Biogeomorphological processes in an arid transgressive dunefield as indicators of human impact by urbanization

Abstract

Urban and tourist developments can have long-lasting impacts on coastal environments and fundamentally alter the evolution of coastal dune systems. This is the case of the Maspalomas dunefield (Gran Canaria, Canary Islands), hosting one of the largest tourist resorts in Spain. The resort was built on top of a sedimentary terrace at 25 meters above sea level (El Inglés) in the 1960s, and has subsequently affected local winds and therefore aeolian sediment transport patterns. Buildings on the terrace deflect the winds to the south of the dunefield, where the rate of sediment transport accelerated. A shadow zone appeared to the lee side of the resort with a consequent decrease in wind speed and aeolian sediment transport and an increase in vegetation cover. In this paper, first we characterize the environmental changes around El Inglés terrace in recent decades, and describe the changes in the shadow zone through an analysis of the evolution of sedimentary volumes and vegetation characteristics (density, spatial patterns, and plants communities). A series of historical aerial photographs, recent orthophotos and digital elevation models obtained by digital photogrammetry and LiDAR, as well as fieldwork were used to characterize plant communities and spatial-temporal changes in erosive landforms. Results show changes in the pattern and migration rates of dunes located at the southern edge of the urbanization, as well as the formation of blowouts and large deflation areas, where the vegetation increases in density and number of plant communities. We discuss eco-anthropogenic factors that have produced these environmental changes.

Keywords: arid coastal dunes system, aeolian shadow zones, biogeomorphological evolution, blowout, environmental changes, urban-tourist buildings

1. INTRODUCTION

The coast has a great diversity of environments and resources, making it a particularly attractive area for human settlements, both as a place of residence and as an ideal location for multiple recreational and economic activities (Cendrero et al., 2005). The last few decades have seen an accelerated *littoralisation* process (accelerated rate of human occupation at the coast) (Cerdá, 2002), with a significant increase in human pressure, which alters natural processes due to human developments, therefore increasing the vulnerability of coastal environments, especially sandy coasts (Brown and McLachlan, 2002; Martinez et al., 2006). This process has accelerated on some arid coastlines, especially those with beach-dune systems, with good climate conditions during the winter driving the development of both tourist and residential urbanization (Hernández-Calvento et al., 2014). The poor, or incorrect location of buildings and infrastructure can generate serious impacts, partial to total destruction of coastal dunes and their vegetation, including building on top of the dunes and interfering with natural beach-dune dynamics (Cooper and McKenna, 2009; Nordstrom, 2004). This has significant implications for both society and management of dunefields, decreasing the ecosystem services and the ability of beach-dune systems to act as a natural coastal defense against storms (Everard et al., 2010; Liquete et al., 2013). It also creates a paradox, where the impacts of anthropogenic activities are directed towards natural resources that are in turn the base of these anthropogenic activities (Cooper and Mckenna, 2008; Cabrera-Vega et al., 2013).

Much research has focused on human impacts on beaches and coastal dunes (Bauer, 2009; Jackson and Nordstrom, 2011; Curr et al., 2000; Martinez et al., 2013 a, b) especially in temperate zones. However, studies on the direct impacts of urbanization on coastal dune fields landwards from the foredune are scarce (Jackson and Nordstrom, 2011; Hernández-Calvento et al., 2014; Smith et al., 2017). Buildings located near or inside dune fields act as rigid and impermeable structures that intrude and modify the Internal Boundary Layer (IBL) and alter aeolian sediment dynamics (Nordstrom and Mcluskey, 1984; Gundlach and Siah, 1987; Nordstrom and Jackson, 1998; Tsoar and Blumberg, 2002; Wiedemann and Pickart, 2004).

Recent research on this topic demonstrated the effects of buildings on modifying the airflow regime and aeolian sediment transport patterns reducing the wind speed by 50% in some places at the dune system of Maspalomas, Gran Canaria, Spain (Hernández-Calvento et al., 2014; Smith et al., 2017), an excellent example of the conflict between urban-tourist development and conservation (García-Romero et al., 2016). At this location, three different geomorphological areas can be identified based on regional disturbances of the wind patterns: an area of air flow acceleration to the south of a terrace upon which much of the tourist infrastructure has been developed; and two 'shadow' areas in the lee-side of the urbanized area, characterized by airflow deceleration, with different degrees of sedimentary stabilization and vegetation growth. All these areas have been described by Hernández-Calvento et al. (2014) and Hernández-Cordero et al. (2017). It has also been shown that these environmental changes have not been produced by a regional climate change: according to Smith et al. (2017), the mobility index (Lancaster 1988) has been maintained since the 1960's with a value greater than 200, indicating a fully active mobile dunefield or aeolian processes.

While airflow patterns in shadow zones within a dunefield have been described in general (Hernandez-Calvento et al., 2014; Smith et al., 2017), little is known about the evolution and temporal dynamics of these aeolian zones, which are determined by a combination of several variables including feedbacks between topographic change, vegetation growth and aeolian processes. Previous research including the combination of geomorphology and biota has aided in the understanding of such dune systems (Stallins, 2006; Corenblit et al., 2011) and can improve our knowledge of, for example, the operation of barrier-island dunes (Stalllins, 2001; 2002; Stallins and Parker, 2003). Vegetation type and density becomes in these cases a good indicator of environmental changes (Moreno-Casasola, 1986; Hesp, 1988; Arens, 1996; Lancaster and Bass, 1998; Martinez et al., 2001; Hernández Calvento, 2006; Miot da Silva et al., 2008; Hernández-Cordero et al., 2017). Similarly, comprehensive analyses of the combined evolution of vegetation cover and density, plant communities and topographic changes within the shadow zone can provide valuable information on how these previously active areas adapt to new environmental conditions as a result of building and developing infrastructure.

This paper analyses the evolution of a shadow zone within an arid transgressive dune field where sediment supply was cut off following the construction of a large resort. First, we quantify volumetric changes and vegetation patterns using a set of orthophotos, historical aerial photographs and digital elevation models (DEMs) since the 1960s. Second, we then focus on the relationship between these parameters, as well as the impact of urbanization on the overall biogeomorphological evolution of this area.

2. STUDY AREA

The arid transgressive dunefield of Maspalomas (360.9 ha.), is located on the fan-delta of the Fataga ravine at the south of Gran Canaria, in Canary Islands (Figure 1). Sediment input to the dune system comes primarily from its eastern beach (El Inglés), where the foredune is located. Above threshold, effective winds are >5.1m/s according to Pérez-Chacón et al., (2007) and the aeolian sediment transport is predominantly ENE-WSW (Máyer et al., 2012), with the sand eventually returning to the sea at the southern end section of the dune system (Maspalomas beach; Figure 1). One of its most foremost geomorphological features is the existence of a high Pleistocene wedge-shaped terrace on its north-eastern boundary. Building of one of the largest tourist resorts in Spain started in the 1960's on this terrace (Domínguez-Mujica et al., 2011), with the consequent alteration of local winds and aeolian sediment transport patterns, and the generation of the shadow zone studied here (Hernández-Calvento et al., 2014; Smith et al., 2017). A few erosive landforms have been detected in this area at a similar distance from the resort (García-Romero et al., 2017). A *trough blowout* according to the classification of Hesp (2002) has also been identified within these landforms (Mir-Gual et al., 2015). However, the origin and evolution of these landforms have not been studied in detail.

