UNIVERSIDAD DE LAS PALMAS DE GRAN CANARIA

FACULTAD DE CIENCIAS DEL MAR

UNIVERSIDAD DE LAS PALMAS DE GRAN CANARIA

CHANGES DETECTED AT CORRALEJO DUNE FIELD FROM 1994 TO 2014

ENRIQUE VAREA LOAYZA

MASTER INTERUNIVERSITARIO EN OCEANOGRAFÍA

TRABAJO DE FIN DE MASTER

LAS PALMAS DE GRAN CANARIA, 2016

MASTER INTERUNIVERSITARIO EN OCEANOGRAFÍA

UNIVERSIDAD DE LAS PALMAS DE GRAN CANARIA

CHANGES DETECTED AT CORRALEJO DUNE FIELD FROM 1994 TO 2014

Tesis de Máster presentada por **ENRIQUE VAREA LOAYZA**

Dirigida por **Dr. IGNACIO ALONSO BILBAO**
Dra. MARÍA JOSÉ SANCHÉZ GARCÍA

LOS DIRECTORES EL TESINADO

Las Palmas de Gran Canaria, 11 de julio de 2016

ABSTRACT

Understanding coastal dune field evolution is a challenge because of their complex dynamic nature. This work has been carried out by means of photointerpretation of 5 orthophotos covering the period 1994-2014. A geographical information system has been developed, including information of the three geomorphological landforms (sand sheets, dune areas, and deflation surfaces) present in the area, as well two additional information layers (vegetation and artificial structures) that interact with the previous ones. The GIS also includes information of the dune crests movement over the same period, which has been correlated with gust wind data. Average migration rates are 8 m/y in the S-SSE direction.

Geomorphological evolution indicates that dune areas are decreasing in the north and increasing in the south, as a result of the southward displacement of the mobile dunes. The opposite patter is found for the sand sheet unit. On the other hand, both vegetation and deflation surfaces shows a continuous increment in surface coverage, which in both cases is explained as a result of the lack of sediment supply into the dune system. Predicted future scenarios shows a trend towards the increase of more stable sedimentary environments.

INDEX

1. INTRODUCTION

Aeolian dunes are embossed shapes produced by wind transport and sedimentation, formed by small size sediments, mainly medium and fine sands (Criado, 1998). Development of coastal dune fields areas is associated with oceanographic, meteorogical, biological and geological aspects like waves, tides, currents, wind strength, precipitations, vegetation inside and near from the dune field, topography, sediment grain size, source and transport (Sanjaume et al. 2011).

In global terms, dune systems formations are related with post glacial processes and sea level variations. For this reason, it is easy to find overlapped dune fields, stable systems and, more frequently, destabilized systems as consequence of human interactions and climate changes (Thomas, 1999).

Because of these particular and fragile meteorological, oceanographic and geological relations, human occupation and activities inside dune fields are very harmful and derives in several alterations which in many cases are permanent (Paskoff, 1998). Moreover, non-regulated urban development, and touristic use of this places could result in their total destruction (Paskoff, 1993; Jaramillo, 1986).

Coastal dunes presents a complex interaction between topography, vegetation and aeolian processes. (Andrews et al. 2002). The alteration of any of this factors is directly reflected in sediment transport changes. This effect probably modify the dune system and its ecologic equilibrium (Lesica & Cooper, 1999).

Dune fields in Canary Islands presents particular characteristics. Arid climate and plain grounds associated with the presence of vegetation from the northwest coast of Africa and Macaronesia generates transgressive ridges which can transport sediments efficiently at long distances (Garcia-Romero et al. 2016). Also, according with Criado et al. 2011, Fuerteventura is an island with high dune development because of their geomorphic and climate characteristics.

In the last decades dune fields are being considered as natural areas to be protected (Kay & Alder, 1999). All Canary dune field are threatened by urban and touristic developments. In the last years several alterations were detected in these systems, with indelible marks (Suarez & Hernandez, 1998). Corralejo Natural Park, located in Fuerteventura Island, is an actual example of how human interference modifies dune fields with significant consequences.

In this context, it's necessary to understand Corralejo Natural Park changes in long term periods related with dune types, space occupied and sand displacements and to stablish which are the principal problems that have been affecting the dune field stability. After this qualitative and quantitative multi temporary analysis, it will be possible to make a prediction about the possible short and medium term geomorphological evolution.

Dune shapes change quickly (Arteaga et al. 2008). For this reason, developing base-models to predict their changes do not give us accurate results. The study of dune fields using remote sensing, is actually a reliable and relatively economic tool to understand provenance, evolution and other important geologic characteristics. The increase of studies using this method is a clear evidence of the interest for the scientific community (Hernandez-Calvento et al. 1999). Nowadays, this technique is useful to analyze spatial characteristics and integrate them in Geographic Information Systems (GIS) (Andrews et al. 2002).

Different studies have been made to understand Corralejo dune field evolution (Jiménez et al. 2006, Fernandez Cabrera et al. 2012, Cabrera-Vega et al. 2013, Malvárez et al. 2013, García-Romero et al. 2016) The present study tries to complement them using remote sensing to analyze this evolution in the medium term including equal time intervals to determinate annual variation tendencies.

1.1 Objectives

The main goal of present study is to quantify the sedimentary evolution in Corralejo Dune Field from 1994 to 2014. Identifying these changes, the next specific objectives will be followed:

- To identify relations between sedimentary environments inside this dune system.
- To stablish the dune dynamic in relation with wind velocity.
- To make projections about future scenarios for this dune system.

1.2 Study Area

Corralejo dune field is located in the Northeast of Fuerteventura Island. By their dimensions (8.3 km large and km 2.5 km width), it is considered the largest active dune field in the Canary Islands. To preserve the geodiversity, biodiversity and touristic value, this place in 1994 was declared by the canarian government as a natural park. It consist of sedimentary deposits of Pleistocene and Holocene periods. The first ones are result of different sea level oscillations, interspersed with volcanic eruptions that contributed to the conservation of sandy deposits (Criado, 1987).

Following the classification suggested by Illenberg & Rust (1996), this area has a combination of stable and transgressive dunes with a clearly interaction coast-dune zone. According with Meco et al. 1997, dune deposits are mainly formed from bioclastic sands with high content of carbonates (fragments from algae, shells and foraminifera). Sediment sources are mainly marine (Hernández-Calvento & Mangas, 2004; Mangas et al. 2012) and comes from the continental platform located in the north of the island. This kind of sand is commonly called *jable* and is present in many submarine sand deposits in the Canary Islands. Also there are occasional fine sediment inputs from Saharian dust, which is transported by eastern winds, situations that receive the local name of *calima* (Criado et al. 2011, Menéndez et al. 2009, 2014, Alcántara-Carrió et al. 2010).

Because of strong winds coming from North and soft slope of 1.2ª (Alonso et al. 2011), these sands are transported towards south, and are deposited on volcanic rocks, forming unique environments with mixed aeolian-volcanic characteristics.

In contrast of the natural importance of this environment, and even though it is a natural park protected by law, human interventions motived for touristic development in the past years are perfectly perceived. Urbanistic expansion in the borders and, in some cases inside it, includes buildings, resorts, hotels, little restaurants near from the beach and parking areas. Moreover, there is a road which crosses and divides the dune field in two parts. All these unnatural structures are affecting the natural dune field processes (Criado, 1990; Hernández-Calvento et al. 1999; Jiménez et al. 2006; Valdemoro et al. 2007; Garcia-Romero et al. 2016).

Knowing their natural, scientific and touristic importance, a specific study about temporal dune evolution related with relevant geologic changes is necessary to understand how natural processes and anthropogenic influence have been affected this dune field and which will be the future scenario for the next decades.

2. MATERIALS AND METHODS

In recent years significant advances in dune research have been made through the application of satellite remote sensing combined with Geographic Information Systems (GIS) because of their availability, relative low cost, and spatial resolution (Hugenholtz & Barchyn, 2010).

For a better understanding of this method, it is important to define two key tools:

- Orthophoto: Graphic document obtained from aerial photographs. It's made correcting photo deformations and georeferencing them. This processes give us products with visual richness and cartographic precision (Wolf & Dewitt, 2000).
- Geographic Information System (GIS): Combination of hardware, software and digital processes to capture, manipulate, analyze model, and represent georeferenced data, which allow us to manage and solve planning problems (Alcala et al. 1995).

Dolan et al. 1978 suggested that technological developments allow for improved monitoring of coastal systems. New, high-resolution satellites provide coverage of large sections, although even the improved resolution does not provide sufficient detail to give precise measurements of changes in coastal dune topography. Aerial photographs still represent the best visual source of information about changes. Horizontal dimensions of coastal landforms can be measured from photos. Moreover, aerial photographs represents an optimal graphic document to make 2-D and 3-D spatial analysis. Using aerial photographs taken in different dates and at the same spatial resolution for the same dune area, make possible to calculate sediment volumes, transport directions, and dynamic regimes of this displacements (Brown & Argobast, 1997).

The use of aerial photographs is recommended for spatial analysis from 1 to 100 km (Moore, 2000). Corralejo dune field, with an approximately 8 km long and 2.5 km width, is case of study perfectly approachable with this methodology. This analysis is the most used to quantify dune field morphological evolutions on big areas (Finkel 1961, Breed et al. 1979, Lancaster et al. 1992, Blumberg 1998).

To achieve the proposed objectives, 5 orthophotos produced by Cartográfica de Canarias S.A (GRAFCAN) covering the period from 1994 to 2014 were selected. Principal metadata is shown in table 1. Criteria for the selection of these orthophotos respond to the need of images with similar elapsed time periods, and the availability of meteorological information during this period.

Used data also includes wind direction, intensity and wind gust in synoptic hours (00, 06, 13 and 18h) from three meteorological stations: a conventional station from 1992 to 2012 and an automatic station from 2012 from 2014 at Corralejo Port and an automatic station from 1994 to 2008 at Fuerteventura airport. Data was provided by Agencia Estatal de Meteorología de España (AEMET). It has to be pointed out that conventional stations records are collected manually and takes one single measurement at that particular instant. Otherwise, automatic stations were programmed to give an average of the last hour of wind measurements before the synoptic hour, being this stations more reliable in their data. The locations of these stations (figure 1) shows that Corralejo conventional and automatic station are in an optimal position to study relationships between winds and environment sediments evolution. It is located 1.6 km to the North border of Corralejo dune field and, considering that wind usually comes from north and northeast (Jimenez et al. 2006), measurements have good correlation with wind parameters inside it. Otherwise, wind data from station at Fuerteventura airport was discarded because of distance (more than 30 km) and perturbations suffered for winds until arriving at this location.

Figure 1. Meteorogical Stations positions in red marks. Corralejo dune Field represented as yellow area. (Google Earth)

Orthophoto	Month / Year	Images	Resolution (cm/pixel)	Observations
1	N.A / 1994	Flight 1:18000	40	Significant restitution errors
2	10 / 1998	Flight 1:18000	100	Ground error <1.5m
3	N.A / 2004	Flight 1:18000	40	Ground error <1m
4	01 /2008	Flight 1:25000	40 - 50	Ground error <1.5m
5	04 / 2014	Flight + satellite images 50cm/pixel	25	Ground error <1.5m

Table 1. Metadata from 5 orthophotos selected for the present study. Notes 1994 orthophoto has restitution errors.

Selected orthophotos were used to digitize the dune field borders and the sedimentary environments and artificial structures inside it. This process was made using ArcGIS 10.3 software using 1:2500 as spatial scale for more precision. Following classification suggested by McKee (1966), as well as ecologic and anthropogenic aspects, five layers of information were created: mobile dunes (barchan, barchaniods and foredunes), sand sheets, deflation surfaces, vegetation areas and artificial structures (buildings and roads).

This delimitation of different sectors was based on geomorphological and environmental criteria, and carried out by mean of traditional photointerpretation of homogeneous units.

For an optimal spatial analysis related to the evolution of any of these layers of information, the study area was divided in 4 areas as shown in figure 2.

