the storms of 2014 caused clear erosion of the coastline, less in the eastern sector as a result of sedimentary accumulation due to beach drift in this direction. Results show a maximum recession of -12.20 m in WP, -13.01 m in CP, and -4.03 m in EP (Figs. 4 and 5; Table I, supplementary material). This dune field was one of the most impacted by this event, including the west jetty of the Avilés Estuary mouth and the seafront promenade of Salinas (Flor et al., 2013).

The Xagó system has on the other hand prograded since the 1980s, with intervening short erosive periods (Figs. 4, 5 and 6), some of which are visible in the rest of the Asturian coast dune systems, with a surface area increase of 1,628.43 m^2 yr^{-1} since the 1980s through to 2006, when it reached its maximum extent of 455,120 m^2 (Figs. 4 and

5; Fig. I, supplementary material). This was mainly due to discharges of dredged material from the Avilés estuary. This increase was more significant in the central and eastern parts, with 39.46 m (1.72 m yr^{-1}) recorded in CP and 36.64 m (1.6 m yr^{-1}) in EP, while in WP, rates were only 8.12 m (0.35 m yr^{-1}) (Table I, supplementary material). It is worth noting that, despite contributions from sediment dredging, dunes are currently experiencing an erosive period in the western and central areas (Flor-Blanco et al., 2013). Between 2006 and 2009, the western and central fringes decreased 12.48 m (-4.16 m yr^{-1}) and 4.70 m (-1.57 m yr^{-1}), respectively; but since 2009, the foredune in general recovered, although it receded 2.27 m specifically in the western part (Figs. 4 and 5; Table I, supplementary material). Since 2011, the seaward most foredune has been decreasing substantially (Figs. 5 and 6).

The storms during the winter of 2014 resulted in significant foredune erosion in all sites, with a maximum of -6.48 m in the western area, a minimum of -2.91 m in the eastern sector, and similar amounts in the central part of the foredune (Figs. 4 and 5; Table I, supplementary material). Small tabular dune in the easternmost has disappeared and the upper beach, like the other studied dune fields, also lost sand, inducing a scarped dune frontage.

Rodiles dune field (Villaviciosa estuary, Fig. 4), up until 2001, showed a recession of -2.78 m in WP (-0.40 m yr^{-1}), -7.41 m in CP (-1.06 m yr^{-1}), and 9.89 m in EP (1.41 m yr^{-1}). Between 2000 and 2011, the dune surface increased 14,145.11 m^2 (1,414.51 m^2 yr^{-1}) with a recovery of sand area to an extent similar to 1970 (Flor-Blanco et al., 2015a) which was probably helped by management intervention restricting access (Flor et al., 2015). However, the erosion trends began to change since 2011, especially in the winter of 2014, when the recession was focused in the foredune of EP (-14.54 m) and to a lesser extent in WP (-0.93 m) and CP (-0.78 m) (Figs. 4 and 5; Table I, supplementary material).

In general, the dune recession in these dune fields has been contrasted with the reduction of their surface, already undermined by the anthropic occupation (Fig. 6)

INSERT FIGURE 6

4.2.2. Shoreline behaviour and dune area changes at natural sites

The 1990s was a significant erosive period in most natural dune systems and in other similar cases outlined below (Fig. 4 and 7; Table II, supplementary material). Barayo presents the most erosion, with a decrease of 6,742 m^2 (749.21 m yr^{-1}). However, the Vega system lost 6,456 m^2 (717.36 m^2 yr^{-1}) in the early twenty-first century (Figs. 6 and 7; Table II, supplementary material). One particular case is La Isla Beach, where the progradation process began in the 1990s, increasing by 2,404 m^2 (171.78 m^2 yr^{-1}) until 2006. In last decade of the twentieth century (1992-2001), the maximum recession took place in Mexota (-3.92 m/-0.44 m yr^{-1}), Sarello (-24.54 m/-2.73 m yr^{-1}), Frejulfe (WP, -0.56 m/-0.06 m yr^{-1}), Carniciega (-1.56 m/-0.09 m yr^{-1}), Espasa (WP, -4.20 m/-0.47 m yr^{-1}), and Vega (CP, -17.28 m/-1.92 m yr^{-1}). However, other dune systems experienced progradation during this time including: Peñarronda (23.27 m/2.59 m yr^{-1}), Frejulfe (EP, 10.65 m/1.18 m yr^{-1}), Barayo (12.1 m/1.34 m yr^{-1}), Otur (6.23 m/0.69 m yr^{-1}), La Isla (20.35 m/2.26 m yr^{-1}), Espasa (EP, 3.96 m/0.44 m yr^{-1}), and Vega (EP and WP, 8.58 m/0.95 m yr^{-1}) (Fig. 7; Table II, supplementary material).

After 2006, a second progradation period occurred in some dune fields with different durations and magnitudes (Figs. 4, 6 and 7). The dunes of Peñarronda, Sarello, Frejulfe, Otur, the western part of Isla, Espasa and Vega all prograded between 2001 to 2006 with values ranging from 20.28 m (4.06 m yr^{-1}) to 4.09 m (0.81 m yr^{-1}) (Fig. 7. Table II, supplementary material). Other dune fields featured by recession beginning in 2001 or before, such as Mexota (-2.46 m/-0.49 m yr^{-1}), Barayo (-4.13 m/-0.83 m yr^{-1}), Carniciega (-1.79 m/-0.30 m yr^{-1}) and the eastern part of Isla (-1.51 m/-0.30 m yr^{-1}) (Figs. 4 and 7; Table II, supplementary material).

INSERT FIGURE 7

However, Barayo and Carniciega began retreating before this period. At 2001 and 2014, the surface decrease was of 10,302.49 m^2 (792.49 m^2 yr^{-1}) and 5,151.18 m^2 (396.24 m^2 yr^{-1}), respectively (Fig. 7; Table II, supplementary material). Another case is Mexota, because the erosion began in 1992 with a recession of 8241.04 (-374.59 m^2 yr^{-1}). The same patterns occurred on the eastern side of La Isla, Espasa, and Vega (Figs. 4 and 7; Table II, supplementary material). Since 1992, dune recession has been widespread for these dune fields, repeating this pattern in intervals between 2006 and 2011 and again between 2011 and 2014.

Dune fronts have also experienced progressive erosion since the 2009 photograph, with different behaviours shown depending on the dune field studied. The maximum erosion until 2014 is highlighted in Sarello (-17.9 m/-3.58 m yr^{-1}), Frejulfe (-28.04 m/-5.68 m yr^{-1}), Barayo (-18.48 m/-3.69 m yr^{-1}), and Otur (-38.73 m/-7.74 m yr^{-1}). The most important recession occurred in the storms of 2014 and other systems, such as in Peñarronda, Carniciega, and Vega, have all decreased their surface extent (Figs. 4 and 7; Table II, supplementary material). All of these dunes experienced progressive erosion (Fig. 6) which has been attenuated until today

4.3. Specific dune behaviour during the 2013/14 storm period

During the winter of 2013/14, the Cantabrian coast was negatively impacted by frequent high-energy storm wave events, which caused extensive damage to infrastructure and civil works (Flor et al., 2014). These storms produced the erosion of the beach-dune systems, affecting mainly the upper intertidal beaches, the fronts of the dune fields, and surface berms, promoting strong remobilisation of sediment in the nearshore. Authorities have estimated the total cost of cleaning and repairing the damage to be more than 40 million euros (Rasilla et al., 2014).

In total, four particularly energetic episodes of storm waves occurred. The first was in mid-December 2013 and early January 2014, which did not cause major damage. In early February, another storm caused significant damage due to the combined effect of strong westerly winds, offshore waves of up to 11.3 m and spring high tides of 4.61 m (Table 2). The final and most damaging storm event occurred on the night of March 3rd and 4th. A combination of Atlantic swell waves, local sea wind and spring tides (Rasilla et al., 2014; Flor et al, 2014) lead to a heighten episode of erosion. Strong winds with severe gusts and high offshore waves resulted in a major impact on the coastline;peak gusts exceeded the threshold, which refers to speeds above 120 km h^{-1} for a period of 3 seconds.

INSERT FIGURE 8

The temporal behaviour of the dune dynamics can be explained by the evolutionary models of Hesp (2002). On the one hand, the model best represented is one in which the dune systems had erosion in the dune front (from the centimetric to metre scale), along the entire dune field, or in localised sections (Figs. 8 A and B). Such erosion occurred in Mexota (Fig. 9A), Sarello, Frejulfe, Barayo (Fig. 9C), Otur (Fig. 9D), Quebrantos, Salinas (Fig. 9F), Xagó, Carniciega (Fig. 9G), Rodiles (Fig. 9E), La Isla, Espasa, and Vega (Fig 9H) dune fields. In addition, dune fields where landward migration took place are well differentiated (Fig. 8C), as noted in Peñarronda, Navia (Fig. 9B) and at the eastern end of Xagó with the aeolian advancement of sand bodies. Other small dune fields, such as Anguieiro (Fig. 1), have been completely eroded (not included in this study).

INSERT FIGURE 9

The maximum erosion value for dune retreat was measured at Sarello, with an average recession of 40.61 m in WP, where the foredune was largely destroyed. Other systems also significantly damaged included: Otur, undergoing a maximum retreat of 30 m; Barayo, with regression of 18 m and 13.63 m (WP and CP, respectively); and Salinas-El Espartal which showed a maximum in WP and 2.55 and 11.57 m of recession in CP and EP (Fig. 10). In all these cases very steep vertical slopes were generated, in some cases reaching 5 metres in height. In proportion, the incident swell caused steeper slopes in the eastern sectors, which have even had worse recovery later on.

Systems where a landward sediment migration was evident by sandy sheets or washover fans, experienced less erosion. For example, Navia, which suffered a recession of between 4.68 m in EP and 1.72 in WP and CP (Table I, supplementary material), Mexota, with 3.40 m, and Xagó, which varied between 6.48 m and 2.91 m in WP and EP, respectively (Fig. 10; Tables I and II, supplementary material).

INSERT FIGURE 10

5- DISCUSSION

The Asturias coastline is a high-energy, wave-dominated system that, over the last half-century, has experienced a series of particularly strong storm wave events, especially during the years, 1959-60, 1960-61, 1971-72, 1976-77 1977-78, 1982-83, 1983-84, 1993-94, 1994-95, and more recently in 2013-2014. (Table 1). In contrast, from 2000 to 2005 they have experienced a more quiescent period, promoting an accretionary phase along most of length (Figs. 4, 5 and 7).