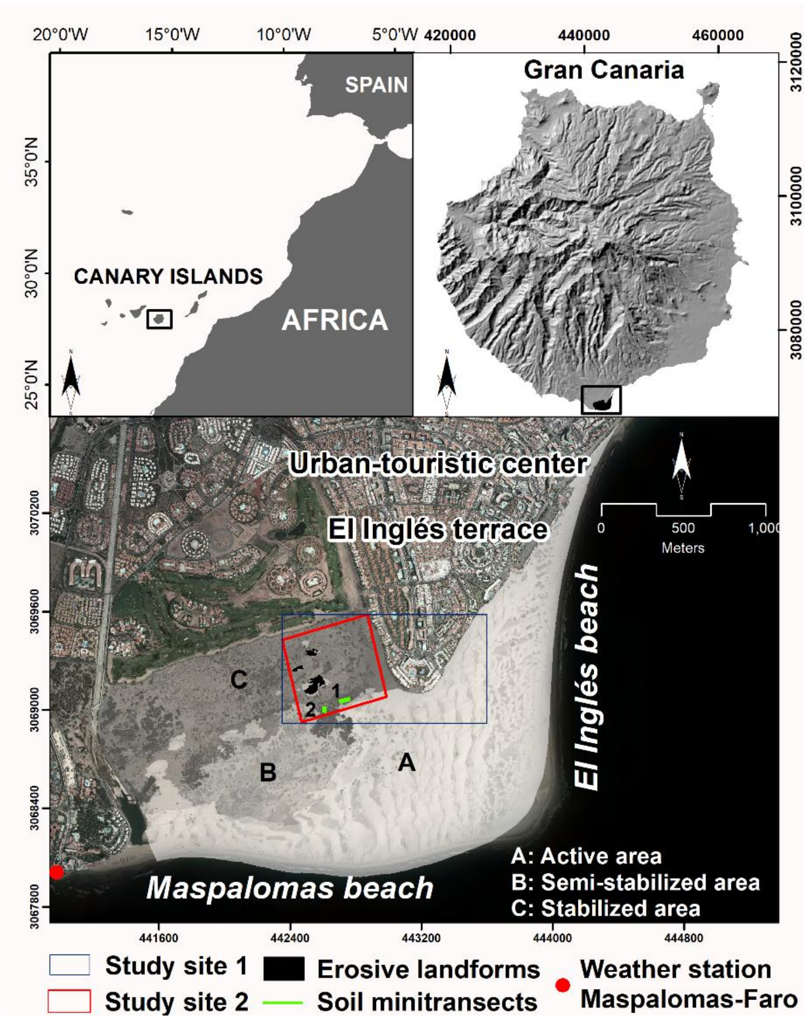


Figure 1. Location of Maspalomas` dunefield. Areas with different aeolian sedimentary activity (Hernández-Cordero et al, 2015a) are indicated on the map (A: active area, B: semi-stabilized area, and C: stabilized area). Study site 1 for examining environmental changes around El Inglés terrace at a regional scale is indicated in blue. Study site 2 for examining the aeolian shadow zone at a local scale is indicated in red. The erosive landforms (in black) and soil mini-transects (in green) in the shadow zone are also shown.

3. METHODOLOGY

Analyses were conducted at two spatial scales and at two study sites. First, a regional scale is used to evaluate if the aeolian shadow zone could be related to disturbances of the sedimentary dynamics induced by the presence of the urban-touristic buildings, or related to a regional climate change (Study site 1). Second, a local scale is used to analyze the biogeomorphological processes in the aeolian shadow zone (Study site 2).

The cartographic documents (aerial photographs, orthophotos and DEMs) which were used in this study are listed in Table 1.

Table 1. Cartographic documents utilized in this study.

Type (source)	Year	Spatial resolution (m)	Use
Historial aerial photographs (1, 2, 3)	1961 (1:5,000)	0.25	Vegetation
	1977 (1:6,500)	0.9	
	1981 (1:4,000)	0.15	
Orthophotos (2, 3, 4)	1987, 2003, 2009, 2012, 2015, 2017(only in the study site 2)	0.15 – 0.25	Topography
DEMs (5)	05/1987, 11/2003	4	
DEMs (6)	10/2006, 03/2009, 03/2011, 03/2015, 03/2017(only in the study site 2)	1	

(1) SDI Gran Canaria; (2) SDI Canarias-Grafcan S.A.; (3) Grupo de Geografía Física y Medio Ambiente (IOCAG, ULPGC); (4) Instituto Geográfico Nacional (IGN); (5) Photogrammetric restitution; (6) LiDAR (2006, 2009, 2011, 2015) and real photogrammetric restitution (2017) from a drone flight (file.las).

3.1. Regional scale

Precipitation data from the 1950s were analyzed to investigate potential changes to the amount of rainfall received by vegetation at the study sites. These could affect the growth rates of vegetation and hence alter the sedimentary dynamics at the study sites, additional to the impact of urbanization. Smith et al. (2017) observed no changes to the mobility index (Lancaster, 1988) in Maspalomas since the 1960's using data from a weather station 25 km northeast of Maspalomas. We have refined previous analyses and used data recorded by a meteorological station of the Agencia Estatal de Meteorología (Meteorology Statal Agency, AEMET) Maspalomas-Faro (Figure 1), approx. 2 km southwest of the study sites, and including some of the oldest meteorological datasets on the island (since 1952). Monthly rainfall was analyzed to identify potential seasonal changes. The time series were 85% complete, so some of the missing data was extrapolated from two weather stations at 4 and 11 km from the study site using regression analyses with R^2 of 0.94 and 0.84 respectively.

Changes to the sedimentary dynamics

Changes to the sedimentary dynamics of study site 1 were analyzed in two steps: first by calculating changes in the direction of the dune brinks (i.e. the top edge of the dune slipface), and, second, by calculating changes in the volume of sediments. The first step was carried out by mapping dune brinks (vector lines), through visual analysis with GIS support, on the 1961 and 1977 aerial mosaics and on the 1987, 2003, 2009 and 2015 orthophotographs (Figure 3, white lines). The direction of each dune brink (each line) was calculated using GIS tools. First, the dune brink lines were converted to points, second, using the central point as the reference and through near-location tools to calculate the direction of the others points corresponding to each dune brink line, the mean direction was calculated to determine the main movement of the dunes. Finally, to show spatially this movement an inverse distance weighting interpolation was carried out, using a local sample (4 points sample), and obtaining a minimum error (4.41 degrees). The movement is represented by arrows every 100 meters (Figure 3, red arrows). In addition, the height of the dunes is calculated through topographic profiles on the 1987, 2003, 2009, 2011 and 2015 LiDAR derived DEMs noted in table 1. Erosion and accumulation volumes were also calculated between 2006 and 2015 from the DoDs using the methodology (Geomorphic Change Detection software) developed by Weathon et al. (2010a; 2010b). DoD error (%) of the erosion: 7.79 and the accumulation: 7.82 from LiDAR data (Figure 3, A).

3.2. Local scale

For the local scale, the study is focused on study site 2, which covers 27.76 ha inside the aeolian shadow zone (Figure 1, study site 2). The medium-term evolution of this zone is characterized based on three variables: spatial patterns of plant communities, vegetation density, and sedimentary volumetric changes. Additionally, the shape and volume of the erosive landforms is also studied. Processing and analyses were conducted using a GIS.