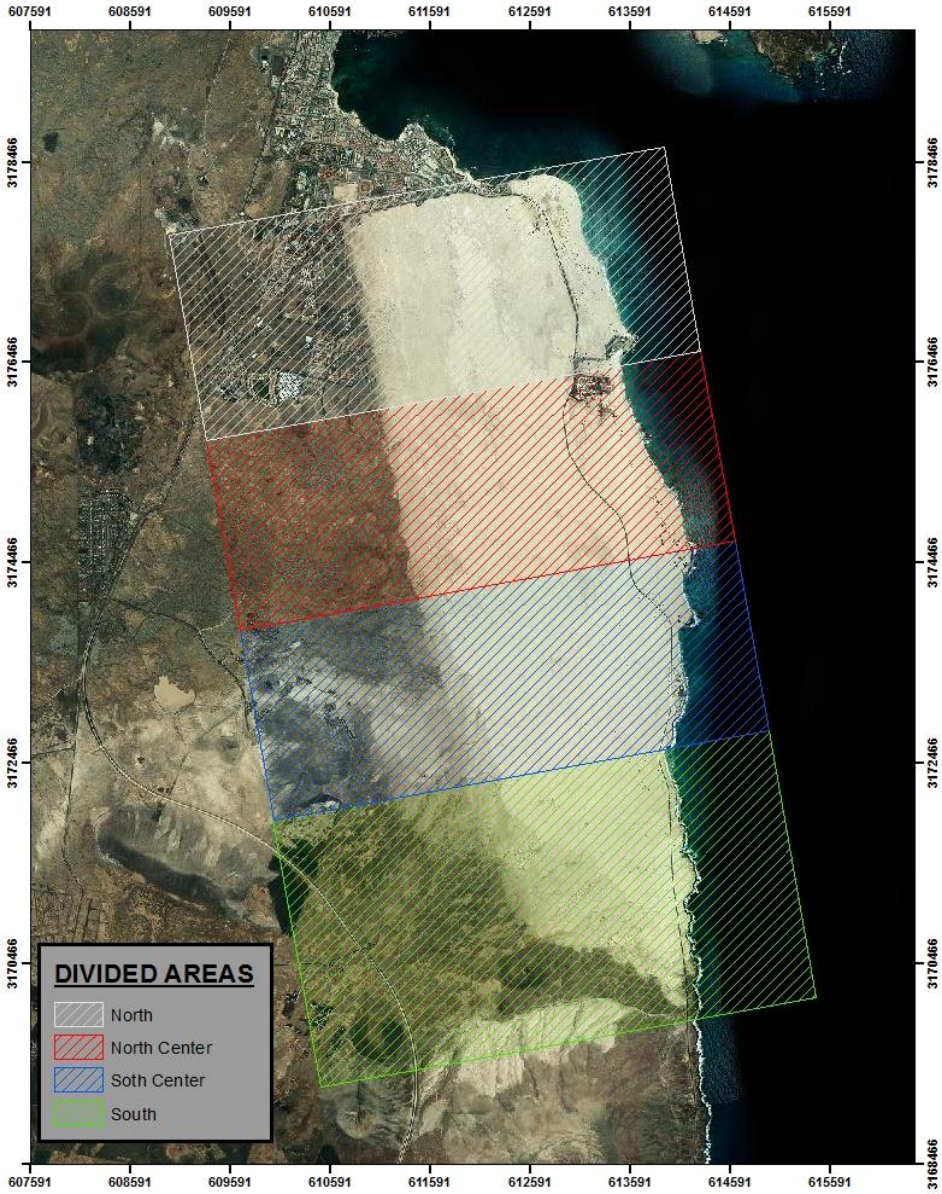


Figure 2. Areas divided for independent spatial analysis.

To account for mobile dunes evolution and transport, the crest of any individual dune ridges was digitized in all orthophotos. Dune ridges with a good correlation between consecutive ortophotos were joined by arrows, so that the arrow length indicates the distance travelled and the arrow azimuth indicates the direction of movement. This method was used because of the lack of LiDAR sequenced images, which is the most used technique in dune mobility studies nowadays (Andrews et al. 2002; Dong, 2015).

3. RESULTS

3.1 Sedimentary environments evolution

The geomorphological cartography of Corralejo dune field corresponding to 1994, 1998, 2004, 2008 and 2014 is shown in the additional information. The area corresponding to each one of the different sedimentary environments has been calculated, both for the total area as well as for the four subareas described before. Line tendencies to determine increase/decrease trends have been also obtained.

In general terms, the whole area of Corralejo dune field has decreased around 2% of its surface. However, the different sedimentary environments have been evolving with particular patterns. In many cases this evolution hasn´t been constant, occurring decrease and increase periods between time intervals. This is clearly identified in sand sheet, mobile dunes and deflation surfaces. Only vegetation is steadily growing on all periods, which also has the highest growth rate, tripling this initial value (Figure 3).

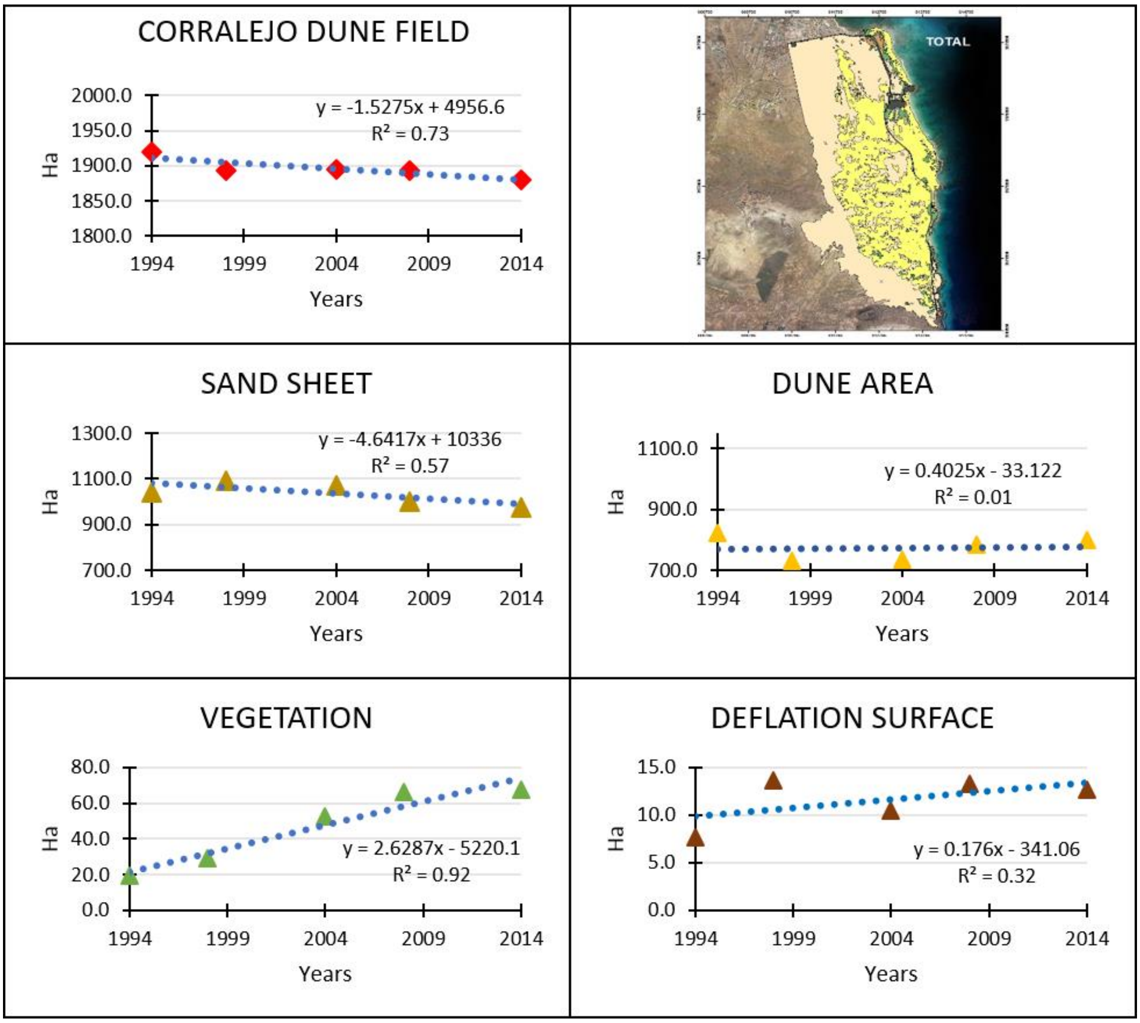


Figure 3. Time evolution of the total study area and the four geomorphological layers of information.

Total area shows a slight negative trend (-1.5 Ha/y) associated with changes in the outer border, which is receding in the south and southwestern limits. Sand sheet is the largest sedimentary environment. It shows a negative trend of about -4.6 Ha/y, that is partially compensated by the increase measured in the three other geomorphological units: Mobile dunes follow an irregular pattern (opposite to that of the sand sheet), but with a slight positive trend of 0.4 Ha/y. Area of deflation surfaces is quite irregular, but it has also a mild positive tendency of 0.2 Ha/y, while area covered by vegetation is steadily growing at 2.6 Ha/y during the whole study period.

This changes becomes more complex when evolutions followed by the different geomorphological units are analyzed in subareas. Results are shown in figures 4, 5, 6 and 7. In general, area covered by mobile dunes decrease in the north and increase in the south, while sand sheets have the opposite pattern, evidencing the clearest relation between both units. Vegetation increases in all areas and deflation surfaces are present mainly in the northern area where it's increasing. Areas increase or decrease tendencies per year are shown in table 2.

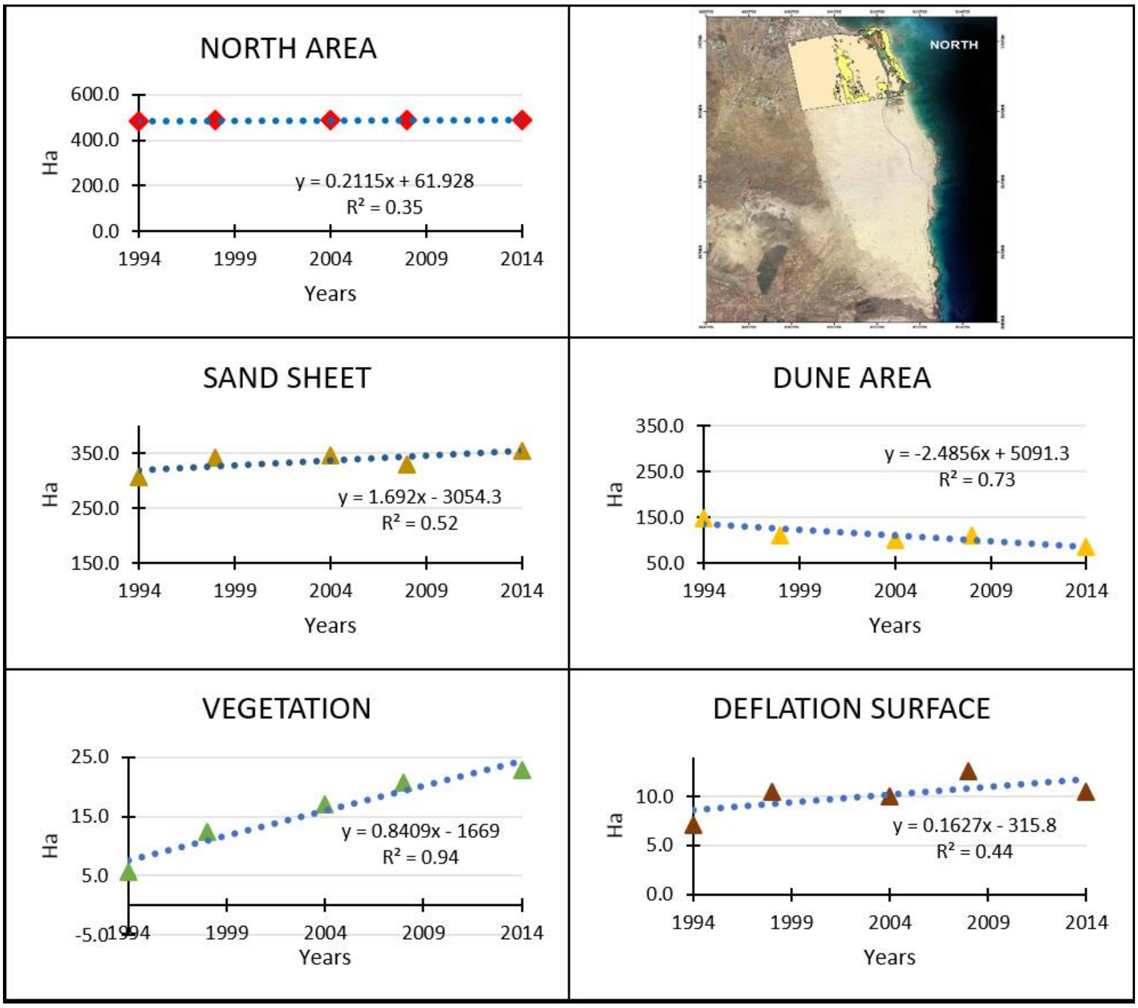


Figure 4. Time evolution of the different geomorphological units at the north area. Total area occupied by sedimentary environments remains a stable pattern. Sand sheet is the most occupied area with an irregular slight growth. Dune areas has a decrease tendency. Vegetation have been growing very fast. Deflation surface, with an irregular increase pattern is almost doubling this initial area.