Estuaries are the main suppliers of sediments for the formation of dunes on the Asturian coast, resulting in the most extensive dune fields located near river mouths. The most obvious case is the Nalon river, which is the most important riverine source of sediment to the Asturian coast (Flor-Blanco and Flor, 2019, García-Ordiales et al, 2020).

Prior to anthropogenic impacts during the 20th century (Flor-Blanco et al, 2015a), all anthropized dune fields in Asturias were supplied by large riverine sources. Some such as the Salinas-El Espartal and Xagó systems, grew as a result of a prograding phase since the Flandrian (MIS 1) high stand sea-level, and subsequently by a sea-level fall according to three different stages of evolution (Flor-Blanco et al., 2016). However, those dune fields affected by the construction of jetties recorded considerable progradation in subsequent years (Flor-Blanco et al., 2015a), as opposed to natural shorelines which progradedmore slowly.

5.1 Shoreline change

During 20th and 21st centuries, natural dune shorelines in Asturias presented two periods of erosion and progradation. As such, Peñarronda, Mexota, Sarello, Frejulfe, Barayo, Otur, Aguilera, Espasa, and Vega (Fig. 7) showed gradual erosion over several decades (Flor-Blanco et al., 2019).

Despite the distinct differences in evolutionary behaviour between natural and human-modified dune fields during the last decades, similar erosional episodes are still apparent (Fig. 11), including a similar morphologic response of the dune front, in terms of triggering vertical erosive slopes or washover lobes. The initial erosive phase occurred between 1980 to the 1990s (Flor et al., 2019) followed by a low-energy period of storm waves (2000-2005) and a general progradation of dune systems. Later, since 2006, most dune coasts underwent a more active erosional phase, as shown in Figure 11, where in both anthropic and natural coastlines there were parallel behaviours in terms of change.

In the case of the anthropic-influenced dunes, both natural phenomena *and* human management impacts where at play. Consequently, shorelines have been subjected to accelerated erosion. All remaining Cantabrian dune fields have experienced natural retreat in recent decades (Lorenzo et al., 2007; Flor et al., 2011, Flor-Blanco et al., 2015a and b; Flor et al., 2015; Borghero, 2015; de SanJosé et al., 2018) although to a lesser extent in those associated with river mouths and confined by jetties (Fig. 11).

INSERT FIGURE 11

5.2 Drivers of shoreline change

Sea level rise measured in Santander (central Cantabrian Sea) for the period of 1943-2010 (García *et al*., 2012), showed an increase of 2.38 mm yr^{-1}. The estimated present rate of sea-level rise is about 2.08 ± 0.33 mm yr^{-1} from the tide gauge records at Santander (Chust et al., 2009). Another previous study has highlighted sea-level rise between 2.0 and 4.3 mm y^{-1} (Lorenzo et al., 2007) as a contributing factor. The occurrence of storms, each time with greater frequency and enhanced intensity, and with increased average wave heights, are also important driving factors in erosion (Conde Criado, 2014; Masselink et al., 2016; Rangel-Buitrago et al., 2016). However, other authors believe that the higher frequency and magnitude of storms in 2013 and 2014 have been enhanced by abrupt changes of the Arctic Oscillation (AO), North Atlantic Oscillation (NAO), and East Atlantic Oscillation (EA) phases, changing from a positive to a negative phase without passing through a slower neutral phase (Rangel-Buitrago et al., 2016).

In the extreme storms of 2014 and similar to the coastal storm impacts noted on the English (Masselink et al., 2016) and French coasts (Castelle et al., 2015), it is also important to consider the effects of local meteorological tides, which when coincident with storms at their maximum tidal levels may potentially induce an increased erosive impact (Cooper et al., 2004; Guisado-Pintado and Jackson, 2018; 2019). In addition, the impact of extreme storm waves in the Cantabrian Sea during the 2014 winter can be classified as a collision and an overwash regime, as described by Sallenger (2000) for barrier islands.

Conde Criado (2014) studied the significant wave heights in the buoy wave station located at NNW of the Peñas Cape (POS05) between the 1st October 2013 and the 10th March 2014, and results showed that 2014's winter storms were exceptional in their recurrence, which is in consonance with our results (Fig. 2). The present study confirms that the key to the erosional power of storm waves in 2013/14 was the higher frequency of H_s>3m and in particular, the incidence of events with H_s > 9 m (Table 1). Flor et al. (2014) have catalogued Asturian coastal damage. Masselink et al. (2016) discussed beach erosion changes in NW Europe, while Castelle et al. (2015) recorded some 22 storms with H_s>H_s,99 % and 4 storms with H_s>9 m during 2013/14, in addition to the fact the Gironde coast was exposed to the most energetic wave conditions over the last 18.3 years. In this sense, Castelle et al. (2017) also examined post-storm recovery on those same coasts.

5.3 Dune-fringed shoreline changes

Ultimately, there has been a notable reduction in the area of dune fields remaining along the Cantabrian coast since the 1990s, albeit produced sometimes by anthropic interventions. This pattern of coastal retreat has intensified since 2006, with dune frontage erosion prevalent across most sites presented in this study, mainly due to the recurrence of high-energy storms. The 2014 storms, therefore, represent some of the most destructive periods along the Spanish Atlantic coast in the last two decades and a prominent change in the approach angle (5º) of the storm waves is highlighted as a potential contributing factor that has helped to magnify their erosive impact. To better understand any changes in onshore wave patterns for the whole beach-dune system of the study area, higher resolution bathymetry for each system would have been desirable to allow shallow water numerical wave models to be applied. However, detailed information of the 1996-2014 geomorphologic evolution of the sublittoral region was not available. Nevertheless, in the eastern sector of some dune fields there is evidence of inhibited recovery such as Frexulfe, Barallo or Rodiles, and even the disappearance of the dune morphologies of larger dune fields such as Xagó and Vega. Other studies in open coasts and beaches in estuaries and bays have shown that moderately high waves can cause significantly enhanced erosion due to atypical direction patterns (Mortlock et al., 2017; Harley et al., 2017, Gallop et al., 2020).

The future prospects of these dune-fringed coasts in NW Spain are somewhat uncertain. Much of the previously storm-eroded sediment still remains in the nearshore zone of many of the sites studied and therefore post-recovery of the beach-dune systems has not fully taken hold, making future impacts from (even of lower magnitude than previous years) storm activity even more likely. According to Thom and Hall (1991), sediments can gradually return during longer period swells and lower wave events. In recent years (2015-2020) the Cantabrian coast has recorded such lower energy conditions and progradation which may provide a catalyst for recovery in case new higher energy events do not arrive in the near future.

Recovery to pre-2014 sediment levels on beaches and dunes are still some way off however, and over the 2015 to 2016 period, only minimal recovery and superficial restoration of beach levels was observed (Flor-Blanco and Flor, 2016). From 2016, there has been a significant reduction in the height of the front dune slopes, and even smaller dune morphologies forming at their base. In the case of the washover lobes, they have seen the proliferation of pioneering dune vegetation (Fig. 12). Therefore, this study represents an advance in our knowledge of the morphodynamics of the dune fields in Asturias so that future more informed-management can be considered (Martínez et al., 2013) or new preventive solutions such as the installation of offshore structures for protection (Abanades et al., 2018).

INSERT FIGURE 12

6- CONCLUSIONS

The exhaustive wave analyses carried out demonstrates a significant increase in storm wave activity especially during 2014. From 1993 to 1994, high-energy storm events dominated, whilst the 2000-2005 period corresponded to a relatively low energy phase. Subsequently, storm wave events became more frequent. Since 2006, almost all dune fields were decreasing in extent, coinciding with this new, higher-energy and erosional phase.

In particular, 2013/14 saw a higher frequency of storm events with offshore H_s>3m, and more importantly, a high recurrence of storm events with offshore H_s> 9 m. Offshore approach direction of storm waves also switched 5º to the west, thereby modifying the wave propagation pattern and incidence angle over the coastal dune-beach systems. In February and March 2014, waves reached a maximum height of up to 11 m offshore, which was combined with spring high tides and a localised wave orientation change, favouring enhanced erosional events and thus triggering the removal of small dune areas, some of them located in the eastern margin of the most important dune fields. This is evident in those beach/dune systems whose orientation is NE-SW or E-W and which, in addition, have a well-developed rocky outcrop on the western margin.

All coastal dune stretches saw enhanced erosion from 2011-2014, including more intensify levels during the winter of 2014, with the greatest impact on Peñarronda, Sarello, Frejulfe, Barayo, Otur, Carniciega, and La Isla dune coasts, reaching up to a maximum horizontal shoreline retreat of 40 m. Eroded sand was relocated into the foreshore and backshore, zones even forming pioneer dunes adjacent to the 2014 dune scarps.

This succession of more intense storm wave activity in the last decade is perhaps evidence of climate change impacts on the Cantabrian coast detected in other parts of the world and for this reason, the dune front has been receding since 2006.

The future of most of these fragile coastal dune systems, which are protected habitats (Gracia et al., 2009), is uncertain because coastalline recession is now prevalent in all Asturias's dune-fringed coasts. This study highlights how dune coasts can dynamically respond to storm impact from heightened wave conditions as well as a small alteration in normal storm conditions (approach direction), helping tip coastlines into highly erosional phases. Understanding the behaviour of these coastines therefore is now even more important in future coastal dune management approaches.

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TABLES.

Table 1. Percentage distribution of storm wave events obtained from the WAM numerical model for the whole period (1st July 1958 - 30th June 2015), and for the nine climatic years with highest total annual energy.

Table 2. Maximum significant height recorded (m) in Cape Peñas buoy and tidal ranges (m) recorded in Musel Port (Source: Puertos del estado. Ministerio de Fomento).

FIGURES

Figure 1. Location of the studied Asturian dune fields (black circles) and the riverine fluvial sources of sediments.1) Peñarronda, 2) Mexota, 3) Sarello, 4) Navia, 5) Frejulfe, 6) Barayo, 7) Otur, 8) Quebrantos, 9) Salinas-El Espartal, 10) Xagó, 11) Carniciega, 12) Rodiles, 13) La Isla, 14) Espasa, 15) Vega. Dune field removed (grey circle): Anguieiro.