Vegetation

Vegetation density was calculated following the procedure developed by García-Romero et al. (2018), using black and white and color historical aerial photographs and digital orthophotos (table 1). The green band is the region of the visible spectrum that best captures vegetation characteristics (Chuvieco, 2010) in the absence of a near infrared band (NIR). Hence, this can be used to equate the behavior of digital levels with black and white historical aerial photographs, and differentiate bush vegetation (low digital levels) from bare sand (high digital levels). Bush plants, present in the zone, are perennial, and the method applied only detects bush plants; hence there are no phenological problems associated to seasonality (García-Romero et al., 2018). The digital vegetation density model was resampled to 1 m pixel resolutions so they can be compared due to historical aerial photographs and orthophotos having different spatial resolution, and pixels were subsequently classified into the following four categories: (1) low densities, with vegetation covering between 0 and 10.65% of the area (including sand sheets and isolated shrubs); (2) low-moderate densities, with vegetation covering 10.65-22.35%; (3) moderate-high densities, with vegetation covering 22.35-49.26%; and (4) high densities, including areas with a vegetation cover of 49.26-84.25% (García-Romero et al., 2018). Changes in plant communities were characterized through elaboration of vegetation maps of the years 1961, 2003 and 2017, using GIS and imagery (table 1). The plant communities' maps for the years 1961 and 2003 were obtained from Hernández-Cordero et al. (2017). The vegetation mapping of 2017 was developed through visual interpretation of digital orthophotos (using variables such as color, size, density, texture and spatial pattern) and supported by field work.

Topography

Sediment volume changes were characterised using digital elevation models (DEMs). Two DEMs were derived from digital photogrammetry (1987 and 2003), another four from LiDAR (2006, 2009, 2011 and 2015) and the last one from real photogrammetric restitution on photography captured by an unmanned aerial vehicle, UAV (only in the shadow zone) (Table 1). The latter included field control from a total station Leica TS06-laser (March, 25^{th} 2017). Occlusion-based methodology (Chang et al., 2008) was applied to produce a digital elevation model (DEM) and a digital surface model (DSM).

DEMs of difference (DoD) were calculated from 1987 and 2003 DEMs (4 m pixel), and from 2006 and 2017 DEMs (1 m pixel). Although the dates of the DEMs do not coincide, it was considered preferable to work with all information sources available and with the highest precision in order to analyze the trends occurring in the past few decades. The DEMs and DoDs, have been cleaned, corrected and calculated through Geomorphic Change Detection (GCD) software, including the calculation between raw and threshold error (Wheaton et al., 2010a; Wheaton et al., 2010b). DoD error (%): Accumulation (15.49) Erosion (18.32) from photogrammetric restitution (Figure 5, C). DoD error (%): Accumulation (7.06) Erosion (8.80) from file .las data (Figure 5, D).

Erosive landforms characterization

Erosive landforms were digitized using historical and current orthophotos and DEMs. These were delimited by visual criteria through photo interpretation and using slope change analyses.

Relationships between variables

Geoprocessing tools in GIS (overlay) were used to investigate spatial trends and relationships between variables. For the characterization of the relationship between vegetation and topography, an algorithm implemented in GRASS software, that produces a covariate-correlation matrix between raster data, was used. This analysis was carried out for the period between 1987 and 2017 because DEMs were only available from this period. The areas occupied by the vegetation cover each year were related to their corresponding DEM classified by similar altitude intervals (m.a.s.l.).

4. Results

4.1. Regional scale

Rainfall in the Maspalomas dune system

Figure 2 shows the monthly mean rainfall from 1952 to 2017. Rainfall is concentrated in winter and autumn months (November- February). Little rain occurs in spring (0.4-5.9 mm), and in summer the rainfall is close to zero. The total monthly rainfall in the year before the vegetation density calculation is also shown in figure 2. Temporal patterns are similar to the ones for monthly mean rainfall using the entire data set (1952-2017), with rainfall concentrated in winter and autumn. The years 1960 and 1976 were dry with no rainy months. 1980 was also a dry year although in January rainfall reached 39.1 mm. 1986 was also a dry year with rain only in March and September (4 mm). In 2002, December was the highest rainfall (78.3 mm) registered in a month, but the rest of the year the rainfall was not significant. 2008 was also a dry year, with December being the rainiest month (15.3 mm). 2011 was the rainiest year, with a total of 132.7 mm year, with November the rainiest month (57.7 mm), followed by December (42.9 mm). Finally, 2014 and 2016 were dry years with November having the highest rainfall recorded, with 30.2 and 22.4 mm respectively. In general, they are dry years, with rainfall concentrated in one month, except 2011, with two rainy months.

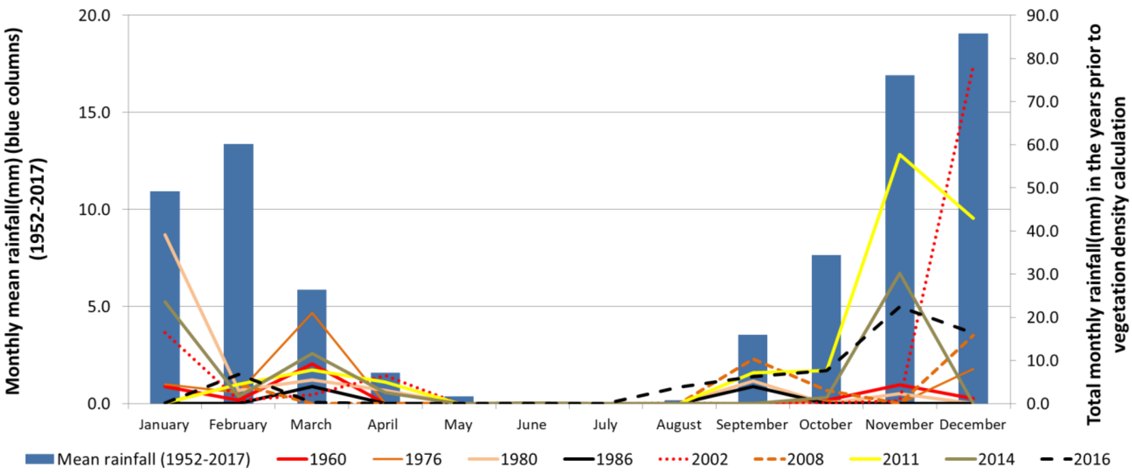


Figure 2. Monthly mean rainfall between 1952 and 2017 (blue columns). Total monthly rainfall in the years prior to vegetation density calculation (lines).