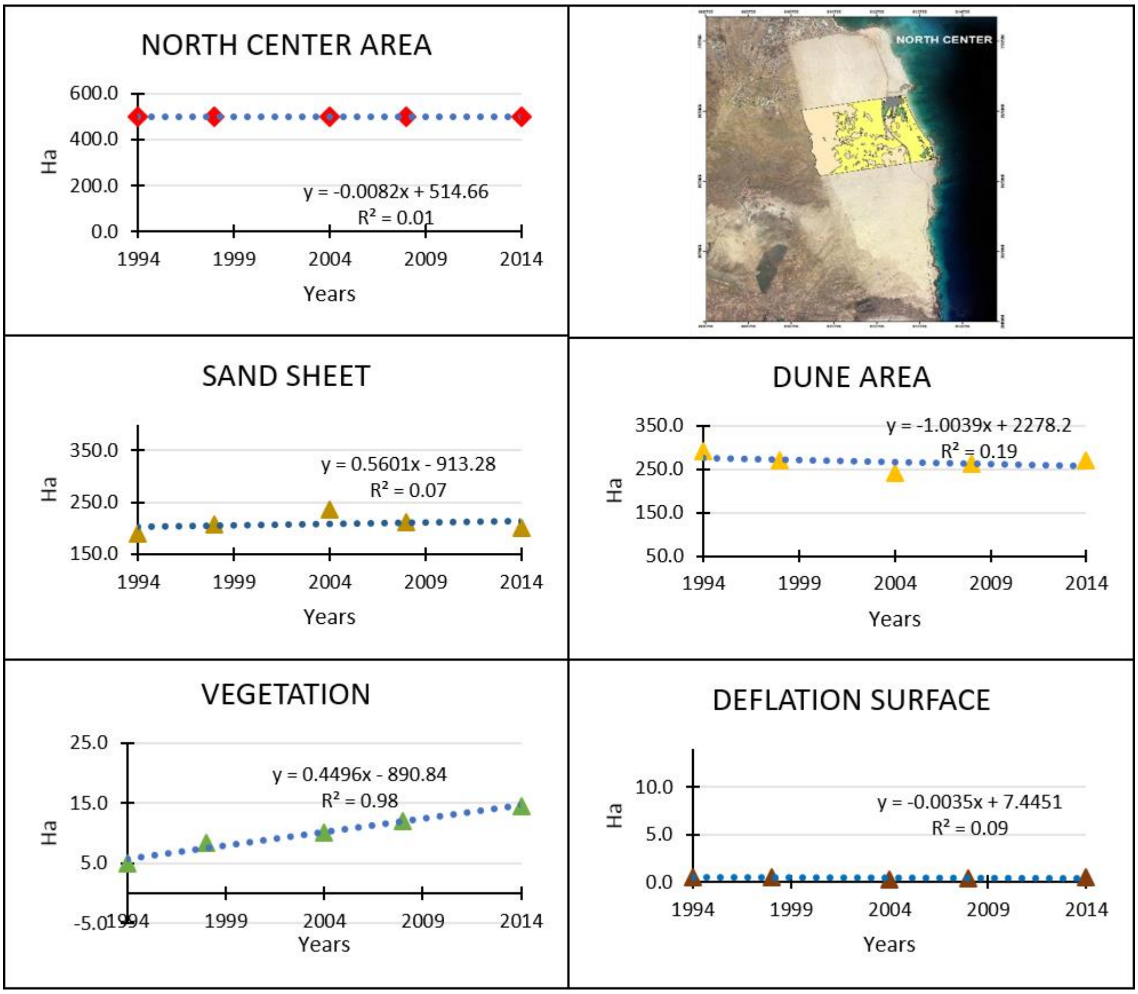


Figure 5. Time evolution of the different geomorphological units at the north center area. Total area occupied by sedimentary environments remains a stable pattern. Sand sheet has irregular slight grow and occupy the same area like dune areas which presents an irregular decrease tendency. Vegetation area gains 300% of area from the first measure. Deflation surface are almost not present and doesn't vary.

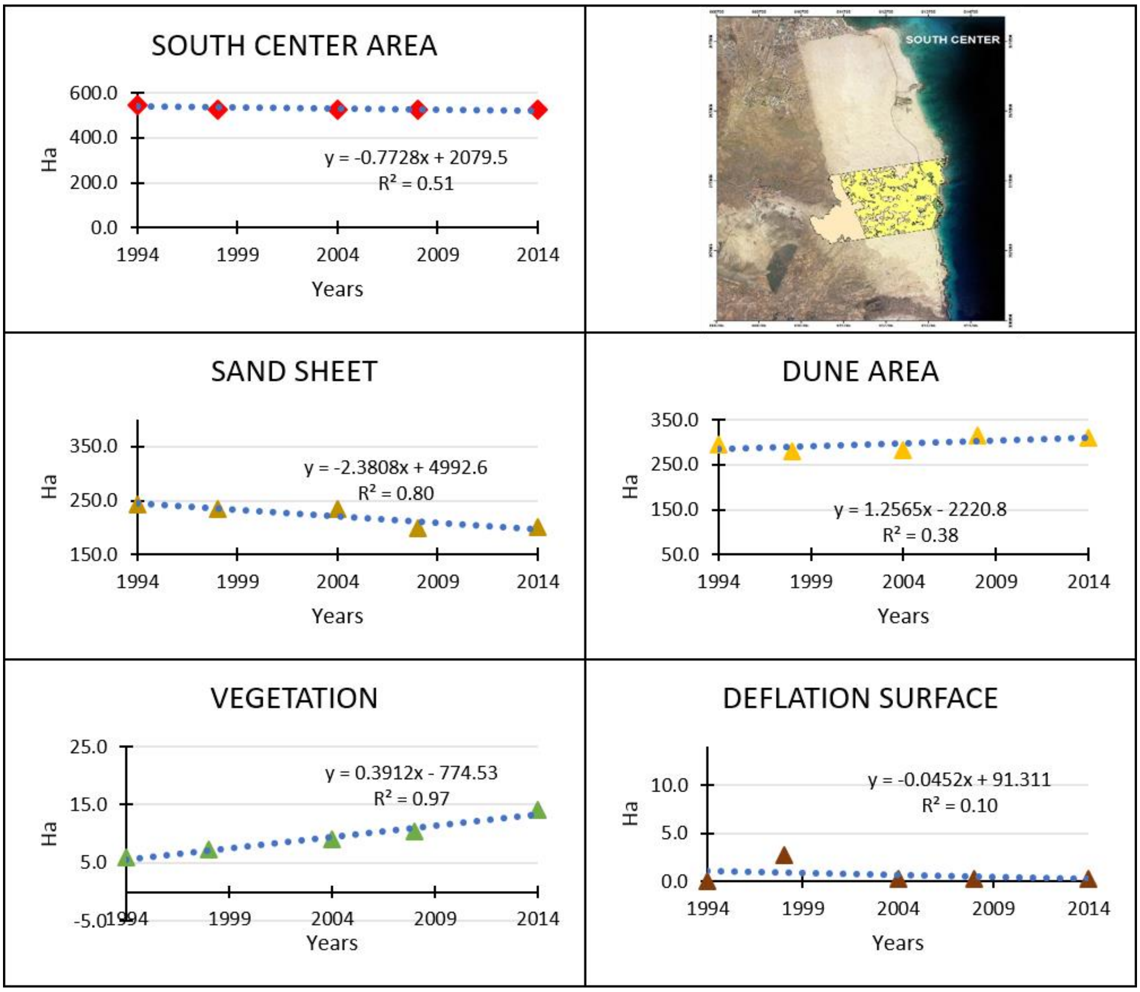


Figure 6. Time evolution of the different geomorphological units at the south center area. Total area occupied by sedimentary environments is decreasing slowly. Sand sheet has irregular patter with a clear decrease tendency. On the opposite, dune areas are increasing. Vegetation area is constantly growing. Deflation surfaces appears at 1998 but then almost disappear.

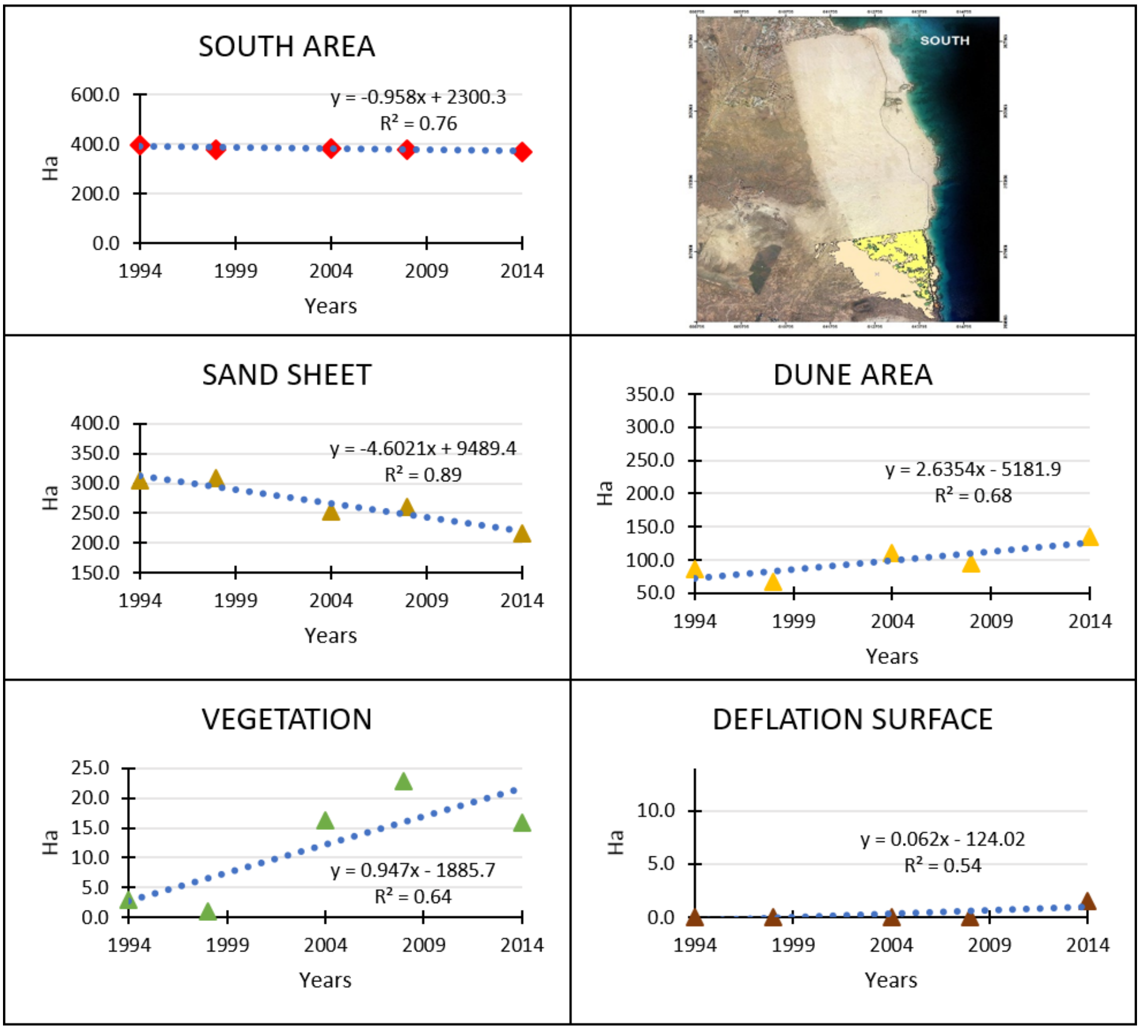


Figure 7. Time evolution of the different geomorphological units at the south area. Total area occupied by sedimentary environments is decreasing more than other subareas. Sand sheet has the highest decrease tendency but it is still the largest landform. Dunes and vegetation are increasing irregularly. Deflation surface appears for the first time in the southeastern limit in 2014.

AREA CHANGE RATES (Ha/y)					
	TOTAL AREA	**SAND SHEETS**	**DUNE AREA**	**VEGETATION**	**DEFLATION SURFACES**
NORTH	0.21	1.69	-2.49	0.84	0.16
NORTH CENTER	-0.01	0.56	-1	0.45	0
SOUTH CENTER	-0.77	-2.38	1.26	0.39	-0.05
SOUTH	-0.96	-4.60	2.64	0.95	0.06
TOTAL	**-1.53**	**-4.64**	**0.4**	**2.63**	**0.17**

Table 2. Change rates for the different geomorphological units in the four sectors in which the dune field has been divided. Note that sand sheets and dunes follow opposite patterns, while there is and efficient vegetation grow in all areas.

With these results, future scenarios were calculated for sedimentary environment distributions for 2050 and 2100 (table 3). Sand sheets is the most affected sedimentary environment and vegetation will become the second largest area. Also, dune areas will be extended.

FUTURE SCENARIO							
Total Areas (Ha)	**YEARS**						
	1994	**1994-2014 (%)**	**2014**	**2014-2050 (%)**	**2050**	**2050-2100 (%)**	**2100**
TOTAL AREA	1918.9	-2.0	1879.9	-2.9	1824.9	-7.0	1748.4
MOBILE DUNES	820.3	-2.6	799.3	1.8	813.7	4.3	833.7
SAND SHEETS	1042.6	-6.5	974.4	-17.1	807.4	-41.0	575.4
VEGETATION	19.6	243.2	67.3	140.8	161.9	81.2	293.4
DEFLATION SURFACES	7.7	64.4	12.7	48.3	18.8	45.3	27.3
MAN MADE INFRAESTRUCTURES	28.7	0.0	28.7	0.0	28.7	0.0	28.7

Table 3. Past and future distribution of the different sedimentary environments. Negative and positive percent values shows erosion and accretion respectively.

3.2 Winds

Wind data obtained for synoptic hours and gust wind was separated in time intervals between orthophotos and represented in wind roses, obtaining two of them for each period, daily average and gust wind (figure 8). Results clearly indicates that prevalent wind direction is from N-NE, both for the daily average and for the highest speed data.