Figure 2. Statistics of storm events (Hs>3m) for each climatic year from 1958-1959 to 2014-2015: A) Maximum Hs; B) Maximum energy of a storm event; C) Number of storm events; D) Total duration for the whole of storm events; E) Maximum duration of a storm event; F) Average duration of storm events; and G) Total annual energy. Data for each climatic year is plotted as corresponding to its starting year (i.e. data for climatic year 2014-2015 are plotted as corresponding to 2014). Hs is in m, duration in hours (h) and energy in x106 J/m^2. The dashed line indicates the climatic year 2013-2014.

Figure 3. Directional histograms of storm waves (Hs>3m) for A) the 1958-2015 period, and B) the climatic year 2013-2014. Directional histograms of extreme storm waves (Hs>7m) for C) the 1958-2015 period, and D) the climatic year 2013-2014.

Figure 4. Evolution (1992-2014) of the beach-dune shoreline and location of measured profiles for each dune field. Orthophotographs are 2011. Dune coastlines include:.a) Peñarronda, b) Mexota, c) Sarello, d) Navia, e) Frejulfe, f) Barayo, g) Otur, h)

Quebrantos, i) Salinas-El Espartal, j) Xagó, k) Carniciega, l) Rodiles, m) La Isla, n) Espasa and o) Vega.

Figure 5. Shoreline evolution and surface area changes at human-impacted dune sites. The dashed red line represents changes in dune field area from 1992 until 2014. Accretion/erosion rates (m yr^{-1}) are shown for the three profiles established at each dune/beach system.

Figure 6. Surface variations (m^2) of dune fields studied, comparing three representative moments: 1992 (blue), 2006 (red) and 2014 (green).

Figure 7. Shoreline evolution and surface area changes at natural sites. The dashed red line represents changes in dune field area from 1992 until 2014. Accretion/erosion rates (m yr^{-1}) are shown for the three profiles established at each dune/beach system.

Figure 8. Conceptual models of beach dunes response to 2013-2014 storm waves (without scale). Based in Hesp (2002).

Figure 9. Photographs were taken on April of 2014 (west to east): A) Mexota. Climbing dune eroded since 70s, nowadays with a high slope, B) Navia, foredune confined by jetties. In 2014 some fan lobe covered the dune field, C) Barayo foredune lost until 18 m in 2014 surge storms, D) Otur was the dune field more affected by 2014 wave storms (-35 m), E) East of Rodiles foredune, with recession of 14.54 m in 2014, F) El Espartal retreated until 13 m since 2014, influenced by port management G) Carniciega climbing dune with a recession of 12.60 m in 2014, H) Vega foredune was one of the most damaged (-7 m). On the beach, a fallen milestone (demarcation line) of the terrestrial public domain (Spanish Coastal Law).

Figure 10. Surface variations (m^2) of dune fields studied after the greatest wave storms during winter of 2014, comparing two periods: 2011 (purple), and 2014 (green).

Figure 11. Statistics of surface averaged evolution during 1990´s to 2014. A) Natural dunes, B) Anthropic-influenced dunes.

Figure 12. Photographs were taken during 2020 (west to east) showing shoreline recovery of sites shown previously in figure 9: A) Mexota. Increased sedimentary volume on the beach and attenuated recession, B) Navia, after continuous overflows in recent years, the dune migrates landward (photograph provided by Efrén García Ordiales), C) Barayo. Dune intervened as part of the Life + Arcos project. re-profiling activities, D) Otur. Slope reduction (3 m high in 2014) and generation of a new foredune with pioneer vegetation at its base, E) East of Rodiles. Great sedimentary increase on the beach and generation of vegetated dunes at its base, F) El Espartal. Sedimentary increase on the beach, less accelerated recession and dependent on dredging from Avilés estuary, G) Carniciega. Continued recession but with more sediment on the beach, slope decreased, H) Vega. Foredune recession ceased (Life + Arcos project) and dunes developing pioneer vegetation.

SUPPLEMENTARY MATERIAL

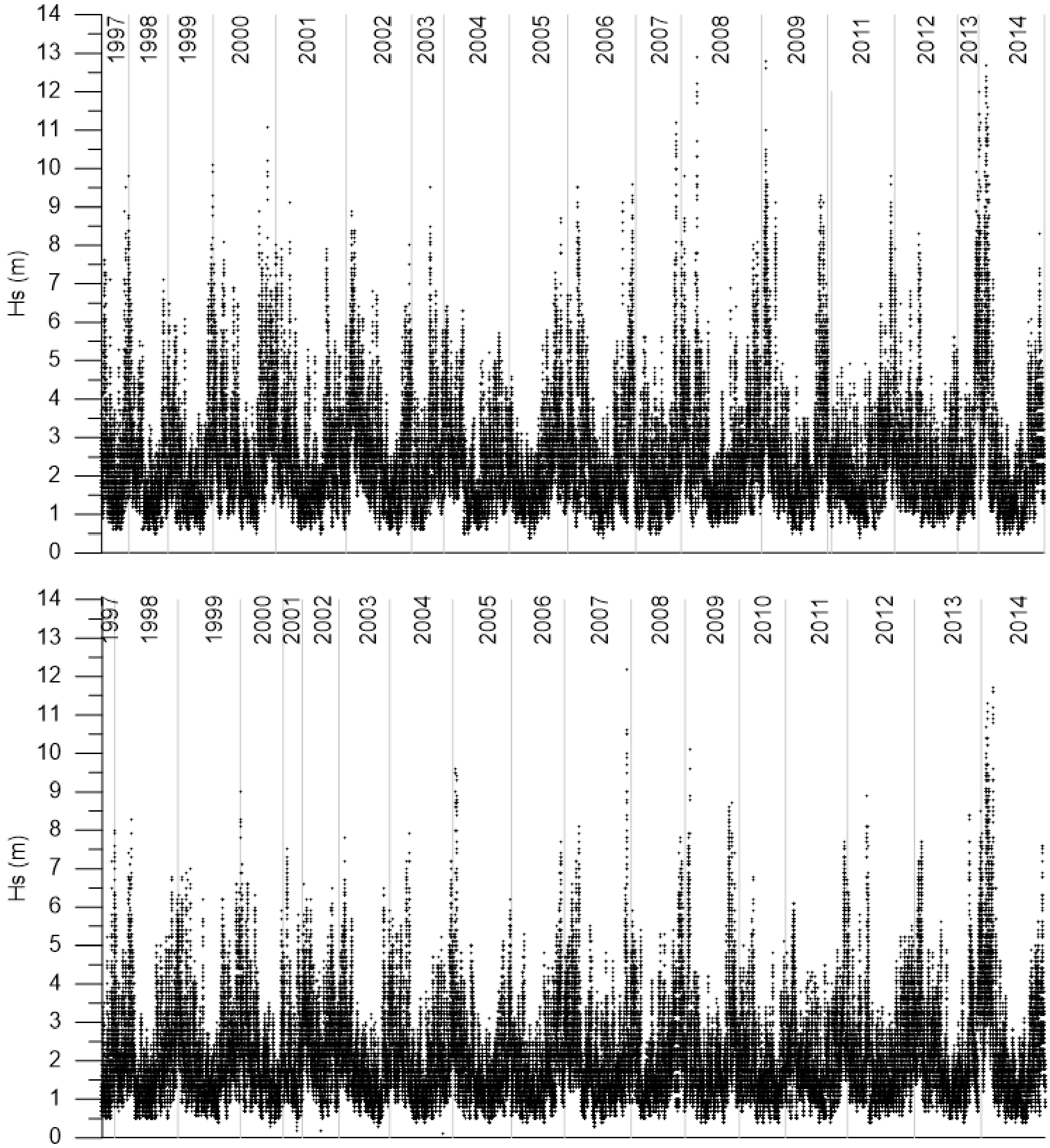


Figure I, supplementary material. Wave distribution (1997-2014) obtained from Estaca de Bares (top) and Cabo de Peñas (bottom) buoys

	DUNE FIELD	Navia	Quebrantos	Salinas-El Espartal	Xagó	Rodiles
Years	**Measurement dates: Surface (m^2) - Surface difference between recorded years (m^2)**					
1992	Surface	73291.94	268430.42	643003.00	425519.7	155800.54
2001	Surface	67987.63	245927.76	421053.81	432659.24	164543.5
	Difference 1992-2001	-5304.31	-22502.66	-221949.19	7139.54	8742.96
2006	Surface	71424.27	244596.00	498395.60	455119.97	172230.76
	Difference 2001-2006	3436.64	-1331.76	77341.79	22460.73	7687.26
2009	Surface	71620.86	242854.03	497071.62	448348.70	173109.17
	Difference 2006-2009	196.59	-1741.97	-1323.98	-6771.27	878.41
2011	Surface	74687.88	242927.7	495886.57	453069.35	178688.61
	Difference 2009-2011	3067.02	73.67	-1185.05	4720.65	5579.44
2014	Surface	73493.97	234436.52	483375.02	417374.16	176001.17
	Difference 2009-2011	-1193.91	-8491.18	-12511.55	-35695.19	-2687.44