Changes in the sedimentary dynamics

Figure 3 shows results for the directions of dune movement indicated by dune brink orientations and their volumes calculated within study site 1. In 1961 the main dune directions were ENE-WSW, with only a few dune brinks facing E-W. This year dune brinks were detected practically throughout the entire area, and continuous, linked barchanoid dunes displayed along-brink lengths of up to 640 m. Where continuous dune brinks were not observed, Hernández-Cordero et al. (2018) mapped cliff-top dunes formed by nebkha dunes (not barchanoid dunes) which were removed to gain agricultural land (Hernández-Calvento. 2006). In 1977, when construction had occurred on a large part of the terrace, the number of dunes and dune brinks was reduced, and the maximum brink length is around 360 m. Dune continuity was therefore beginning to break up. As for the direction of dune movement, three sectors can be observed: i) the dune brinks to the east and south of the terrace face to the ENE-WSW direction, although some of them are oriented to the E-W, especially those closest to the terrace; ii) the second sector is formed by the dunes closer to the southern edge of the terrace. Their dune brinks are clearly oriented to the W-NW; iii) finally, the dune brinks in the current shadow zone of the terrace display both orientations, E-W and ENE-WSW. Similar aspects can be identified in 1987, although there is more infrastructure present on the terrace, and the eastern and western sides have been completely occupied by urban development (Figure 3, A). Also on the southern edge of the terrace, the dunes show some changes: the last dune brink facing E-W is located 30 m to the south in relation to the last brink in 1977 (Figure 3, A), and the number of dunes moving westward has reduced slightly. In 2003 the terrace is fully covered with built structures (Figure 3, A), and the orientations of the dune brinks maintain the same pattern as in 1987. In addition, the last dune brink facing W-NW is now about 105 meters south of the last dune brink in 1987. Also the number of dunes in the aeolian shadow zone (in the west) have reduced. The same tendency can be seen in the images of 2009 and 2015.

Topographic changes around El Inglés terrace

From the DoD between 2006 and 2015 DEMs, three different zones can be observed (Figure 3, A): i) to the east and south of the terrace, accumulation processes predominate over erosion; ii) the erosion predominates in practically the entire shadow zone; iii) erosion predominates on the southern edge of the terrace, as shown in the profile between 1987 and 2015 (Figure 3, B). Elevation differences range from 1 m in some areas and up to 3.5 m height at 150 m from the profile in the NW-SE direction. The circles on the profiles show where the last dune brinks in the zone where the dunes turn to the W-NW were/are located. The location of the circles indicate a migration to the southern edge of the terrace (125 m). The lower height of these dunes also indicates a reduction in the transport of sediments toward the shadow zone since 2003 (Figure 3, 2003).

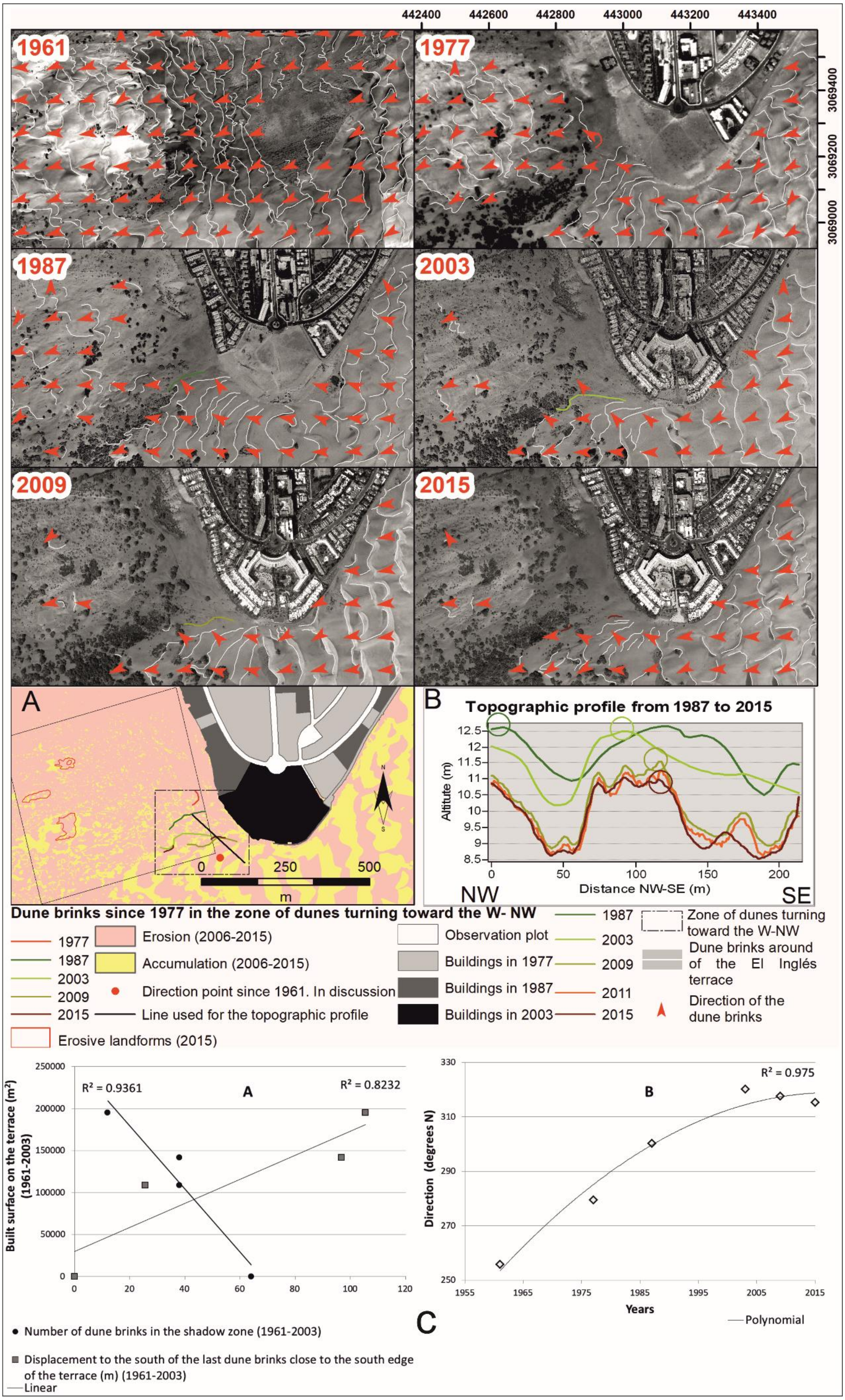

1961
1977
1987
2003
2009
2015
442400
442600
442800
443000
443200
443400
3069400
3069200
3069000
A
0
250
500
m
B
Topographic profile from 1987 to 2015
Altitude (m)
Distance NW-SE (m)
NW
SE
Dune brinks since 1977 in the zone of dunes turning toward the W- NW
1977
1987
2003
2009
2015
Erosion (2006-2015)
Accumulation (2006-2015)
Direction point since 1961. In discussion
Line used for the topographic profile
Erosive landforms (2015)
Observation plot
Buildings in 1977
Buildings in 1987
Buildings in 2003
1987
2003
2009
2011
2015
Zone of dunes turning toward the W-NW
Dune brinks around of the El Inglés terrace
Direction of the dune brinks
Built surface on the terrace (m²) (1961-2003)
R² = 0.9361
A
R² = 0.8232
Number of dune brinks in the shadow zone (1961-2003)
Displacement to the south of the last dune brinks close to the south edge of the terrace (m) (1961-2003)
Linear
B
R² = 0.975
Direction (degrees N)
Years
Polynomial
C

Figure 3. Changes in the orientation of the dune brinks and in the dune heights in relation with the building development on El Inglés terrace. C (left, A) Disappearance of the dune brinks in the shadow zone and displacement to the south of the last dune brinks close to the south edge of the terrace, while increasing the built surface on El Inglés terrace. C (right, B) Changes in the direction of the dune brinks (red point in the figure 3, A) close to the southern edge of the terrace overthe years before, and during which construction occurred on the El Inglés terrace.