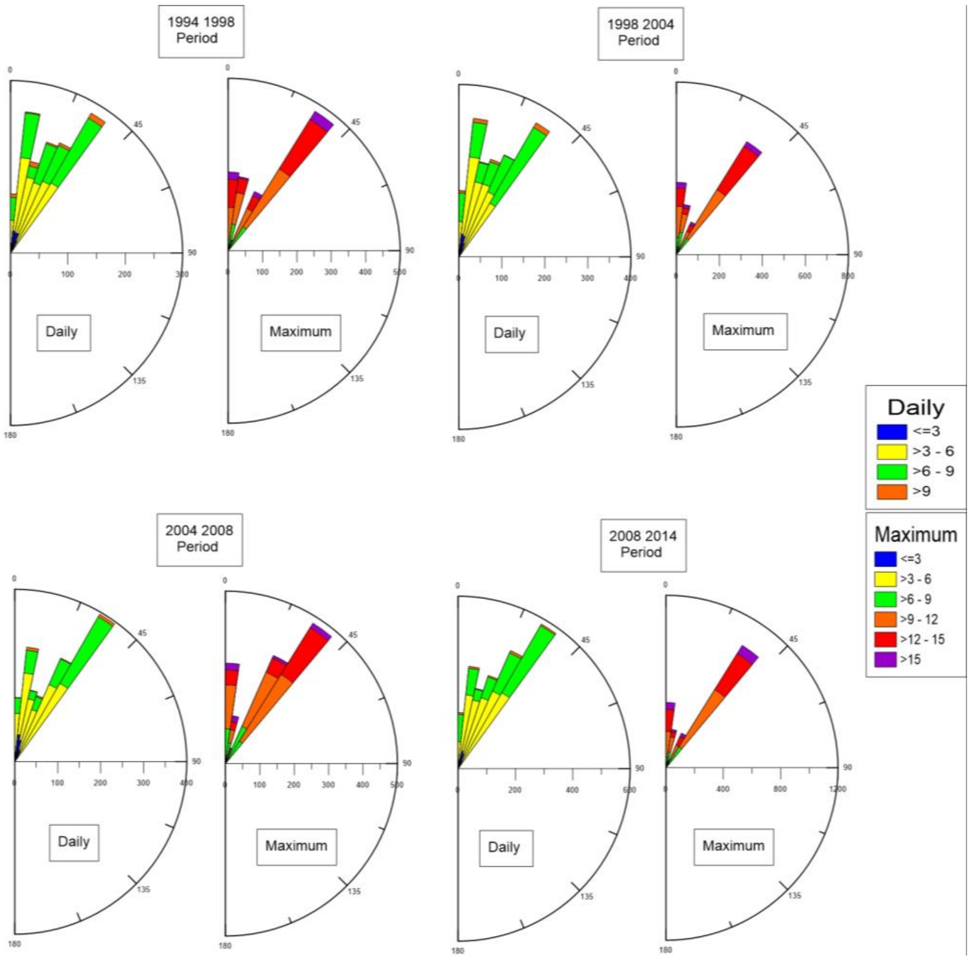


Figure 8. Wind roses for the daily average and the daily wind gust divided in periods.

Average data values (table 4) show little differences between periods, varying their directions in +/- 1.4 degrees and speed +/- 0.4 m/s. Speed maximum wind records are more than double of daily values. Also, wind directions for maximum winds show deviations in around 7 degrees eastward compared with daily wind data.

	Synoptic hours		Wind gust	
Period	**Speed (m/s)**	**Direction (°N)**	**Speed (m/s)**	**Direction (°N)**
1994-1998	5.28	20.17	11.32	26.25
1998-2004	5.32	20	10.84	28.33
2004-2008	4.97	20.74	10.5	27.69
2008-2014	5.32	21.36	11.18	27.85

Table 4. Average wind values for the four time periods.

3.3 Dune Migration

In general terms dunes move southwards, confirming results postulated by Malvárez et al, 2013. However, average direction of dune migration have been changing along time from southwest (183° N in 1994-1998) to southeast (166° N in 2008-2014) (table 5). On the other hand, dune mobility rates are not constant at all, showing significant changes from 6.8 m/y in the period 2004-08 to 9.9 m/y in 1994-98.

Period	Dune Ridges	Distance (m)	Displacement (m/y)	Azimuth (°N)
1994-1998	105	39.6	9.9	182.6
1998-2004	58	45.1	7.5	177.4
2004-2008	66	27.4	6.8	172.5
2008-2014	94	46.9	7.8	166.1

Table 5. Average distances and directions calculated for the total area for each time period. Dune ridges quantity represent the number of crests that could be clearly correlated between consecutive periods.

Representation of the whole amount of dune ridges displacement in wind roses (figure 9) shows that dune transport can reach distances higher than 15 m/y for south, southeast and southwest directions depending on time periods. Also, it seems that transport in changing its course to southeast.

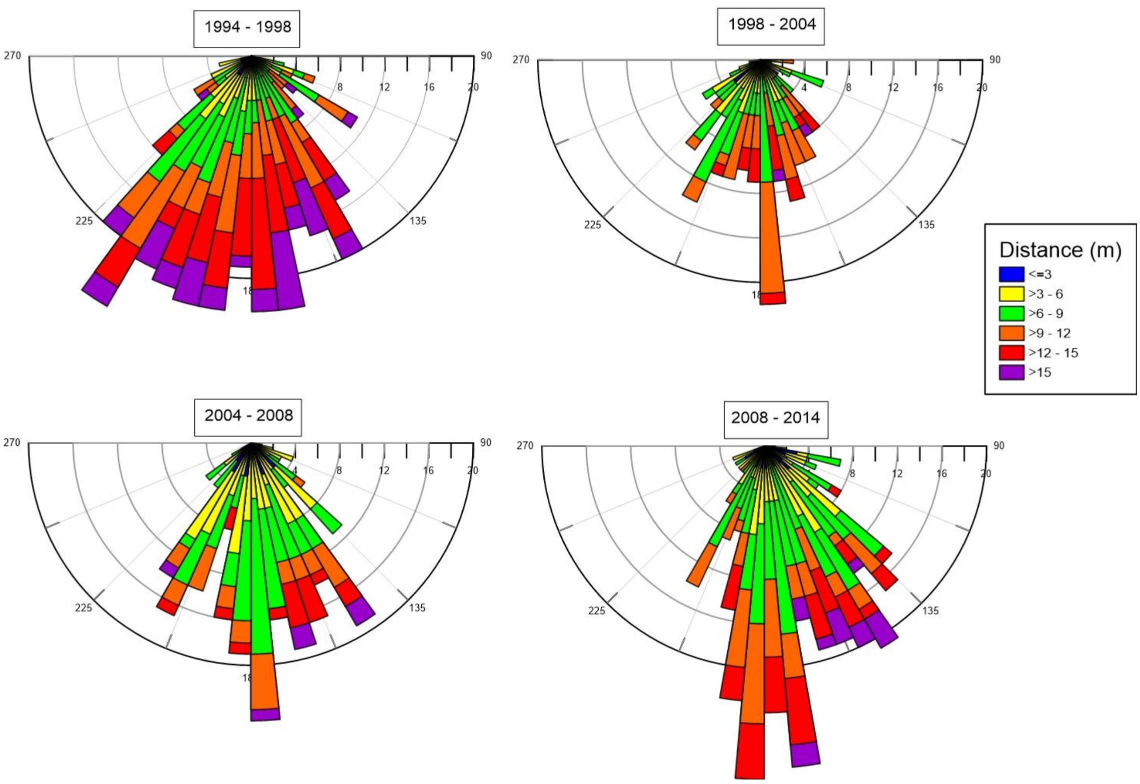


Figure 9. Wind roses for dune ridges displacement for the different elapsed time periods. Values correspond to the total area.

Dune evolution for defined subareas shows significant variations between them. North area has the lowest dune transport. Also, lack of dune ridges makes difficult to estimate dune migration for all periods. Only at 2008 – 2014 period (Figure 10) is possible to estimate dune transport.

Northcenter (figure 11) and southcenter (figure 12) subareas have a greter number of time correlated dune ridges. Direction follows south, southeast and southwest patterns but, transport is changing during periods to southeast tendency. In addition, displacement of dunes is more intense in the southcenter subarea than in the northcenter one.
Lack of dune ridges is also present at the southern subarea (figure 13), allowing only evaluate 1994-1998 and 2008-2014 periods. Dune direction and transport is changing from southwest to south.

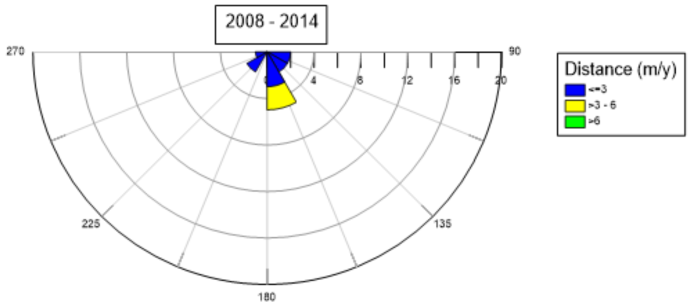


Figure 10. Wind rose for dune ridges displacement at the North area. Only values for the period 2008-2014 are plotted because in the rest of periods there were no enough data.

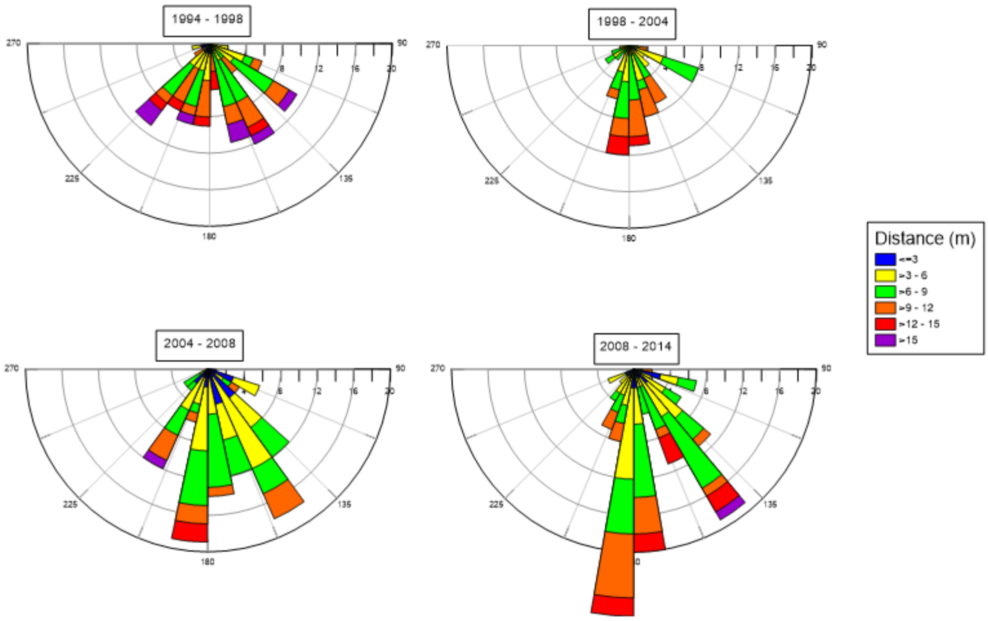


Figure 11. Wind roses for dune ridges displacement for the different elapsed time periods. Values correspond to the North-center area.

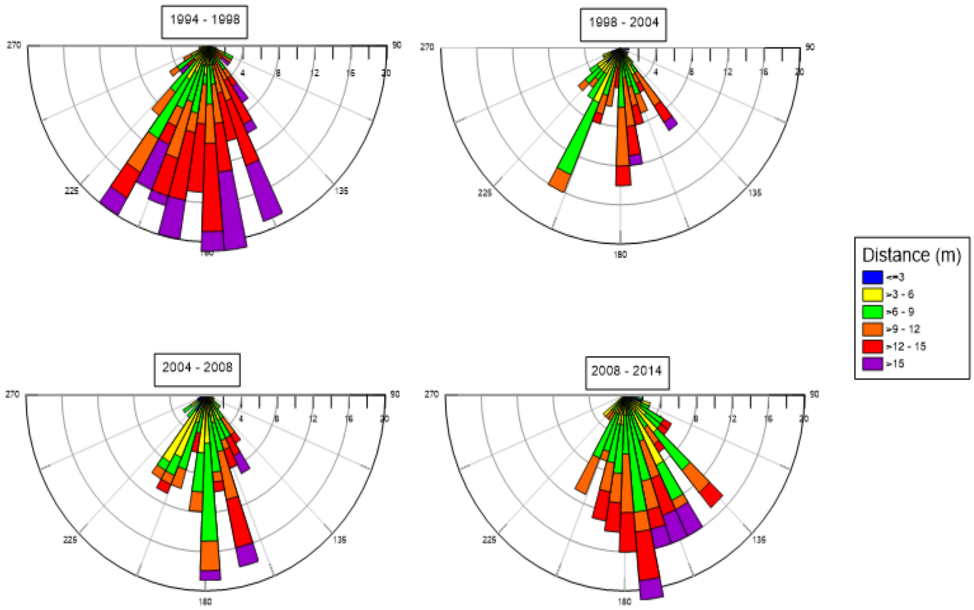


Figure 12. Wind roses for dune ridges displacement for the different elapsed time periods. Values correspond to the Sourth-center area.