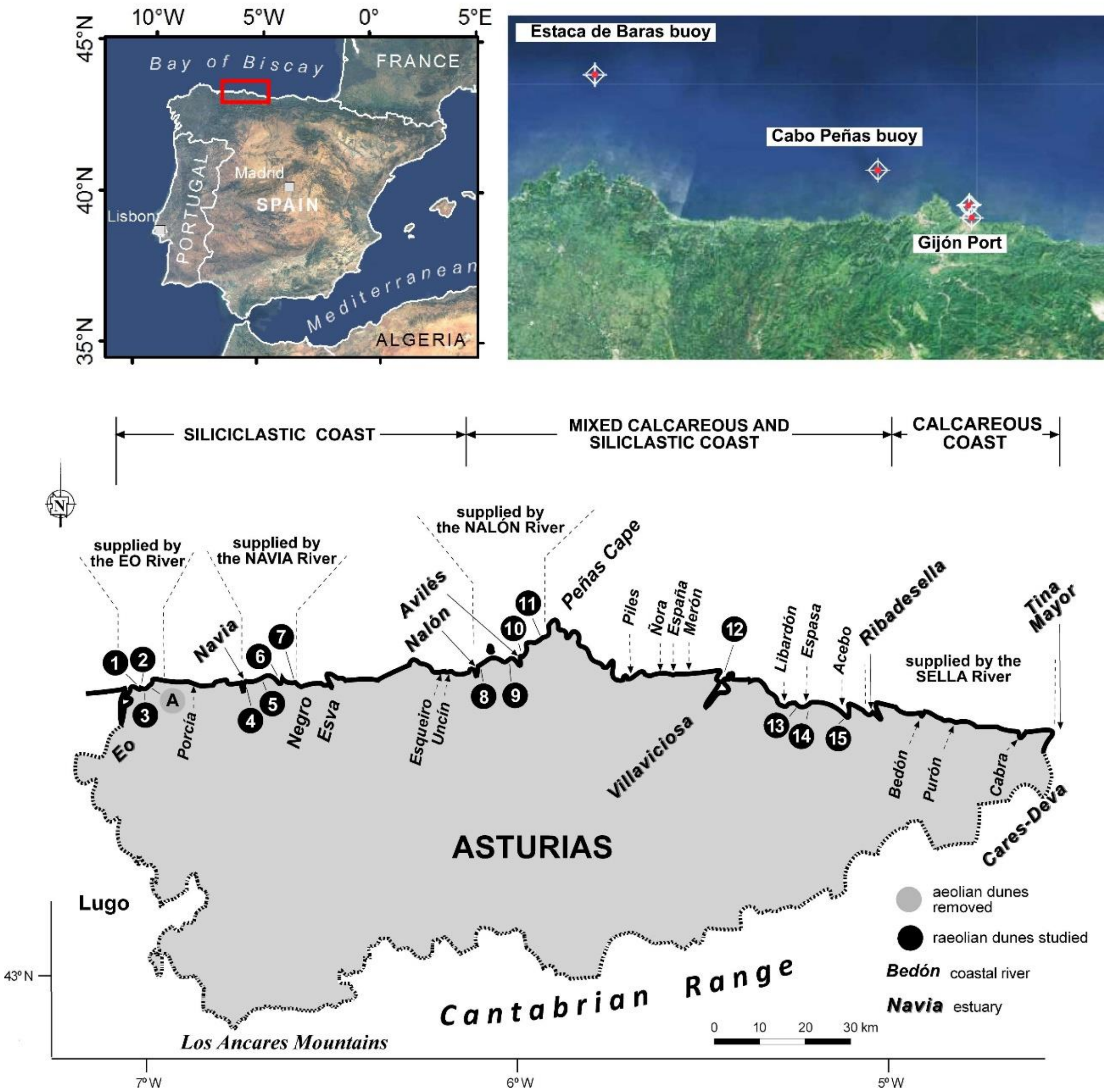
	DUNE FIELD	Navia	Quebrantos	Salinas-El Espartal	Xagó	Rodiles
Years	**Measurement dates: Accretion/recession rates (m/yr) for each profile**					
1992	**INITIAL MEASUREMENT**					
2001	WP	-3.56/-0.51	6.99/1.00	-11.36/-1.26	0.95/0.11	6.45/0.72
	CP	5.03/0.72	10.64/1.52	-9.89/-1.10	8.39/0.93	11.36/1.26
	EP	-8.26/-1.18	13.36/1.91	-3.90/-0.43	1.4/0.16	14.16/1.57
2006	WP	3.52/0.70	5.71/1.14	-4.50/-0.90	26.26/5.25	14.88/2.98
	CP	6.39/1.28	5.73/1.15	-4.23/-0.85	9.52/1.90	15.66/3.13
	EP	7.86/1.57	8.39/1.68	-2.00/-0.40	4.86/0.97	5.20/1.04
2009	WP	-0.95/-0.32	0.00	-1.81/-0.60	-12.48/-4.16	0.10/0.03
	CP	1.41/0.47	-0.88/-0.29	-2.02/-0.67	-4.70/-1.57	2.38/0.79
	EP	-0.10/-0,03	-2.71/-0.90	0.00/0.00	0.39/0.13	-0.08/-0.03
2011	WP	-0.5/-0.25	0.38/0.19	-2.33/-1.17	-1.26/-0.63	1.96/0.98
	CP	-4.09/-2.05	-3.00/-1.50	-2.42/-1.21	3.45/1.72	3.41/1.71
	EP	2.98/1.49	-1.21/-0.60	-0.30/-0.15	2.74/1.37	0.10/0.05
2014	WP	-4.68/-1.56	-16.00/-5.33	-12.20/-4.07	-6.48/-2.16	-0.93/-0.31
	CP	-1.72/-0.57	-10.42/-3.47	-13.01/-4.34	-3.13/-1.04	-0.78/-0.26
	EP	-1.77/-0.59	-11.52/-3.84	-4.03/-1.34	-2.91/-0.97	-14.54/-4.85

Table I Supplementary material. Changes in area (m^2) and accretion/erosion rates ($m\ yr^{-1}$) for the western (W), central (C) and eastern (E) profile for each anthropized dune field from 1992 to 2014.

	Dune field	Peñarronda	Mexota	Sarello	Frejulfe	Barayo	Otur	Carniciega	La Isla	Espasa	Vega
Year	**Measurement dates: Surface (m²) - Surface difference between recorded years (m²)**										
1992	Surface	70299.01	11663.7	13422.75	49446.96	58952.20	26690.08	12828.15	3836.90	18022.29	76234.60
2001	Surface	76884.80	4190.07	11229.48	54717.43	64340.76	28526.10	12603.98	5532.22	19841.18	69778.40
	Difference 1992-2001	6585.79	-7473.63	-2193.27	5270.47	5388.56	1836.02	-224.17	1695.32	1818.89	-6456.20
2006	Surface	81093.09	4028.72	13191.99	59561.32	63833.34	31337.32	12208.01	6241.75	19601.80	80169.64
	Difference 2001-2006	4208.29	-161.35	1962.51	4843.89	-507.42	2811.22	-395.97	709.53	-239.38	10391.24
2009	Surface	79083.16	3910.97	10363.02	585090.3	62801.24	30499.28	10719.28	5356.82	7311.52	75055.86
	Difference 2006-2009	-2009.93	-117.75	-2828.97	525528.98	-1032.1	-838.04	-1488.73	-884.93	-12290.28	-5113.78
2011	Surface	79288.38	3870.06	9681.86	52289.79	61348.19	29142.25	10039.34	4830.02	15732.67	72964.79
	Difference 2009-2011	205.22	-40.91	-681.16	-532800.51	-1453.05	-1357.03	-679.94	-526.80	8421.15	-2091.07
2014	Surface	76702.38	3422.66	4061.62	48938.04	54038.27	20535.68	8452.80	3723.88	14016.00	68617.11
	Difference 2009-2011	-2586.00	-447.40	-5620.24	-3351.75	-7309.92	-8606.57	-1586.54	-1106.14	-1716.67	-4347.68

	Dune field	Peñarronda	Mexota	Sarello	Frejulfe	Barayo	Otur	Carniciega	La Isla	Espasa	Vega
Year	Measurement dates: area (m²) and accretion/recession rates (m/yr) for each profile										
1992	INITIIAL MEASUREMENT										
2001	WP CP EP	13.00/1.44 23.27/2.59 22.52/2.50	-3.92/-0.44	-18.06/-2.01 -24.54/-2.73	10.83/1.20 8.16/0.91 9.34/1.04	1.53/0.17 3.68/0.41 12.1/1.34	2.49/0.28 6.18/0.69 7.57/0.84	-3.66/-0.41 0.00	20.35/2.26 17.07/1.90	-4.20/-0.47 3.96/0.44	8.58/0.95 -17.28/-1.92 8.47/0.94
2006	WP CP EP	2.12/0.42 5.00/1.00 19.10/3.82	-2.46/-0.49	21.40/4.28 15.69/3.14	16.90/3.38 7.00/1.40 5.50/1.10	-2.15/-0.43 -3.52/-0.70 -4.13/-0.83	7.80/1.56 8.30/1.66 10.89/2.18	-1.3/-0.26 -2.03/-0.41	3.64/0.73 -2.66/-0.53	-1.80/-0.36 0.55/0.11	5.83/1.17 13.24/2.65 11.96/2.39
2009	WP CP EP	0.50/0.17 2.63/0.88 -5.63/-1.88	-1.7/-0.58	-13.00/-4.33 -11.9/-3.97	-12.05/-4.02 -1.43/-0.48 11.57/3.86	-1.04/-0.35 0.00 -1.37/-0.46	0.77/0.26 0.83/0.28 -3.88/-1.29	-6.85/-2.28 -9.2/-3.07	-1.60/-0.53 --4.58/-1.53	-7.06/-2.35 -5.10/-1.70	-9.68/-3.06 -10.83/-3.42 -12.58/-4.19
2011	WP CP EP	-1.68/-0.84 0.23/0.11 -3.77/-1.89	0.00/0.00	-2.85/-1.43 0.87/0.44	-5.09/-2.55 -8.44/-4.22 -27.06/-13.53	-0.49/-0.25 0.00 -1.07/-0.53	-5.75/-2.88 -1.23/-0.62 -7.31/-3.66	-2.21/-1.11 -0.4/-0.20	-2.14/-1.07 -2.44/-1.22	-3.65/-1.83 -3.19/-1.60	-1.69/-0.84 -0.81/-0.41 -4.97/-2.49
2014	WP CP EP	-12.30/-4.10 1.50/0.50 -14.13/-4.71	-3.40/-1.13	-40.61/-13.54 -8.06/-2.74	-2.77/-0.92 -4.85/-1.62 -0.98/-0.33	-17.99/-6.00 -13.63/-4.54 -1.82/-0.61	-21.86/-7.29 -35.04/-11.68 -31.42/-10.47	-11.81/-3.94 -12.63/-4.21	-10.50/-3.50 -8.56/-2.85	-5.82/-1.94 -8.18/-2.73	-2.81/-0,94 -7.00/-2,33 -5.90/-1.97

Table II. Supplementary material. Changes in area (m²) and accretion/erosion rates (m yr⁻¹) for the western (W), central (C) and eastern (E) profile for each natural dune field from 1992 to 2014.