4.2. Local scale

Vegetation density in the aeolian shadow zone

Figure 4 shows an increase in vegetation density from 1961 to 2017. 1961 was characterized by lower vegetation densities (0-10.65) and isolated plants, with some aggregate units to the south of the study area. Vegetation density was highest in 2017 where the category 1 (lower vegetation density) decreased -53.58%, while the categories 2, 3 and 4 increased 368.62%, 574.51% and 1513.64% respectively, with the species *Tamarix canariensis* and *Launaea arborescens* dominating the area (Figure 4, C).

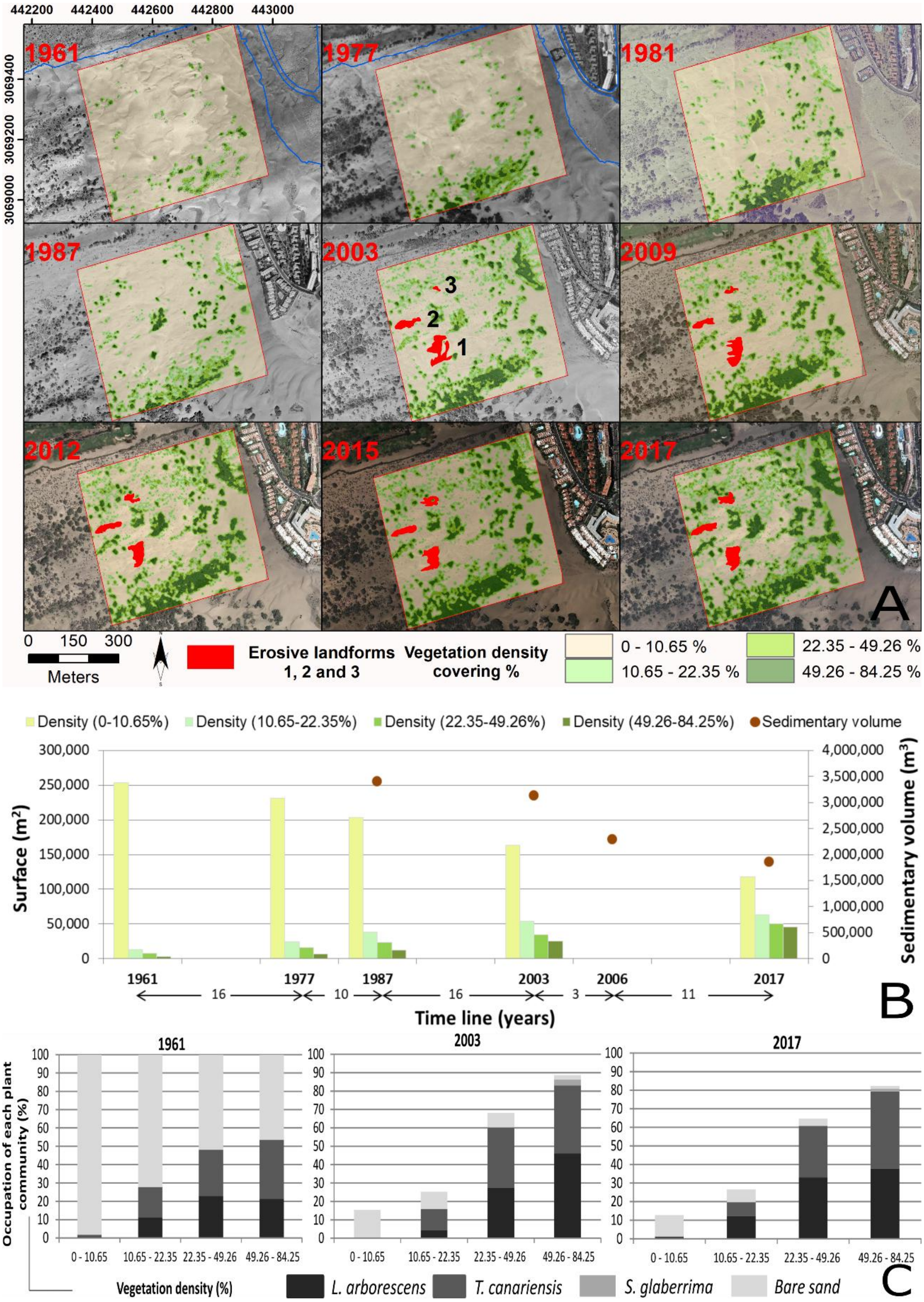


Figure 4. Evolution of the vegetation density in study site 2. The three erosive landforms first detected in 2003 are shown in red. B: Changes in the vegetation density per categories and variation of the sedimentary volume in the study site. C. Evolution of plant communities and vegetation density in the study site.

Vegetation growth was mainly concentrated in the southern and central areas of the study site between 1961 and 1977. In 1981, isolated plants started to grow to the east, close to the resort. Moderate-high and high vegetation densities increased to the north of the study area, close to the golf course bordering the plot, from 2003-2009, with the remaining of the study period characterized by a general increase in vegetation densities everywhere within the study site (Figure 4, A).

Plant communities and bare sand in the aeolian shadow zone

Vegetation spread widely at the study site from 1961 to 2017 (Figure 4, A) which lost up to 92.28% of the original bare and mobile sand in 56 years (at a rate of 1.6% bare sand loss per year) (Table 2). Only two plant communities were identified in 1961: *Launaea arborescens* (xerophilous low shrub), principally located in dry slacks in stabilized and mobile dunes, and *Tamarix canariensis* (hygrophilous low tree), a typical plant community of wet slacks in mobile, semi-stabilized and stabilized dunes. In 2003, six additional plant communities were identified: *Cyperus capitatus*-*Ononis tournefortii* (psammophilous perennial rhizomatous forb; psammophilous annual forb), belonging to stabilized dunes; *Mesembryanthemum crystallinum* (nitrophilous annual forb); *Aizoon canariense* (nitrophilous annual forb); *Volutaria canariensis* (annual forb); *Cenchrus ciliaris* (perennial grass) and *Schizogyne glaberrima* (xerophilous low shrub), belonging to ruderal areas. All plant communities expanded spatially from 2003 to 2017, especially the *Cyperus capitatus*-*Ononis tournefortii* community.

Table 2. Changes of the plant communities since 1961 in the aeolian shadow zone.