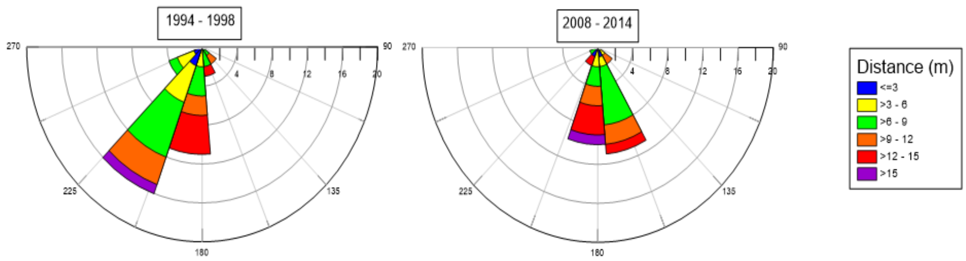


Figure 13. Wind roses for dune ridges displacement corresponding to the Sourthern area. Only values for the periods 1994-1998 and 2008-2014 are plotted because in the rest of periods there were no enough data.

Average dune transport for the studied time period is 8 m/y, higher than values shown by Jiménez et al. 2006 who obtained the average value of 5.8 m/y between 1987 and 2002. Migration rates data measured for the different time periods (table 5) show that there is a decrease in migration rate with time, though in the last period it has increased again (figure 14).

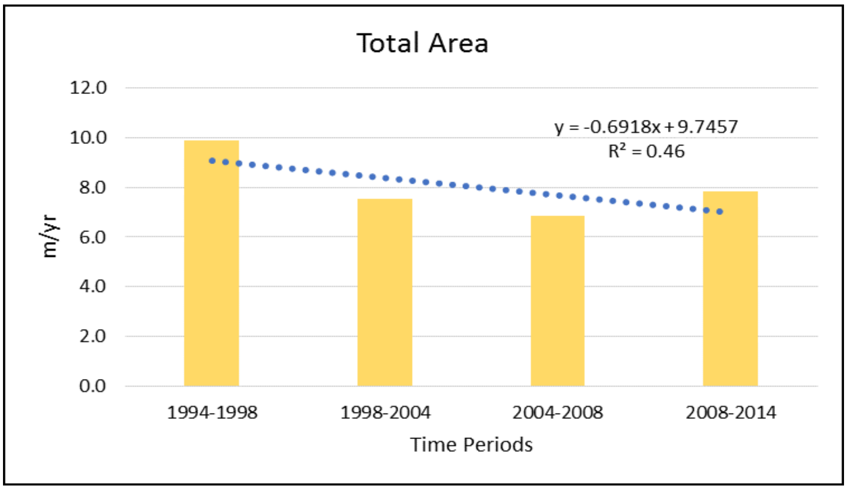


Figure 14. Migration rates at Corralejo dune field total area.

4. DISCUSSION

Detailed cartographic evolution of Corralejo dune filed has been previously carried out in different studies. Criado (1990) analyzed the changes that took place between 1975 and 1987. Jiménez et al. 2006 did the same for the period 1987-2002, and García-Romero et al. 2016 considered changes in the largest time scale, between 1969 and 2009. In order to compare their results with results presented in this work, three main differences have to be highlighted:

The three previous works used only two sets of images for their work, one corresponding to the initial date and the other one for the final date. This a substantial difference between these works and this study, since we have used five orthophotos between 1994 and 2014, so that the evolution trends we show are based not only in an initial and final date but also in three intermediate data.

A second difference is that previous works do not make any spatial differentia, so that when they refer for example to sand sheets, they refer to all the sand sheets in the whole study area. This work includes a spatial analysis so that the Corralejo dune field was divided in four regular north-south sectors, so that the evolution of the different landforms was considered for each sector. This is of critical importance when a certain geomorphological unit follows different patterns in the different sectors.

Another key aspect is that not all authors have digitized the same geomorphological units, or give different names for same landforms. For example, we have called sand sheets all areas were the color and texture in the orthophotos indicates that there is a layer of sand without dunes and with scarce vegetation and/or small outcrops of the underlying substrate. García-Romero et al. 2016 differentiate between sand sheets, hummock dunes and stabilized dunes, and this study consider that these sedimentary environments cannot be differentiated by classical photointerpretation without field work and in situ observations.

Therefore, comparison of evolution trends obtained by previously mentioned authors has to be carefully done. One example is the evolution of mobile dunes. Criado (1990) indicates that the area covered by mobile dunes decreased in 125 Ha between 1975 and 1987 (-10.4 Ha/y). Jiménez et al. 2006 measured an increment of 42 Ha in the period 1987-2002 (+2.8 Ha/y), and García-Romero et al. 2016 state that the area covered by mobile dunes (barchanoid ridges and barchan dunes) present a decline of 412 Ha between 1969 and 2009 (-10.3 Ha/y). According with our study, dune areas remains virtually stable but with a small increment of +0.4 Ha/y.

Nevertheless those differences, there is agreement with them that aeolian landforms in the Canary Islands have undergone significant environmental changes in the last decades. The most relevant observed changes in Corralejo dune field are the southwards displacement of

mobile dunes, the reduction of sand sheets in the southern half and the increase of vegetation in the whole area.
Even though we have not got access to LiDAR data to compute volume changes, detected evolution of landforms indicate that there is a smaller amount of mobile sediments, which is directly related to a limited sediment supply. Jiménez et al. 2006, Valdemoro et al. 2007 and Alonso et al. 2011 agree that there are two main reasons that could explain the lack of sediment inputs: the urban all along the north coast of Corralejo dune field, which reduce wind stress retaining sediments and the depletion of sand in the continental platform, which has been the main source of sediments over time (Hernández-Calvento & Mangas, 2004). In fact, Hidtma-Iberinsa (2005) indicates that there are hardly any submerged sand banks along the northern coast of Fuerteventura that could feed the Corralejo beaches and dunes.

Regarding mobile dunes landform, it clearly shows a southwards migration, losing area in the north and increasing in the south, while the opposite scenario is reported for sand sheets. This inverse correlation between sand sheets and dune areas can be perfectly visualized in figure 15, and can be explained by two different processes: in the north area mobile dunes are migrating southwards and the lack of new sedimentary inputs determine that no new dunes are formed that could eventually substitute the ones that are leaving the area. The resultant landform is a sand sheet that is steadily colonized by vegetation. On the other hand, in the southern area the opposite process is taking place, since mobile dunes migrating southwards are slowly occupying an area that was a former sand sheet. In fact, Jiménez et al. 2006 state that between 1987 and 2002 the southern limit of mobile dunes showed a net displacement of 80 m towards the south.

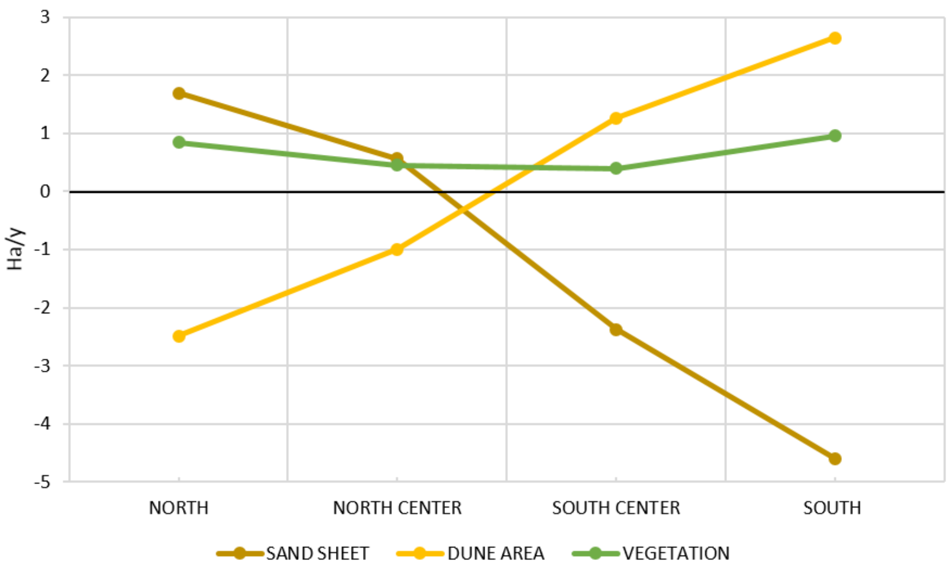


Figure 15. Spatial changes for the three mayor units along the study area. Note the opposite pattern followed by sand sheets and dunes.

At this point, it's also important to consider that sand sheets are mostly decreasing in south areas much faster than the growth of dune areas. This is happening because in south areas sand sheets are not only being replaced by mobile dunes, but also by areas densely covered by vegetation.

Regarding changes in vegetal cover, Criado (1990) indicates that there is an increasing trend of 3.18 Ha/y from 1975 to 1987 and this study shows that vegetation increases 2.63 Ha/y from 1994 to 2014, which are quite similar numbers. According with Hesse & Simpson (2006), loss of sediment supply plays a role in favor of growing vegetation, which gain height and volume. This is clearly seen along and across the entire area. There is also a more local factor related with anthropic infrastructures. Buildings and other structures modifies wind and sediment transport patterns, generating shadow zones with less wind stress on the leeward where vegetation can grow easily. This process can be seen on figure 16, where La Oliva Beach Resort is located and vegetation is growing faster than any other area. Moreover, vegetal cover produces stabilization of sediments (Alcantara-Carrio & Alonso 2001) reducing dune areas.

Different vegetation evolution pattern identified for south area is related to dune areas which are migrating to south and could cover plant periodically.

Figure 16. Vegetation growth near La Oliva Beach Hotel inside Corralejo dune field.

Deflation surfaces are present where dunes and sand sheets disappear, so that a hardened clayed substrate is visible. These landforms are interpreted in other canarian dune fields as indicators of shortage of sediments (Hernández et al. 2007), and their continuous and increasing presence in the northern area of Corralejo seems also to be related with the lack sedimentary inputs. Other small and occasional spots of deflation surfaces, such as those found in the south-center area in 1998 or in the south area in 2014 could be also initial indicators of the thin layer of sand that cover these areas. They do not seem to be related with seasonal rains because they are located just at certain locations.

Trade winds from NNE are dominant in the area (Malvárez et al. 2013). Average wind direction maintain closer values along time, but maximum wind directions are approximately deviated 7 degrees eastward related to daily winds. This difference is probably a consequence of Lanzarote Island, located north of Corralejo, which originates deflection of the strong winds, causing this deviation.

Wind observations area generally representative of the directions of strong sand transporting winds (Mason et al. 2008), but because of complex physical interactions, the wind direction interpreted for dunes in some circumstances may or may not correspond to the main persistent prevailing wind (Bigarella et al. 2006). In the study area wind data directions doesn't correspond with dune direction transport. Topography may deflect winds inside dune fields (Bigarella et al. 2006). The increase in ground topography on the western border of the dune field may cause this effect.

It is clear that dunes move southwards as general trend (figure 17), but it is not clear why dune ridges tend to change towards an eastward direction along time (table 5). This change does not seem to be related with winds, which does not show any range in direction. Maybe topographic, grain size or another physical characteristics are producing this deviation.