947

948 **Figure 2.** Location of the Asturian dune fields studied (black circles) and the riverine fluvial
949 sources of sediments.1) Peñarronda, 2) Mexota, 3) Sarello, 4) Navia, 5) Frejulfe, 6) Barayo, 7)
950 Otur, 8) Quebrantos, 9) Salinas-El Espartal, 10) Xagó, 11) Carniciega, 12) Rodiles, 13) La Isla,
951 14) Espasa, 15) Vega. Dune field removed (grey circle): Anguieiro.

952

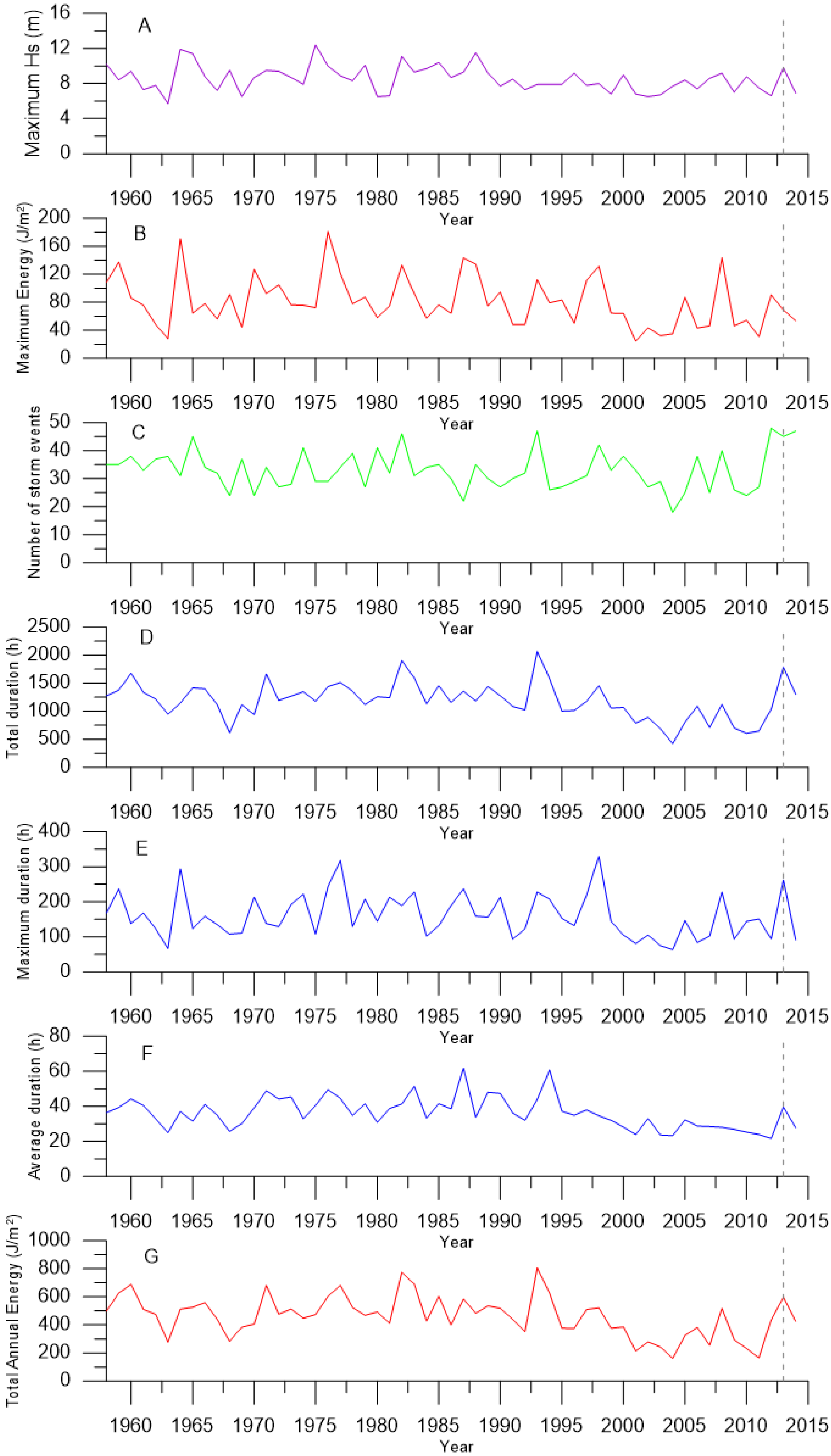

A
Maximum Hs (m)
0
4
8
12
16
B
Maximum Energy (J/m^2)
0
40
80
120
160
200
C
Number of storm events
0
10
20
30
40
50
D
Total duration (h)
0
500
1000
1500
2000
2500
E
Maximum duration (h)
0
100
200
300
400
F
Average duration (h)
0
20
40
60
80
G
Total Annual Energy (J/m^2)
0
200
400
600
800
1000
1960
1965
1970
1975
1980
1985
1990
1995
2000
2005
2010
2015
Year

Figure 2. Statistics of storm events (H_s>3m) for each climatic year from 1958-1959 to 2014-2015: A) Maximum H_s; B) Maximum energy of a storm event; C) Number of storm events; D) Total duration for the whole of storm events; E) Maximum duration of a storm event; F) Average duration of storm events; and G) Total annual energy. Data for each climatic year is plotted as corresponding to its starting year (i.e. data for climatic year 2014-2015 are plotted as corresponding to 2014). H_s is in m, duration in hours (h) and energy in x10^6 J/m^2. The dashed line indicates the climatic year 2013-2014.

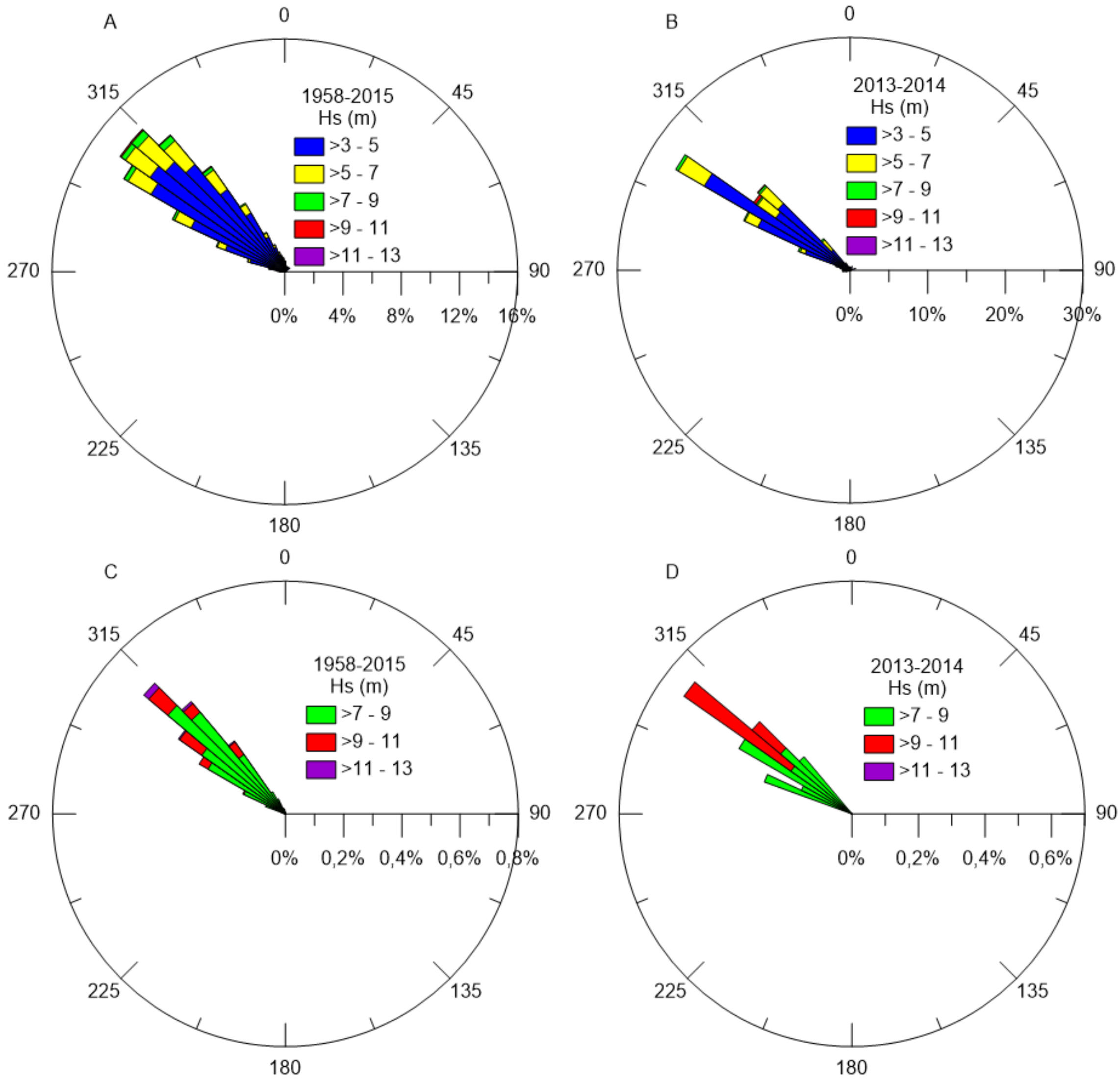
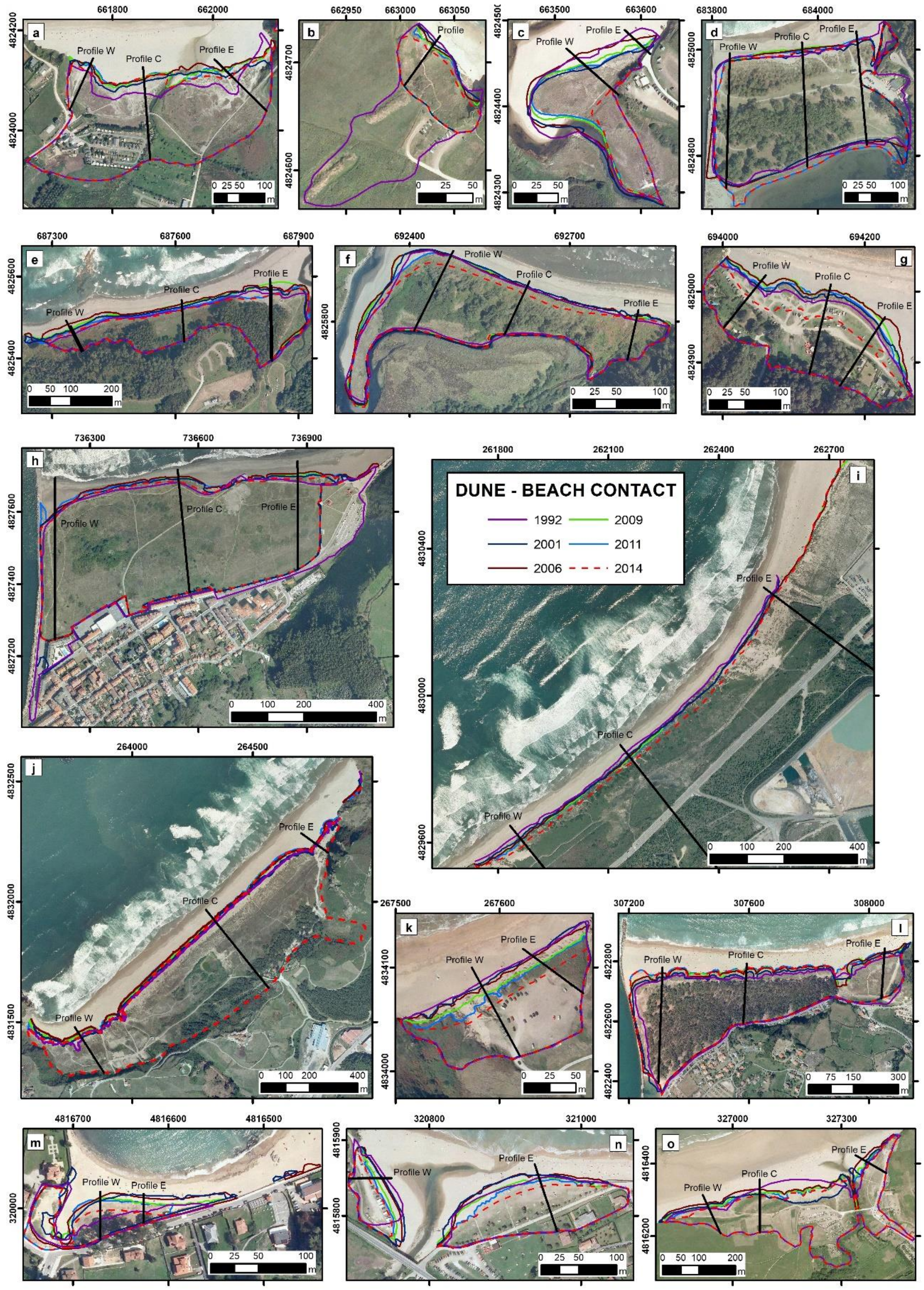