Plant community	Surface area 1961		Surface area 2003		Surface area 2017		Variation (1961-2017	
	m^2	%	m^2	%	m^2	%	m^2	%
A. canariense	0.00	0.00	987.26	0.36	960.64	0.35	960.64	100
C. ciliaris	0.00	0.00	262.03	0.09	287.66	0.10	287.66	100
C. capitatus-O. tournefortii	0.00	0.00	190505.87	68.60	173370.23	62.43	173370.23	100
L. arborescens	5420.39	1.95	23685.71	8.53	42893.46	15.45	37473.07	691
M. crystallinum	0.00	0.00	544.31	0.20	510.42	0.18	510.42	100
S. glaberrima	0.00	0.00	904.46	0.33	873.41	0.31	873.41	100

T. canariensis	7795.71	2.81	27299.48	9.83	38126.84	13.73	30331.13	389
V. canariensis	0.00	0.00	224.98	0.08	261.00	0.09	261.00	100
Bare sand	264474.01	95.24	33276.02	11.98	20406.43	7.35	-244067.58	-92

Relationships between vegetation density and plant communities in the aeolian shadow zone

The relationships between vegetation density and plant communities were analyzed to identify which communities expanded the most and were more competitive (Figure 4, C). In 1961, only two shrub plant communities were detected (*Tamarix canariensis* and *Launaea arborescens*) scattered all over the study plot (Hernández-Cordero et al., 2017), but forming some groups to the south of it. Bare sand occupied a large part of the low densities range (0-10.65) as one would expect. In 2003, the bare sand had practically disappeared, occupying just around 15% of the lower density range. *Tamarix canariensis* is the community that occupied the most area in the intermediate densities, followed by *Launaea arborescens*. This last community represents the highest density range, followed by *Tamarix canariensis*. That year (2003), a new shrub community was detected, the *Schizogyne glaberrima* community, represented also in the highest density range. These trends are similar in 2017, but with some differences: bare sand has decreased; the *Tamarix canariensis* community has decreased in the highest densities range, while the *Launaea arborescens* community has increased in this range, so both communities have a similar percent cover. Finally, in contrast with 2003, the *Schizogyne glaberrima* community has lost cover in the highest density range.

Volumetric changes in the aeolian shadow zone

Study site 2 shows a negative sediment budget between 1987 and 2017 (Figure 4, B). The largest erosion rate was registered between 2003 and 2006. Sediment losses of up to 279,445.68 m^3 (8.19% of its volume above 0 m.a.s.l.) between 1987 and 2003. Erosion was larger from 2006 to 2017, with a deficit of 429,791.27 m^3 (18.76% of the total sand volume in the study site 2; García-Romero et al., 2017). Some sediment accumulation areas are observed locally in zones with topographic lows or dense vegetation, or both. A substantial amount of these accumulation areas are located to the southwest of erosional ones (Figure 5 C, D). Since regional predominant winds in this area are ENE-WSW, these particular spatial patterns indicate active aeolian processes in this shadow zone, with wind erosion, sediment transport, and surface growth as a result of sand accumulation towards the W and in the direction of the predominant winds.

In the erosive zones there is a sector (to the west and southwest of the study site 2) with significant erosion (Figure 5 C, D). In this sector there have been losses of around 5 and 6 meters depth and these coincide with the erosive landforms that will be explained in the next section.

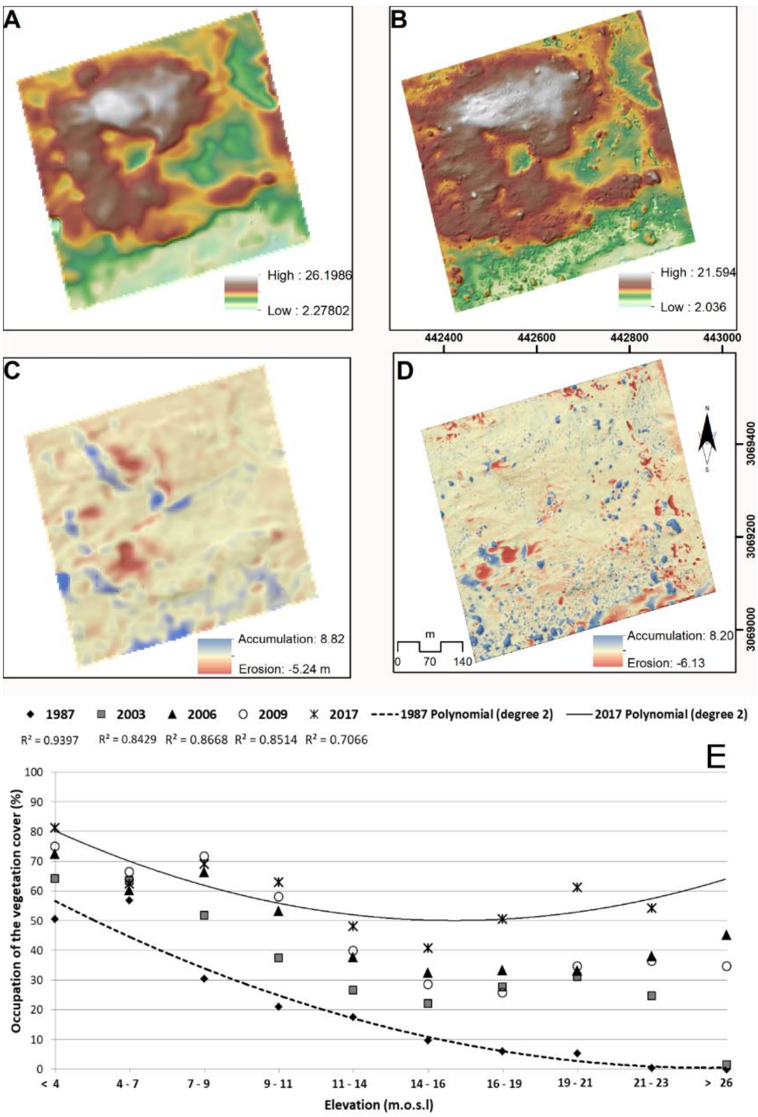


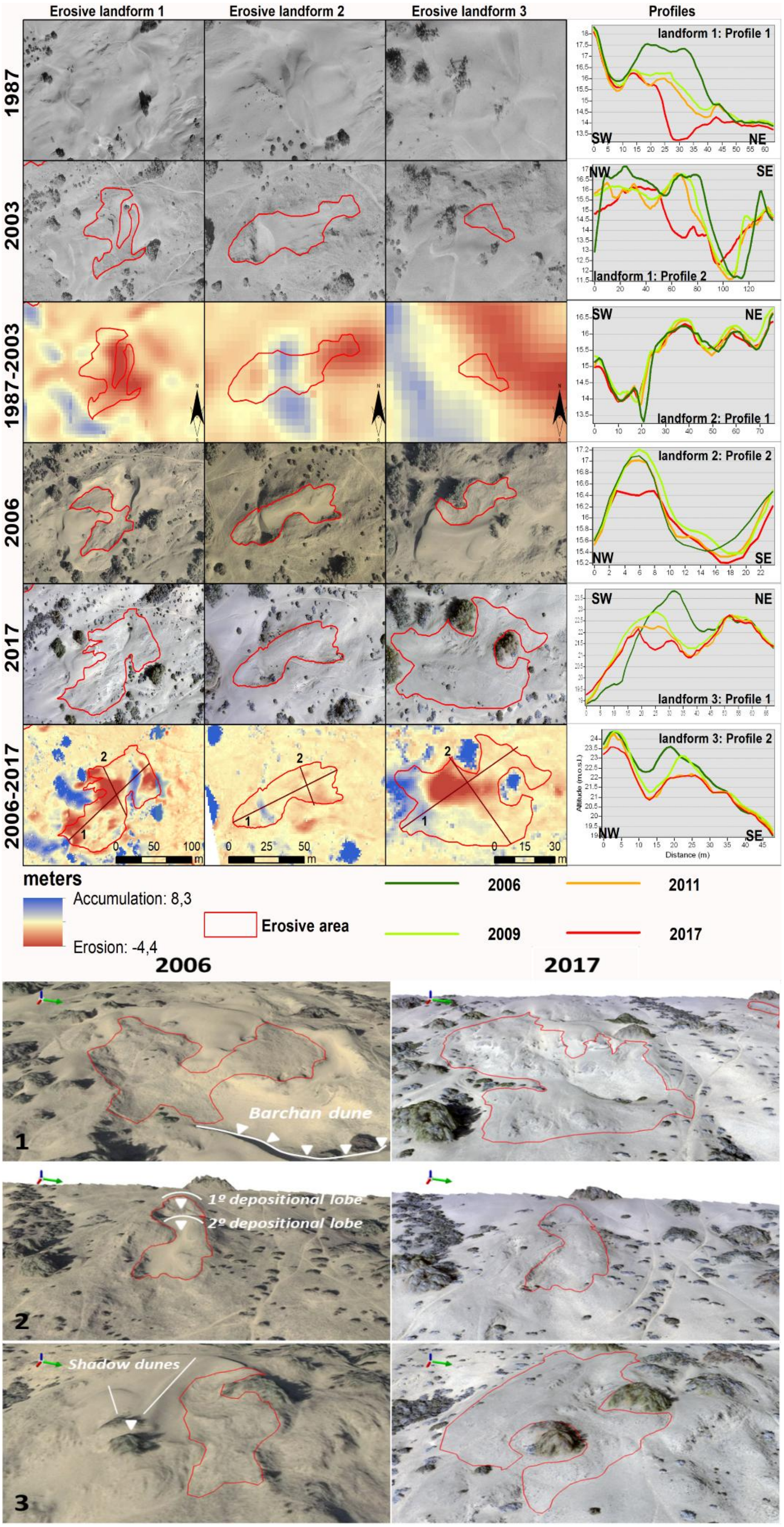
Figure 5. A. DEM in 1987 (resolution: 4 m); B. DEM in 2017 (resolution: 1 m); C. Net topographic changes for the period of 1987 to 2003 (resolution: 4 m); D. Net topographic changes between 2006 and 2017 (resolution: 1 m); E. Relationship between the vegetation cover (%) and elevations in in study site 2. The < 4m altitude zone shows a greater percentage vegetation cover compared to the zone above 26m in 1987. In 2017, the highest elevations do not reach 26 m.a.s.l., and for this reason there are no vegetation data.