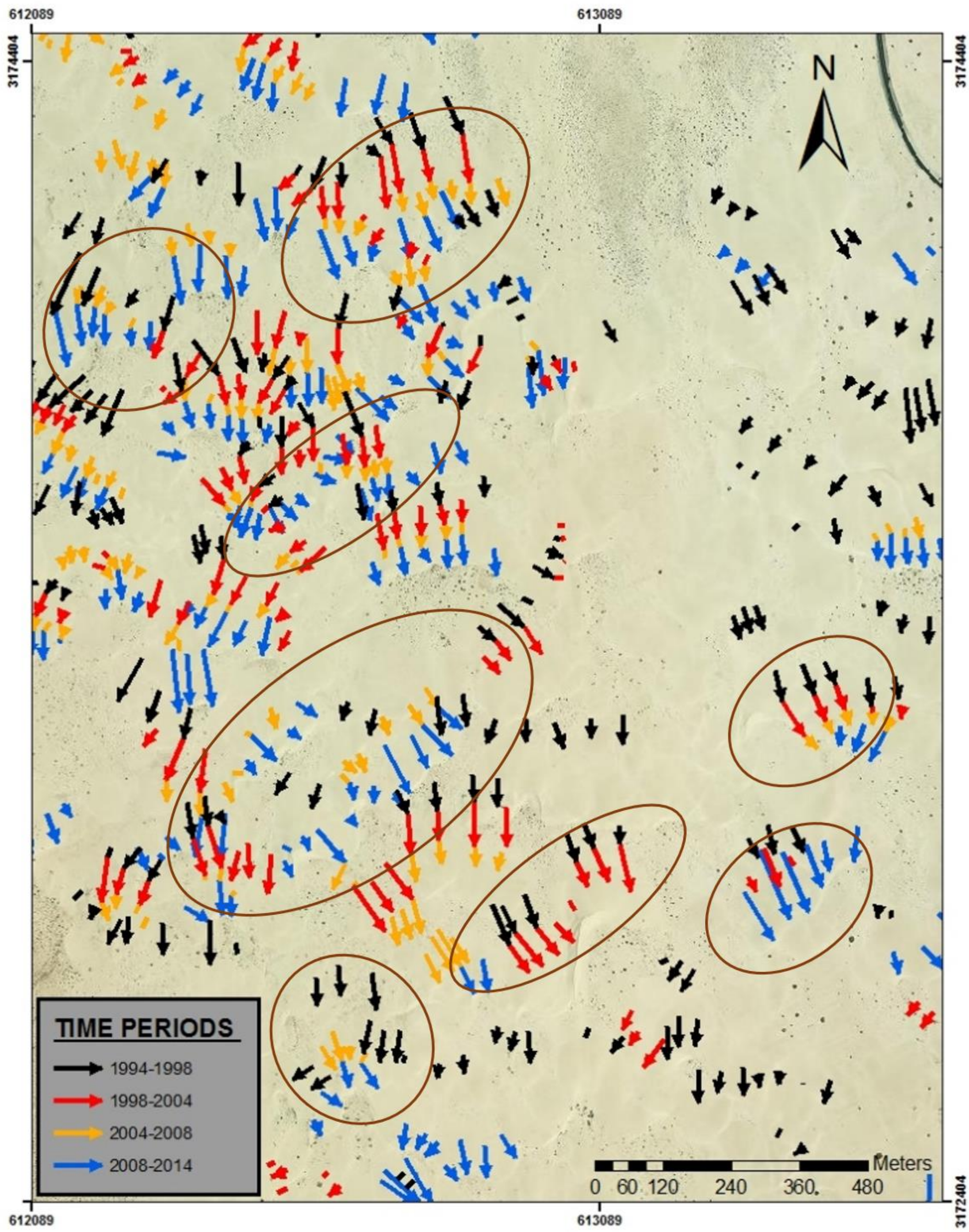


Figure 17. Example of dune ridges movement with correlated evolution in time. Dune ridges changing directions towards east is marked in brown elipses.

Dune average migration rates were compared with average wind daily data and wind gust data. There is not good correlations with daily winds but there is a quite good correlation between wind gust and migration rates (figure 18). This result confirms that stronger winds are responsible for dune transport (Houser et al. 2008), and that the average dune crest displacement is function of the average wind gust.

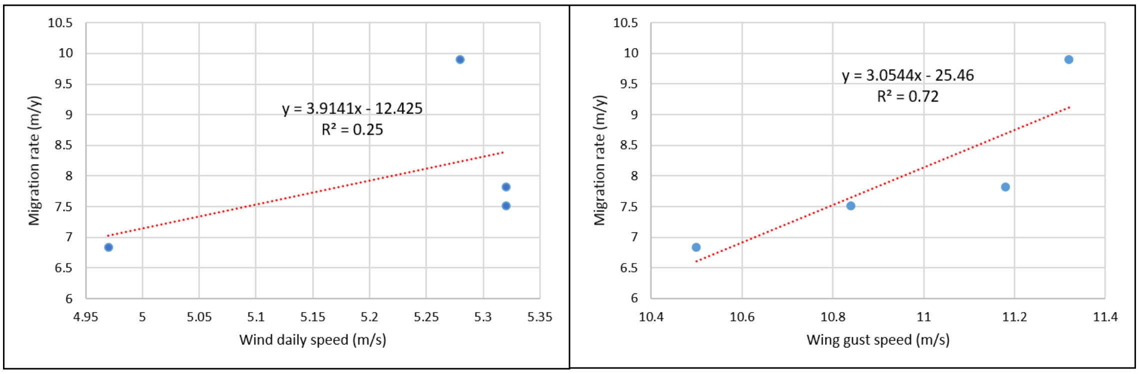
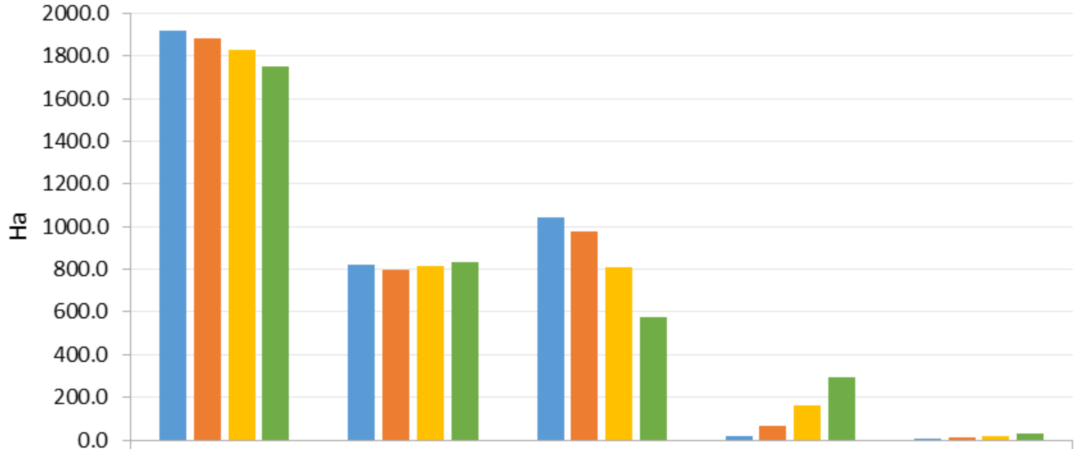


Figure 18. Relationship between average daily wind speed and annual migration rate of dune crests (left) and between average wind gust speed and annual migration rate of dune crests (right).

Some examples for migration rates influenced by high winds registered at different dune fields ranges from 3 m/y from French Atlantic Coast (Lorin & Viguier, 1987), 8.5 m/y from Cantabria (Arteaga et al. 2008), 10 m/yr from Brazilian coasts (Barbosa & Dominguez, 2004) and 17.5 m/y for Ceara coast, Brazil (Jimenez et al. 1999). The average value obtained in this work (8 m/y) is slightly higher than the one obtained by Jiménez et al. 2006 in the same area (5.8 m/y).

Assuming that the evolution rates we have obtained will keep constant in the mid-term, the future scenarios at Corralejo dune field show a slight but constant loss of the dune field area, which will be replaced by volcanic rocks. It will be a great increment of vegetated areas all along the dune field, but particularly in the northern sector and related to man-made infrastructures. It will be a clear reduction in sand sheets landforms, particularly at the southern limit. Deflation surfaces will slightly increase, although its extension will only reach 1.5% of the total area by 2100. Finally, areas covered by dunes will have a nearly stable evolution, since the dunes will keep moving southwards, so that at the north area mobile dunes will eventually disappear but at the south they will keep growing. (Figure 19).



	CORRALEJO DUNE FIELD	DUNE AREA	SAND SHEETS	VEGETATION	DEFLATION SURFACES
1994	1918.9	820.3	1042.6	19.6	7.7
2014	1879.9	799.3	974.4	67.3	12.7
2050	1824.9	813.7	807.4	161.9	18.8
2100	1748.4	833.7	575.4	293.4	27.3

Figure 19. Future Corralejo dune field scenarios proyected for 2050 and 2100. Values in Ha.

5. CONCLUSIONS

Techniques for GIS are highly recommended to analyze dune field evolutions. In this study, geospatial analysis using GIS was determinant to identify current and future changes at Corralejo dune field giving reliable information that allowed to achieve the proposed objectives.

Corralejo dune field is suffering changes from 1994 to 2014 mainly because of urban development and loss sediment supply.

Dunes has migration rates of 8 m/y with south-southeast direction and are mainly influenced by wind gust speed. Absence of dune ridges on north areas evidence low sediment accumulation which is also related with the absence of sedimentary inputs.

Interaction between sedimentary environments inside Corralejo dune field are clearly evidenced. Current conditions suggest significant balances between them will be more visible at medium and long term periods. These changes indicates progressive dune field area loss and predominance of static environments.

Future studies at this dune system should also include LiDAR measurements to account for dune heights and sediment volume evolution, which could be related with geomorphological landforms and sediment transport.

6. REFERENCES

Alcalá, A., 1995. Diccionario de cartografía topografía, fotogrametría, teledetección, GPS, GIS, MDT (Otero, I., coord.). *Madrid Ciencias Sociales D.L,* pp. 266.

Alcantara-Carrió, J. & Alonso, I., 2001. Aeolian sediment availability in coastal areas defined from sedimentary parameters. Application to a case study in Fuerteventura. *Scientia Marina*, 65, pp.7–20.

Alcántara-Carrió, J., Fernández-Bastero, S., Alonso, I., 2010. Source area determination of aeolian sediments at Jandia Isthmus (Fuerteventura, Canary Islands). *Journal of Marine Systems,* 80, pp. 219-234.

Alonso, I., Hernández, L., Alcántara-Carrió, J., Cabrera, L., Yanes, A., 2011. Los grandes campos de dunas actuales de Canarias. Las Dunas de España, pp. 467-496.

Agencia Estatal de Meteorología de España. Daily wind and wind gust direction and speed synoptic registries from 1994 to 2014 from Corralejo port and fuerteventura airport meteorogical stations.

Andrews, B., Gares, P., Colby, J., 2002. Techniques for GIS modeling of coastal dunes. *Geomorphology*, 48(1-3), pp.289–308.

Arteaga, C., Sanjosé, J., Serrano, E., 2008. Terrestrial photogrammetric techniques applied to the control of a parabolic dune in the Liencres dune system, Cantabria (Spain). *Earth Surface Processes and Landforms*, 34, pp.155–161.

Barbosa, L. & Domínguez, J., 2004. Migration of parabolic dunes at Aberffraw, Anglesey, north Wales. Geormophology, 59, pp. 165-174.

Bigarella, J., Klein, A., Menezes, J., Vintérm G., 2006. Southern Brazilian Coastal Dunes: Movement and Structures. *Journal of Coastal Research*, 2004(SI 39), pp.1–15.

Blumberg, D., 1998. Remote sensing of desert dune forms by Polarimetric Synthetic Aperture Radar (SAR). *Remote Sensing of the Environment*, 65, 204-216.

Breed, C., Fryeberger, S., Andrews, S., 1979. Regional studies of sand seas, using Landsat ERTS imagery. *A Study of Global San Seas, McKee Edition, USGS*, pp. 305-393.

Brown, D. & Argobast, A., 1997. Application of digital photogrammetry to the study of active coastal dunes. *AAG Annual Meeting* (w/n).

Cabrera-Vega, L., Cruz-Avero, N., Hernández-Calvento, L., Hernández-Cordero, A., Fernández-Cabrera, E., 2013. Morphological changes in dunes as an indicator of anthropogenic interferences in arid dune fields. *Journal of Coastal Research*, (65), pp.1271–1276.

Cartográfica de Canarias (GRAFCAN). 1994, 1998, 2004, 2008 and 2014 Orthophotos from Fuerteventura Island. Geotiff format. *Infraestructura de Datos Espaciales de Canarias (IDECANARIAS).*

Criado, C., 1988. El relieve erosivo; VV.AA. Geografía de Canarias, Editorial Interinsular Canaria, I: 105-142.

Criado, C., 1990. Dinámica de dunas, paleosuelos y torrencialidad en el Pleistonceno reciente y Holoceno de Fuerteventura (Islas Canarias). *I Reunión Nacional de Geomorfología* (Gutiérez, M., Peña J., & Lozano, M., eds), SEG e Instituto de Estudios de Turolenses, pp. 245-254.

Criado, C., Yanes, A., Hernández, L., Alonso, I., 2011. 18. Origen y formación de depositos eólicos en Canarias. *Las Dunas de España.* pp. 447–465.

Dolan, R., Hayden, B., Heywood, J., 1987. A new photogrammetric method for determining shoreline erosion. *Coastal Engineering,* 2, pp. 21-39.

Dong, P., 2015. Automated measurement of sand dune migration using multi-temporal lidar data and GIS. *International Journal of Remote Sensing*, 36(21), pp.5426–5447.

Fernandez-Cabrera E., Roca-Bosch E., Cabrera-Vega L., Hernandéz-Calvento L., Pérez-Chacón E., 2012. Estudio de la perecepción social en el entorno del parque natural de las dunas de Corralejo (Fuerteventura, Islas Canarias): Aplicaciones para la gestión integrada de zonas costeras. *I Congreso Iberoamericano de Gestión Integrada de Áreas Litorales*, pp.1186–1196.

Finkel, H., 1961. Movement of barchan dunes measured by earial photography. *Photogrammetric Engineering,* 27, pp. 439-444.

García-Romero L., Henández-Cordero A., Fernandéz-Cabrera E., Peña C., Hernández-Calvento L., Pérez-Chacón E., 2016. Urban-touristic impacts on the aeolian sedimentary systems of the Canary Islands: conflict between development and conservation. Island Studies Journal, 11(1), pp. 91-112.