Figure 3. Directional histograms of storm waves (Hs>3m) for A) the 1958-2015 period, and B) the climatic year 2013-2014. Directional histograms of extreme storm waves (H_s>7m) for C) the 1958-2015 period, and D) the climatic year 2013-2014.



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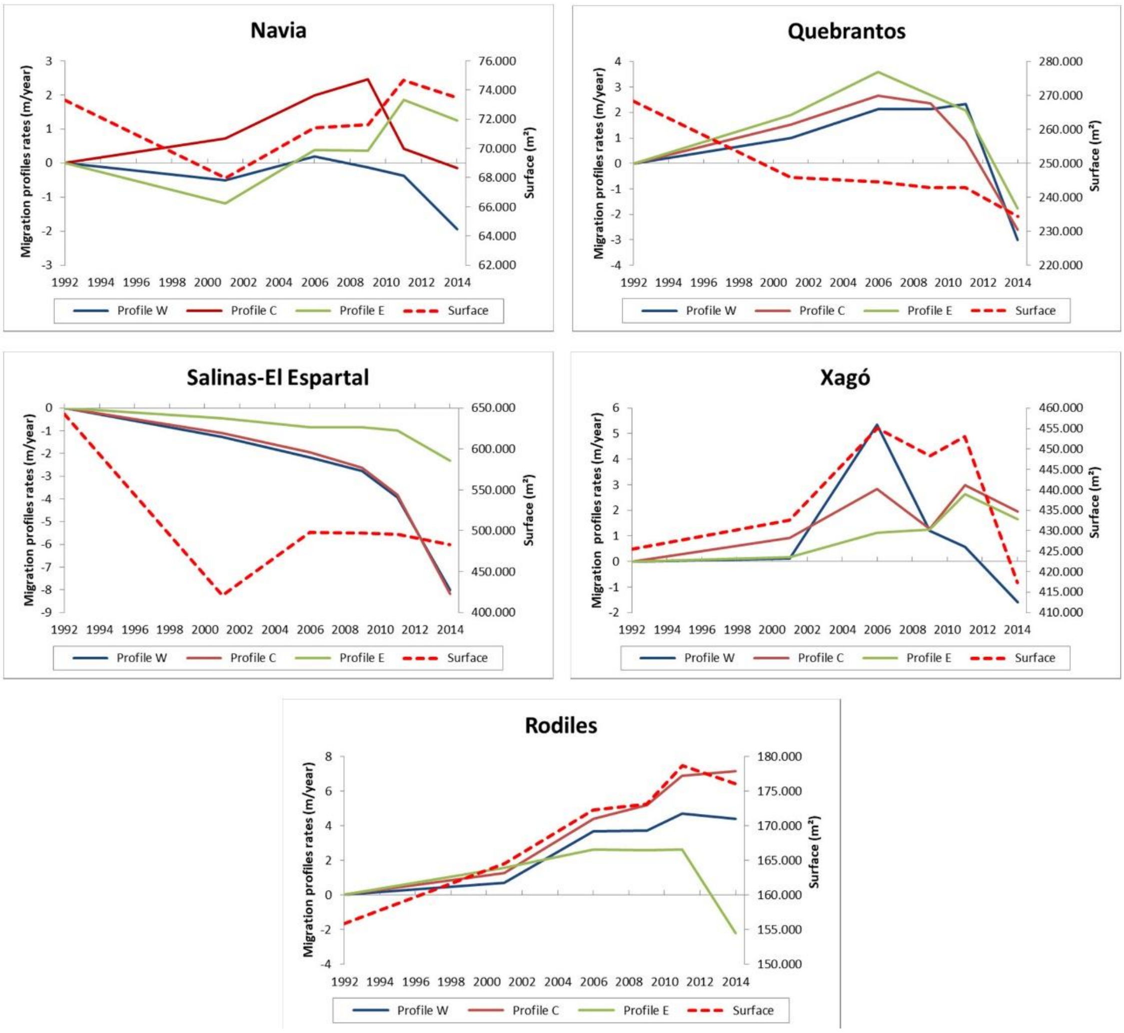

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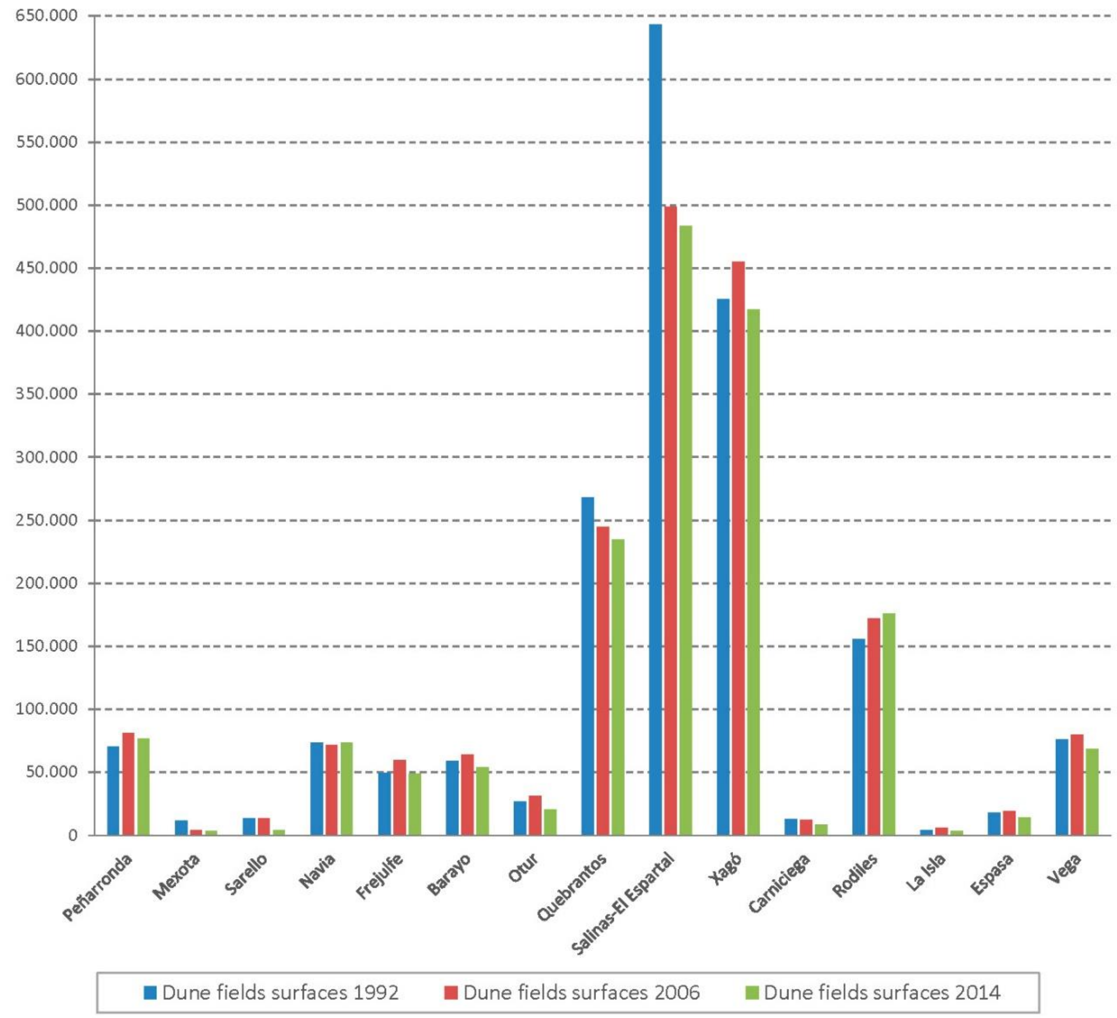