Relationships between vegetation and topography in the aeolian shadow zone

The vegetation cover has increased from 1961 to 2017. As shown in figure 5, E, there is a relationship between the topography of study site 2 and the increase in the vegetation cover from 1987 (first DEM available) to 2017 (last DEM obtained from drone flight). The graph shows that the tendency of vegetation in 1987 was to occupy the lowest elevations, while its presence in relatively high elevations is not significant. However, from 2003 to 2017, vegetation has not only increased its cover at lower elevations by 30%, but also it has done so in the rest of study site 2. Currently, this trend has changed and vegetation also colonizes higher elevations, although between 4 and 7 m.a.s.l. the increase in the vegetation cover has been insignificant.

Erosive landform evolution

Since 2003 three erosional landforms were detected at a similar distance from the urbanization area, with an ENE-WSW direction (Figure 1 and 4; erosive landforms 1, 2 and 3). These landforms experienced an increase in surface area and a decrease in volume between 1987 and 2017 (Figure 6). They have different morphologies: landform 2 is a trough blowout with a relatively stable shape over time. Landforms 1 and 3 are characterized by aeolian deflation surfaces characterised by exhumation of plant roots, but little development yet of actual blowouts. The sediment eroded from these landforms was deposited around the shrub vegetation that has grown downwind of them.



Erosive landform 1
Erosive landform 2
Erosive landform 3
Profiles
1987
2003
1987-2003
2006
2017
2006-2017
landform 1: Profile 1
landform 1: Profile 2
landform 2: Profile 1
landform 2: Profile 2
landform 3: Profile 1
landform 3: Profile 2
SW
NE
NW
SE
Altitude (m.o.s.l.)
Distance (m)
meters
Accumulation: 8,3
Erosion: -4,4
Erosive area
2006
2009
2011
2017
Barchan dune
1º depositional lobe
2º depositional lobe
Shadow dunes

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Figure 6. Surface area (in red) and height evolution of the erosional surfaces and landforms between 1987 and 2017 (illustrated in the photographs). Topographic profiles (right hand column) showing differences in elevation from 2006 (dark green) to 2017 (red). 1-3. Erosive landforms in 2006 and 2017. 1. Erosive landform 1 has increased in aeolian deflation area while accumulation landforms, such as a barchan dune, have disappeared or stabilized (pictures 1 and 2 are not at the same scale because there is more visible erosional area in 2017). 2. *Trough blowout* with two depositional lobes. 3. Erosional landform 3 has increased the deflation area while accumulation landforms, such as shadow dunes, have disappeared. In landforms 1 and 3 the scale is different between 2006 and 2017 (lower in 2017) because the deflation areas have increased by the second date.

3D views of the erosional surfaces in 2006 and 2017 can be observed in figure 6, 1-3. Erosional surface 1 shows considerable spatial change and it has increased in deflation area, while the principal downwind accumulation landform, present as a barchan dune in 2006 (Figure 6-1, right and bottom) has been stabilized in 2017 due to plant colonization, especially by herbaceous plants. The volumetric deficit measured in the area is 924.23 m^3 (-24.11%). Blowout No. 2 (Figure 6-2) has maintained a similar surface area over time but has eroded by 557.35 m^3 (-20.19%). Two depositional lobes are associated with this blowout. The erosional deflation surface 3 has increased while adjacent accumulation landforms, such as the shadow dunes (Figure 6-3) have disappeared or stabilized. The sedimentary volume has decreased by 73.46 m^3 (-33.42%).

5. Discussion

5.1. Changes to environmental conditions in the Maspalomas dune system

In line with previous climate studies (Smith et al., 2017), there were no significant changes in precipitation levels or patterns from the 1950's in the study area. Figure 2 shows that 1960, 1976, 1980, 1986, 2008, 2014 and 2016 were dry years but these were linked to increasing trends in vegetation density. In 2002 and 2011 there was high rainfall but this was mainly concentrated in one or two months (November and December), with close to zero rainfall from April to September as is characteristic of arid climates (Köppen, 1990).

In contrast, the development of the urban-tourist infrastructure has been significant as shown in Figure 3, and appears to have been a primary control on the sedimentary dynamics of the dune field. First, the buildings occupied a section of the old bypass dune system on the top of the terrace (Hernández-Calvento et al., 2014, García-Romero et al., 2016, Hernández-Cordero et al., 2018). Second, dune directions and movement trends changed around the terrace following development with dune migration directions being steered by the infrastructure as it developed. The geomorphology of the dunes in the shadow zone have changed also, with the number of free and mobile dunes decreasing at site 2 simultaneously with an increase in the number of buildings on El Inglés terrace (Figure 3, C:A). This decrease can be explained by the changes which occurred on the southern edge of the terrace. In this area, the dunes moved to the SW before the terrace was built. The construction of new buildings in the 1970's created a barrier to dune movement, with dunes being deflected around the edge of the terrace and adopting new migration directions towards the W-NW as indicated by dune crest and brinkline orientations in Figure 3. New constructions at the southern edge of the terrace in 1989 had a marked impact on decreasing the number of actively moving dunes (Figure 3, C: B). In the last 13 years, the trend of the dune brinks is not to turn towards the W-NW but instead take a W-WSW direction. This new turn is accompanied by the movement of the dune brinks towards the southern edge of the terrace (Figure 3, C: B), and causing the movement of these active landforms away from the terrace, and a decrease in the sediment inputs to the current shadow zone. These changes are related with changes in the direction of the wind flow, as Smith et al. (2017) explain. Since the original dune migration path across the terrace has been eliminated by development, and the further infrastructure changes have produced a marked shadow zone, dunes can no longer migrate into the shadow zone region. In consequence, vegetation growth has occurred stabilising the region. The existence of some wind corridors between the buildings on the terrace induces limited sand transport in the shadow zone, but overall there is a net reduction in the volume of sand being transported through this portion of the dunefield. In summary, the construction of buildings at Maspalomas has generated an erosive (negative budget) zone in an area that was previously active and had pronounced dune mobility and dynamic aeolian activity.