Hernandez-Calvento, L., Ruiz, P., Naranjo, A., Camino, J., Romero, L., Perez-Chacón, E., 1999. Aplicaciones de las unidades de paisaje en los diagnósticos de limitaciones para acoger usos urbanos. *Monografías de L´Equip*, 7, pp. 91-104.

Hernández-Calvento, L. & Mangas, J., 2004. Caracterización de los materiales sedimentarios aflorantes en el sistema de dunas de Maspalomas (Gran Canaria). *Procesos geomorfológicos y evolución costera (R. Blanco-Chao, J. López-Bedoya* *y A. Pérez-Alberti). Universidad de Santiago de Compostela,* pp. 67-81.

Hernández, L., Alonso, I., Sánchez-Pérez, I., Alcántara-Carrió, J., Montesdeoca, I., 2007. Shortage sediments is the Maspalomas Dune Field (Gran Canaria, Canary Islands) Deduced from analysis of aerial photographs, Foraminiferal content and sediment transport trends. *Journal of Coastal Research,* 23(4), pp. 993-999.

Hesse, P. & Simpson, R., 2006. Variable vegetation cover and episodic sand movement on longitudinal desert sand dunes. *Geomorphology*, 81(3-4), pp.276–291.

Hidtma-Iberinsa., 2005. Estudio ecocartográficodel litoral de la Isla de Fuerteventura. *Dirección General de Costas, Ministerio del Medio Ambiente*.

Houser, C., Hapke, C., Hamilton, S., 2008. Controls on coastal dune morphology, shoreline erosion and barrier island response to extreme storms. *Geomorphology*, 100(3-4), pp.223–240.

Hugenholtz, C. & Barchyn, T., 2010. Spatial analysis of sand dunes with a new global topographic dataset: New approaches and opportunities. *Earth Surface Processes and Landforms*, 35(8), pp.986–992.

Illenberger, W. & Rust, I., 1988. A sand budget for the Alexandria coastal dunefield, South Africa. *Sedimentology,* 35, pp. 513-521.

Jaramillo, A., 1986. Las dunas del litoral: al capricho del viento. *MOPU magazine*, 336, pp.18-24.

Jimenez, A., Maia, L., Serra, J., Morais, J., 1999. Aeolian dune migration along Ceara coast, north-eastern Brazil. *Sedimentology,* 46, pp. 689-701.

Jiménez J., Alonso, I., Valdemoro H., 2006. Estudio del estado actual de los sistemas dunares de Corralejo y Jandía (Fuerteventura). Identificación de Problemas y propuestas de actuación. Informe I, Corralejo. *Direccion General de Costas, Ministerio de Medio Ambiente.*

Kay, R., & Alder, J., 1999. Coastal management and planning. *E & FN SPON. New York*, pp. 375.

Lancaster, N., Gaddis, L., Greely, R., 1992. New airborne imaging radar observations of sand dunes: Kelso Dunes, California. *Remote Sensing of the Environment,* 39, pp. 233-238.

Lesica, P. & Cooper S., Succession and disturbance ins sandhills vegetation: constructing models for managing biological diversity. *Conservation Biology*, 13 (29), pp. 239-302.

Lorin, j. & Viguier, J., 1987. Hydrosedimentary conditions and present evolution af Aquitain Coast. *Bulletin Institute Bassin dÀquiataine,* 41, pp. 95-108.

Malvárez, G., Jackson D., Navas F., Alonso I., Hernandez-Calvento L., 2013. A Conceptual Model for Dune Morphodynamics of the Corralejo Dune System, Fuerteventura, Spain. *Journal of Coastal Research*, 2(65), pp.1539–1544.

Mangas, J., Pérez-Chacón, E., Hernández-Calvento, L., Menéndez, I. y Rodriguez, S., 2012. Procedencia y características texturales de las arenas eólicas costeras en la isla de la Graciosa (Islas Canarias). *Geotemas*, pp. 577-580.

Mason, J., Swinehart, J., Huayu, L., Xiaodong, M., Phueng, C., Yali, Z., 2008. Limited change in dune mobility in response to a large decrease in wind power in semi-arid northern China since the 1970s. *Geomorphology*, 102(3-4), pp.351–363.

Mckee, E., 1966. Structure of dunes at white Sands National Monument, New Mexico. *Sedimentology,* 3, pp. 1-69.

Meco, J., Petit-Marie, N., Fontugne, M., Shimmield, G., Ramos, A., 1997. The quaternary deposits in Lanzarote and Fuerteventura (Eastern Canary Islands, Spain): An overview. *Climates of the Past, Proceeding CLIP Project,* pp. 123-136.

Menéndez, I., Cabrera, L., Sánchez-Pérez, I., Mangas, J., Alonso, I., 2009. Characterisation of two-lacustrine loessoid deposits on the island of Gran Canaria, Canary Islands. *Quaternary International,* 196, pp. 36-43.

Menéndez, I., Pérez-Chacón, E., Manfas, J., Tauler, E., Engelbrecht, J., Derbyshire, E., Cana, L., Alonso, I., 2014. Dust Deposits on La Graciosa Isalnd (Canary Islands, Spain): Texture, mineralogy and a case study of recent dust plume transport. *Catena*, 117, pp. 133-144.

Moore, L., 2000. Shoreline Mapping Techniques. *Journal of Coastal Research,* 16(1), pp.111–124.

Paskoff, R., 1993. *Cótes in danger; Masson*, pp. 250

Paskoff, R., 1998. *Les littoraux. Impact des aménagement sur leur évolution; Armand Colin*, pp. 260

Sanjaume E., Gracia F., Flor G., 2011. 1: Introducción a la geomorfología de sistemas dunares. *Las Dunas de España.* pp. 13–63.

Suarez C., & Henandéz-Calvento L., 1998. Impactos ambientales provocados por los equipamientos turísticos en los ecosistemas dunares. *Medio Ambiente Canarias*, 7, pp. 16-18.

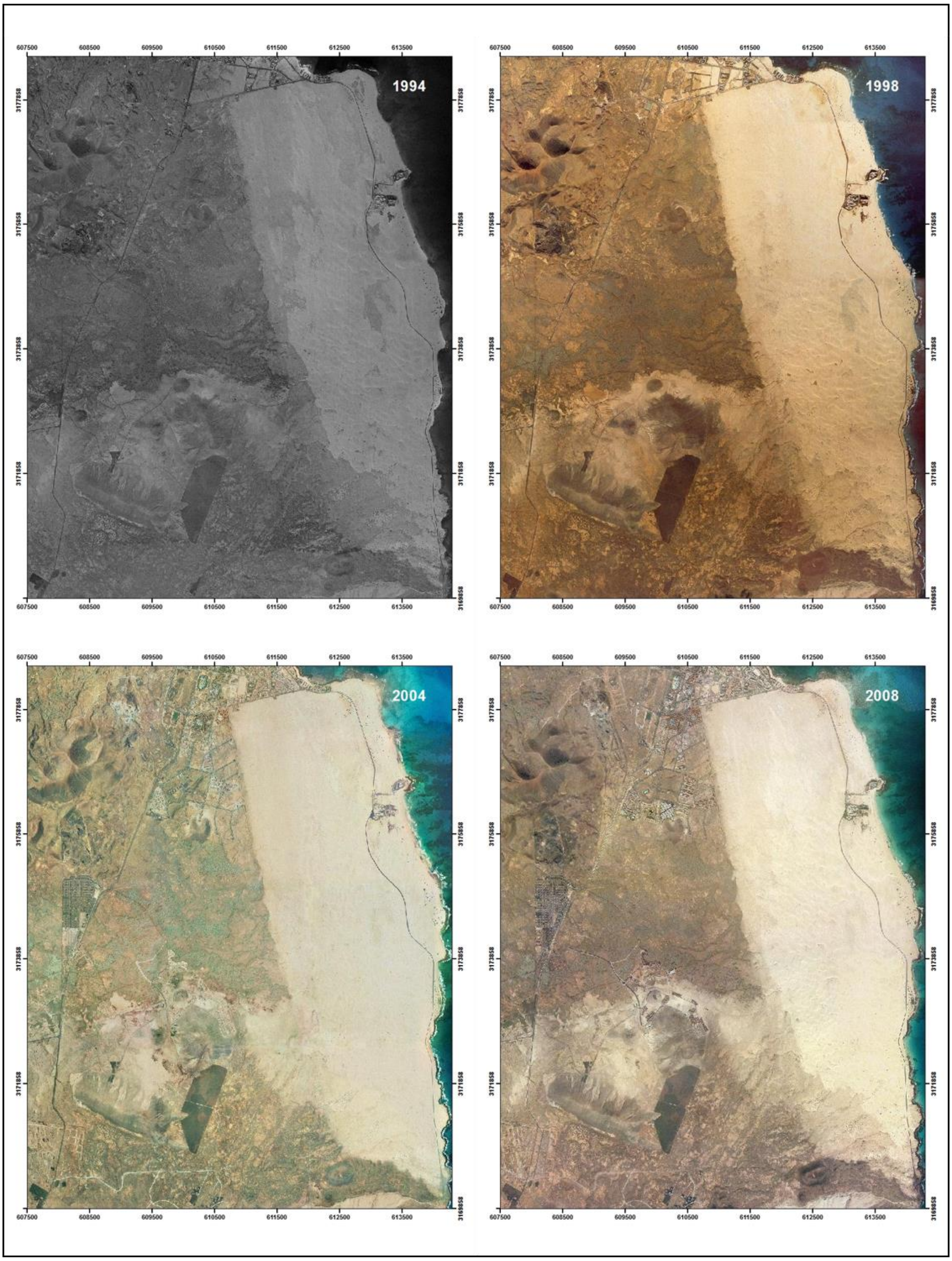
Thomas D., 1999. Coastal and continental dune management into the twenty-fisrt century. *Aeolian environments, sediments and landforms; Jhon Wiley and sons.* pp. 105-127.

Valdemoro, H., Jiménez, J., Alonso, I., Lorente, P., Rodriguez-Herrerías, M., 2007. Coastal dunefield evolution in conditions of limited sediment availability. Natural and anthropogenic controls of the Corralejo dunes. 6th International Symposium on Coastal Sediment Processes. Coastal Sediments '07, pp. 1283-1296

Wolf, P. & Dewitt, B., 2000. Elements of Photogrammetry with Applications in GIS. McGraw-Hill, pp. 624.