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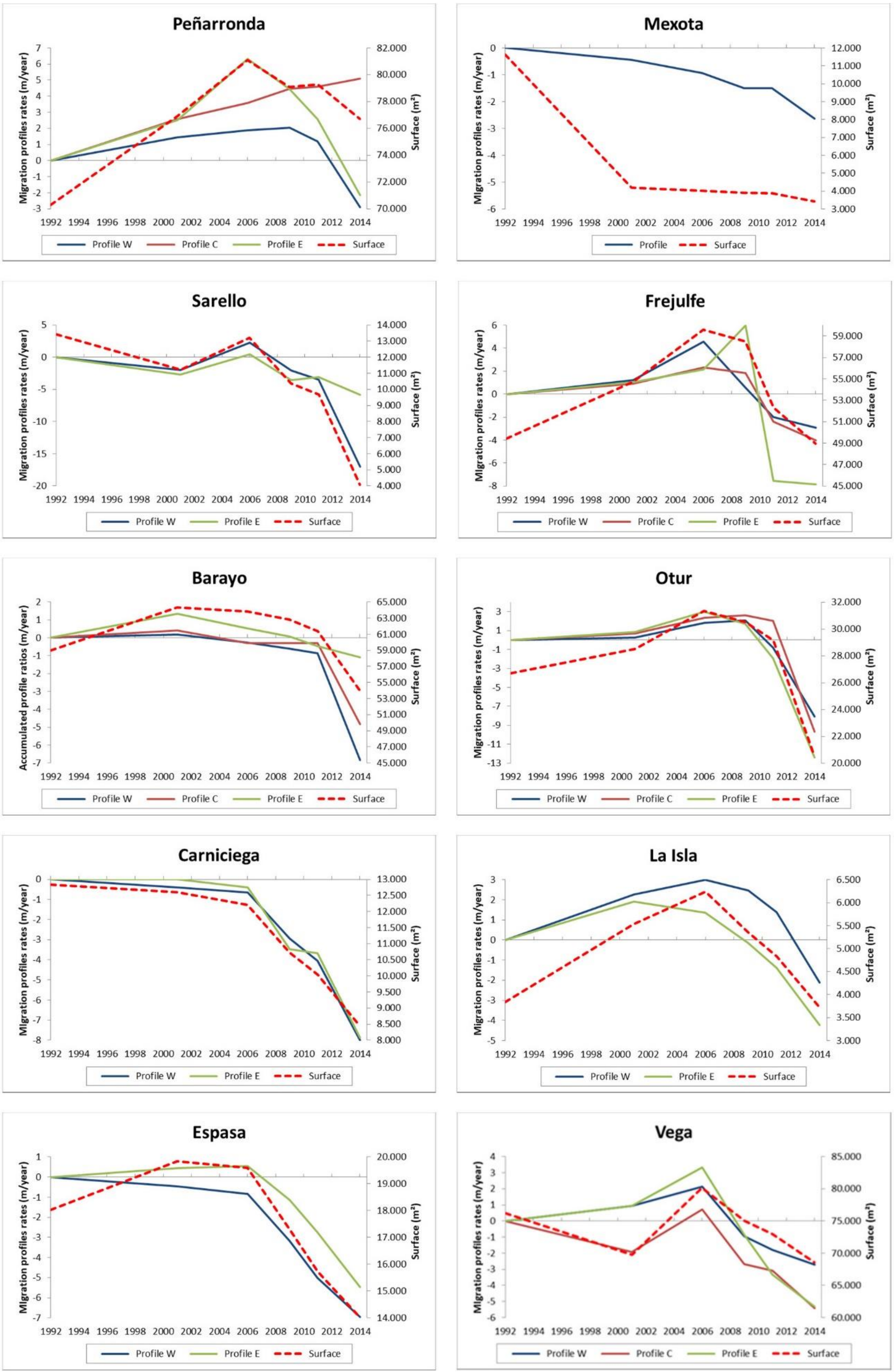

Peñarronda
Migration profiles rates (m/year)
Surface (m²)
Profile W
Profile C
Profile E
Surface
Mexota
Migration profiles rates (m/year)
Surface (m²)
Profile
Surface
Sarello
Migration profiles rates (m/year)
Surface (m²)
Profile W
Profile E
Surface
Frejulfe
Migration profiles rates (m/year)
Surface (m²)
Profile W
Profile C
Profile E
Surface
Barayo
Accumulated profile ratios (m/year)
Surface (m²)
Profile W
Profile C
Profile E
Surface
Otur
Migration profiles rates (m/year)
Surface (m²)
Profile W
Profile C
Profile E
Surface
Carniciega
Migration profiles rates (m/year)
Surface (m²)
Profile W
Profile E
Surface
La Isla
Migration profiles rates (m/year)
Surface (m²)
Profile W
Profile E
Surface
Espasa
Migration profiles rates (m/year)
Surface (m²)
Profile W
Profile E
Surface
Vega
Migration profiles rates (m/year)
Surface (m²)
Profile W
Profile C
Profile E
Surface

Figure 7. Shoreline evolution and surface area changes at natural sites. The dashed red line represents changes in dune field area from 1992 until 2014. Accretion/erosion rates (m yr^{-1}) are shown for the three profiles established at each dune/beach system.

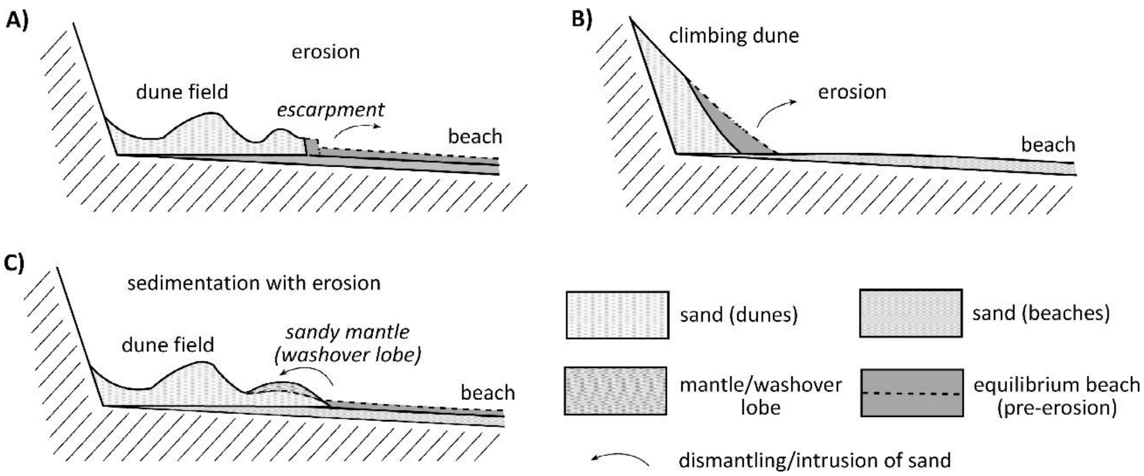
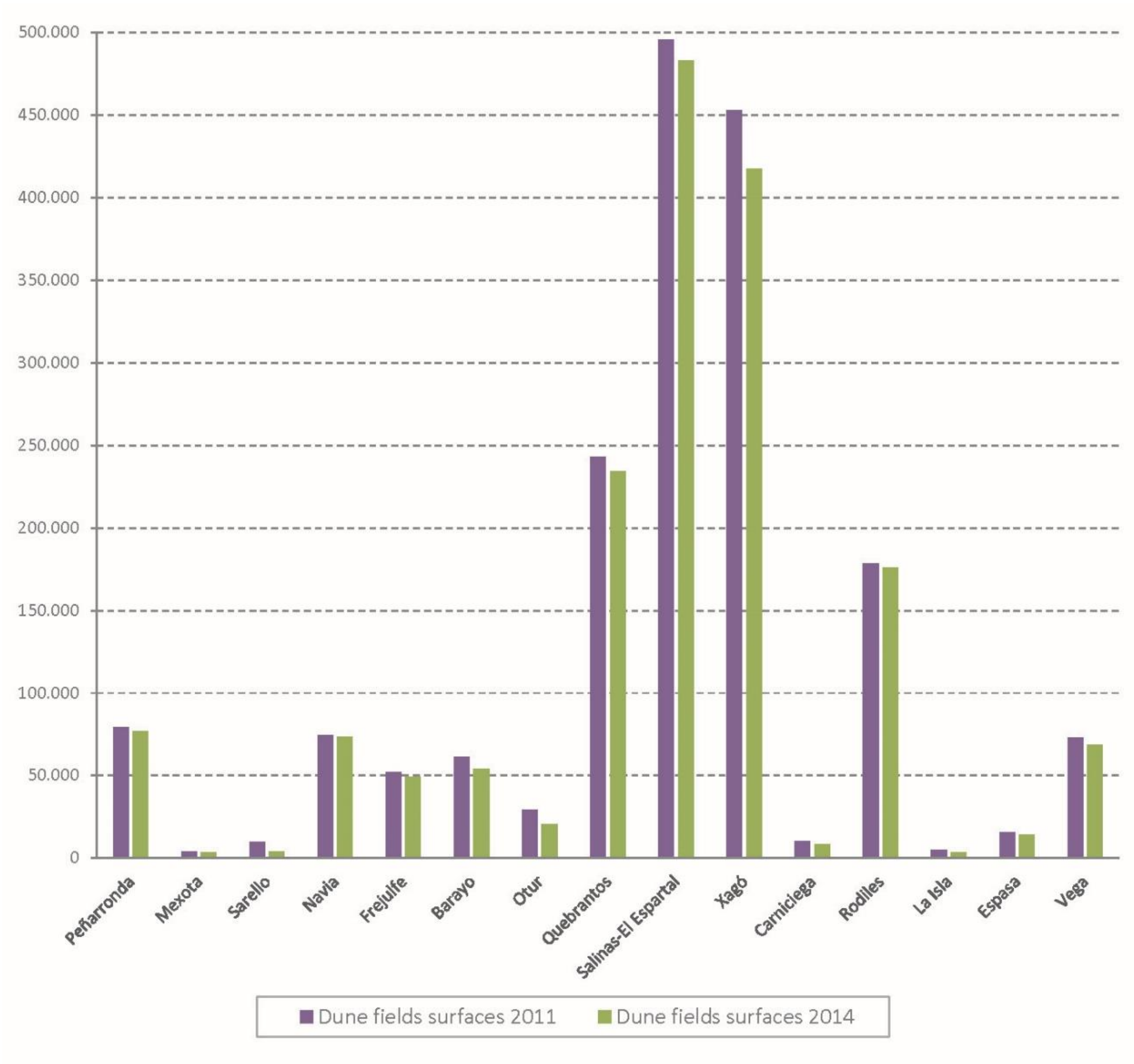


Figure 8. Conceptual models of beach dunes response to 2013-2014 storm waves (without scale). Based in Hesp (2002).