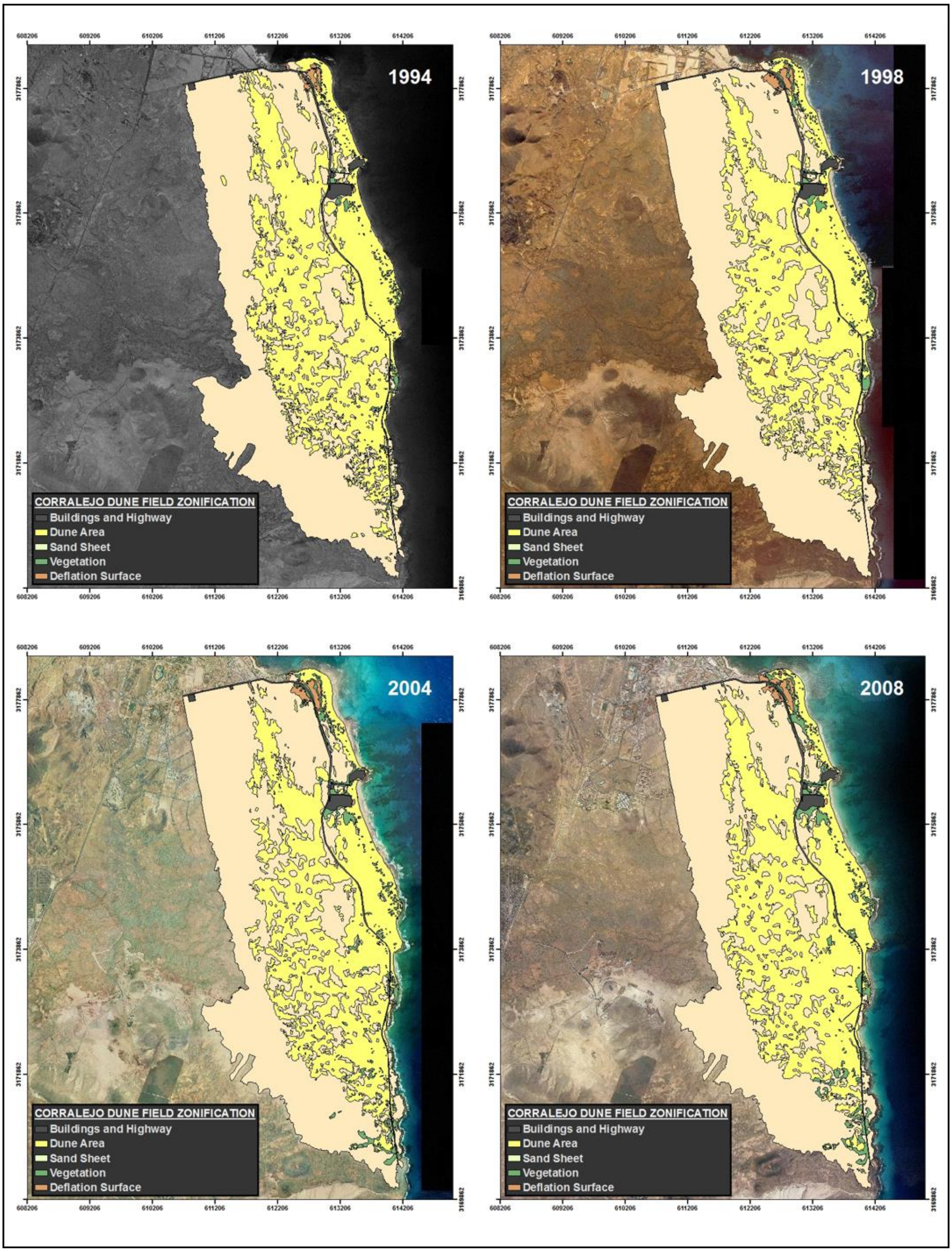
ADDITIONAL INFORMATION

ORTHOPHOTOS SELECTED

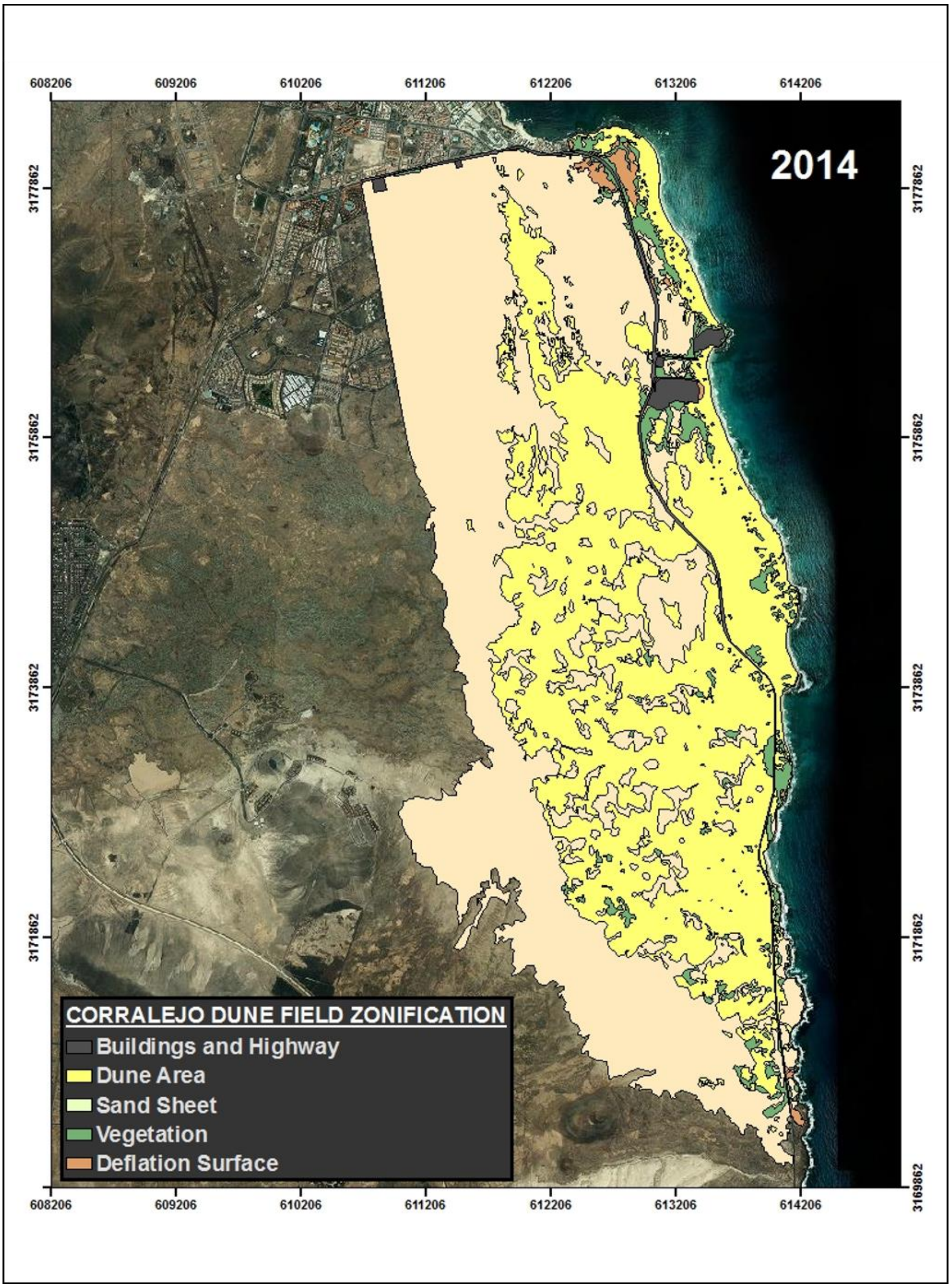


ORTHOPHOTOS SELECTED

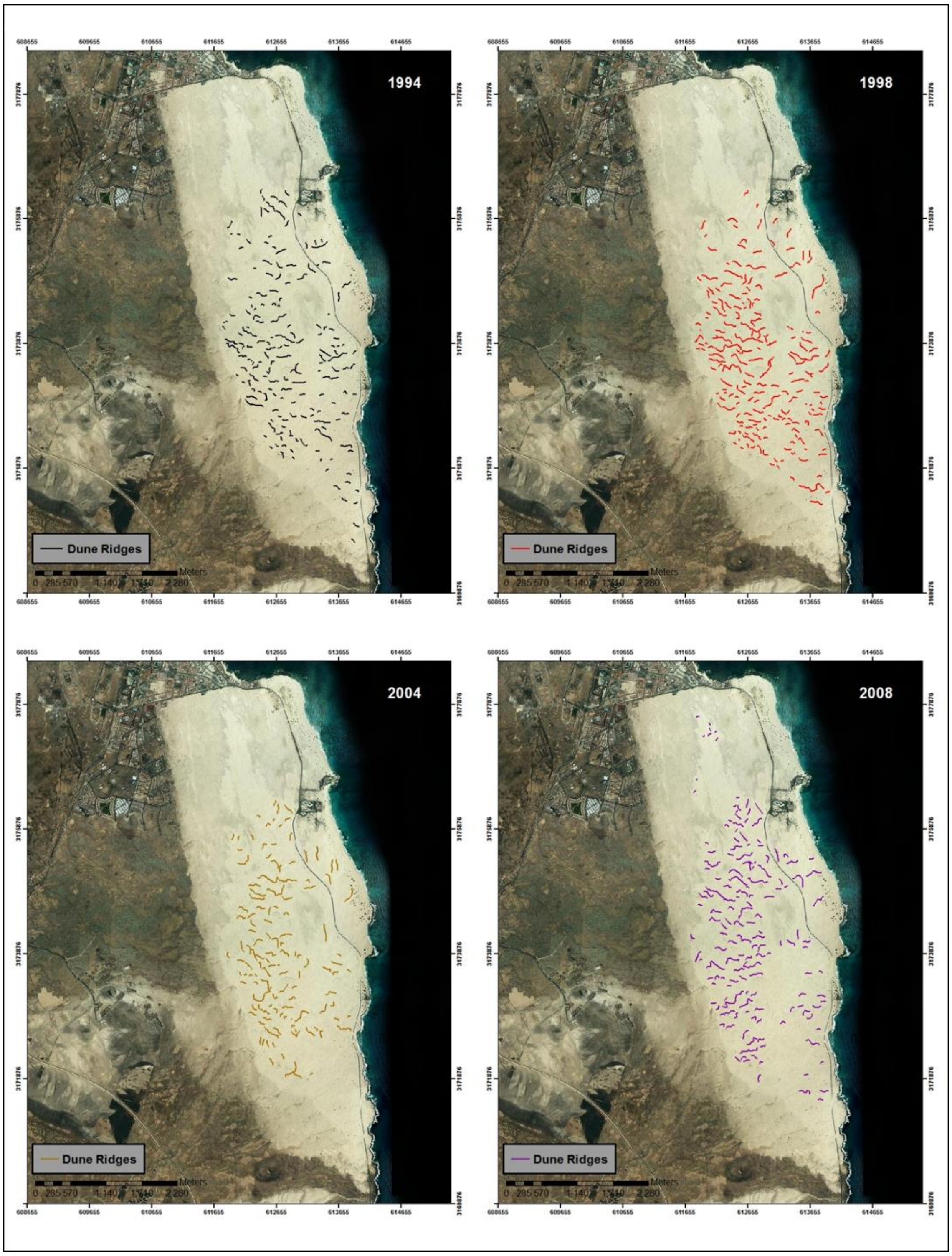
SEDIMENTARY ENVIRONMENTS



SEDIMENTARY ENVIRONMENTS

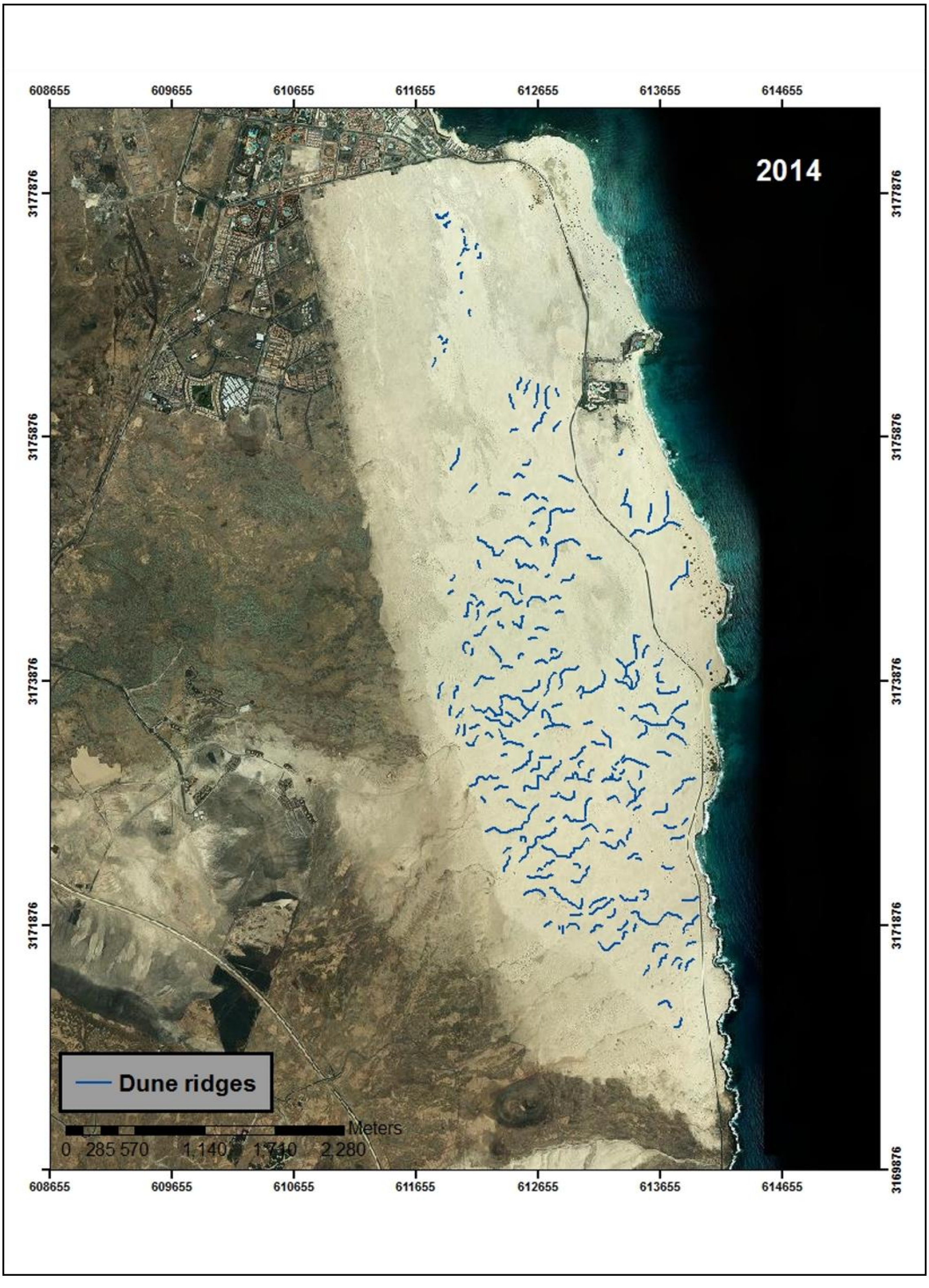


DUNE RIDGES



608655
609655
610655
611655
612655
613655
614655
3177876
3175876
3173876
3171876
3169876
1994
Dune Ridges
Meters
0 285 570 1 140 1 710 2 280
1998
Dune Ridges
Meters
0 285 570 1 140 1 710 2 280
2004
Dune Ridges
Meters
0 285 570 1 140 1 710 2 280
2008
Dune Ridges
Meters
0 285 570 1 140 1 710 2 280

DUNE RIDGES



608655
609655
610655
611655
612655
613655
614655
3177876
3175876
3173876
3171876
3169876
2014
Dune ridges
Meters
0 285 570 1,140 1,710 2,280