Figure 9. Photographs were taken on April of 2014 (west to east): A) Mexota. Climbing dune eroded since 70s, nowadays with a high slope, B) Navia, foredune confined by jetties. In 2014

some fan lobe covered the dune field, C) Barayo foredune lost until 18 m in 2014 surge storms, D) Otur was the dune field more affected by 2014 wave storms (-35 m), E) East of Rodiles foredune, with recession of 14.54 m in 2014, F) El Espartal retreated until 13 m since 2014, influenced by port management G) Carniciega climbing dune with a recession of 12.60 m in 2014, H) Vega foredune was one of the most damaged (-7 m). On the beach, a fallen milestone (demarcation line) of the terrestrial public domain (Spanish Coastal Law).

1004



1005 **Figure 10.** Surface variations (m^2) of dune fields studied after the greatest wave storms during
1006 winter of 2014, comparing two periods: 2011 (purple), and 2014 (green).

1007

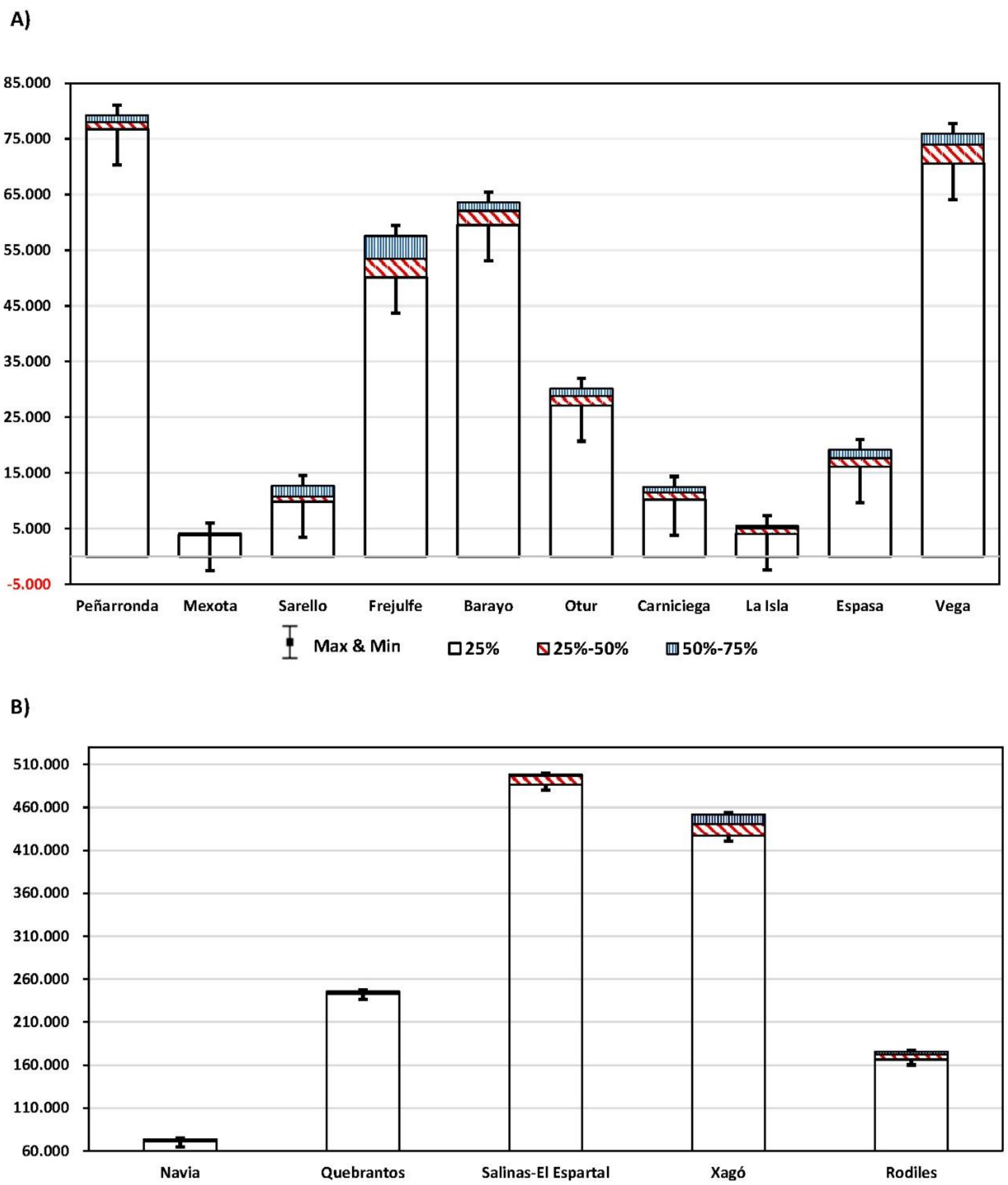


Figure 11. Statistics of surface averaged evolution during 1990´s to 2014. A) Natural dunes, B) Anthropic-influenced dunes**.**

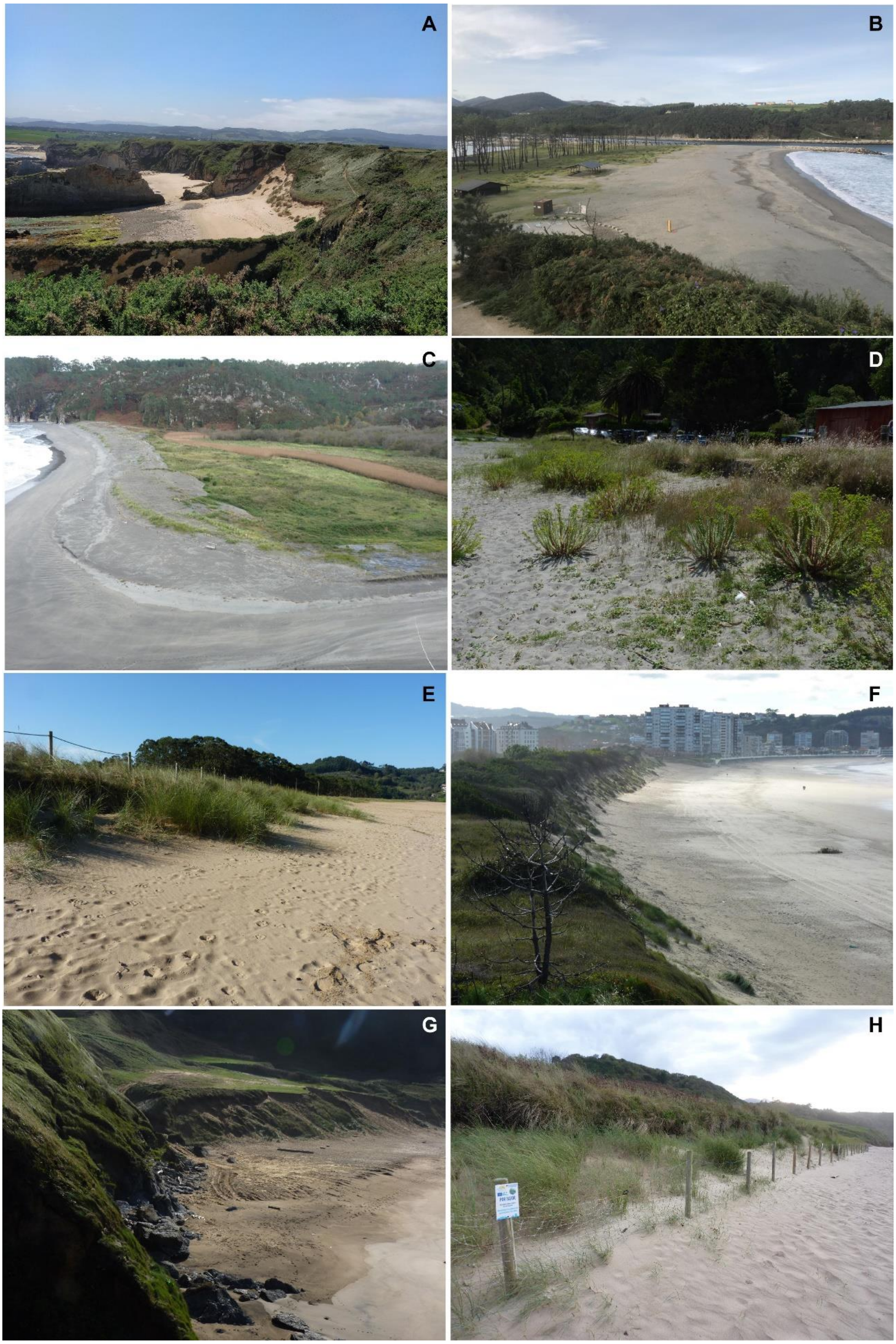

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Figure 12. Photographs were taken during 2020 (west to east) showing shoreline recovery of sites shown previously in figure 9: A) Mexota. Increased sedimentary volume on the beach and attenuated recession, B) Navia, after continuous overflows in recent years, the dune has migrated landward (photograph provided by Efrén García Ordiales), C) Barayo. Dune intervened as part of the Life + Arcos project. re-profiling activities, D) Otur. Slope reduction (3 m high in 2014) and generation of a new foredune with pioneer vegetation at its base, E) East of Rodiles. Large sandy volumetric increase on the beach and generation of vegetated dunes at its base, F) El Espartal. Volumetric increase on the beach, less accelerated recession and dependent on dredging from Avilés estuary, G) Carniciega. Continued recession but with more sediment on the beach, slope decreased, H) Vega. Foredune recession stopped (Life + Arcos project) and dunes developing pioneer vegetation.