5.2. Spatio-temporal trends in vegetation cover in the aeolian shadow zone and their relationship with the topography

The results show that the vegetation density has increased between 1961 and 2017.This is common in places where the wind regime has been altered by buildings (Nordstrom and McCluskey, 1985; Nordstrom, 1994), leading to a stabilized dune area (Hernández-Calvento et al., 2014; Hernández-Cordero et al., 2015a). This is unlike other studies, for example, in Israel, where plant colonization was promoted by agricultural and pastoral activity, producing a negative rate in dune advance (Tsoar and Blumberg, 2002), and in China, where the vegetation cover has increased due to the decadal changes in wind strength, interannual fluctuations in precipitation, and large ecological restoration projects implemented in recent decades (Xu et al., 2018). Results of this study indicate that medium to high density vegetation does not first appear close to buildings, but rather to the south and in the central areas of the study site further away from urbanization. This trend could be related to the topography, because these areas are located in the lower elevation and deflation zones (Figure 5, E) where one would expect more shallow sub-surface moisture. Additionally, findings by Hernández-Cordero (2012) across transects in figure 1 and Table 3 suggest a strong correlation between vegetation species and water table heights leading to differences in soil characteristics potentially involved in this process. *Tamarix canariensis* and *Launaea arborescens* communities and *Launaea arborescens* and *Schizogyne glaberrima* communities predominated in areas with a higher water table. Both communities first colonized slack and deflation areas with higher water tables than adjacent areas with lower water tables, and soil and stratigraphic type then determined community type. Slacks or deflation and interdune zones are fundamental sites for plant colonization in mobile dune fields such as Maspalomas (Hernández-Cordero et al., 2015b) and elsewhere in transgressive dunefields (Hesp et al., 2011; Hesp, 2013). However, since the 1970's and more clearly during the 1980s, dense vegetation began to colonize other areas closer to buildings. As shown in figure 5 E, plants first occupied lower elevations followed by higher elevations. Some of this could be related to aeolian deflation and dune erosion because these result in the local groundwater table being relatively closer to the surface hence increasing moisture availability to plants. A reduction in the process of plant burial has also likely favored plant colonization, since high rates of dune migration and arid climates are the main constraints of vegetation growth in mobile dunes at Maspalomas (Hernández-Cordero et al., 2015b; Hernández-Cordero et al., 2017). Additionally, human activities such as garden irrigation and/or the presence of adjacent golf courses could also have favored vegetation growth similar to other sites in Argentina and Germany (Grunewald, 2006; Grunewald and Schubert, 2007; Faggi and Dadon, 2010, 2011).

Table 3. Soil characteristics in the south of study site 2 (Adapted from Hernández-Cordero, 2012).

Transect (with 2 extractions of 125 cm depth)	Plant communities	Soil layers composition
1	- *Launaea arborescens* - *Schizogyne glaberrima*	- 0-5 cm (dry sand) - 5-7 cm and 5-36 cm (wet sand) - >7 cm (wet alluvial deposit) and >36 (wet sand with rocks)
2	- *Tamarix canariensis* - *Launaea arborescens*	- 0-8 and 0-10 cm (dry sand) - 8-84 cm and 10-85 cm (wet sand) - > 84 cm (wet alluvial deposit with rocks) and >85 cm (water)

Before the tourist development (post- 1970) mobile dunes were present and migrating downwind of El Inglés high terrace. At the beginning of the study only two plant communities where found, formed by one bush species and one tree species. As described above, the construction of new buildings in the 1970s blocked aeolian transport and slowed down dune migration leeward of the terrace, with vegetation burial being now produced only by local re-mobilization of sand deposits. A total of eight plant communities have colonized study site 2 since then with marked growth during the 1970’s and 1980’s. The community that has experienced the greatest expansion has been the *Cyperus capitatus-Ononis tournefortii* community, herbaceous species very common in the dune systems of the Canary Islands (Del Arco Aguilar et al., 2010). Hernández-Cordero et al. (2017) suggested that this plant community benefits and expands the most in stabilized and semi-stabilized dunes of Maspalomas, being a clear indicator of the stabilization of the dune system. This is contrary to what happens in stabilization areas in other climatic regions, such as Israel, where stabilization is produced by shrub species (Levin et al., 2008). *Cyperus capitatus* is thus a pioneer species in the colonization of semi-stabilized dunes in the Canaries (Hernández-Cordero, 2012; Hernández-Cordero et al., 2015a). This species is the only psammophilous perennial rhizomatous species in study site 2, what likely favors its colonization ability. In dune systems, water and nutrient resources are usually very limited, so the clonal growth of these species, mainly through the production of rhizomes, contributes more to the colonization of plants than the reproduction of seeds (Dong and Alaten, 1999). So the responsiveness of clonal growth, due to the scarcity of resources, may allow the rapid occupation of new habitats by plants (Cook 1985; De Kroon and Van Groenendael 1990; Hutchings and De Kroon 1994). *Launaea arborescens* is the second plant community that has increased its cover in the study site 2, as it has in the rest of the Maspalomas dune system, according to Hernández-Cordero et al. (2017). This growth has taken place especially in the new stabilized dunes, but also in ruderal areas due its ecological plasticity (Hernández-Cordero et al., 2017). The *Tamarix canariensis* community has also shown an increase in cover and again is strongly related to the deflation which has occurred in the study area The rest of the plant communities began appearing after 2003 and their increase in cover, although not significant, is observed mainly near, or downwind of the infrastructure/developed area further indicating the impact that development has had on plant growth.

The evident plant colonization shows a decrease in the low vegetation density range (0-10.65), which corresponds to bare sand and isolated individuals of plants. However, among the shrub communities that have been detected, and could be related to vegetation density (due to the limitations of the procedure for calculating this last variable) the *Launaea arborescens* and

Tamarix canariensis communities have been remarkable in colonizing the dune system and establishing intermediate and high density covers. Each community replaced the other community, especially the *Tamarix canariensis* community by the *Launaea arborescens* community, as also detected by Hernández-Cordero et al. (2017), even in the stabilized areas. In the case addressed in this study, the substitution of *Tamarix canariensis* by *Launaea arborescens* is around 40%, while the substitutions of *Launaea arborescens* by *Tamarix canariensis* is 25% of the cases until 2003 (Hernández-Cordero et al., 2017). In recent years the changes in both communities show a similar percentage change.

So far, a relationship between an increase in the vegetation cover and elevation has been observed. This relationship is likley conditioned by the height of the local groundwater table, but also possibly by areas experiencing lower wind speeds. This latter variable should be added into future research to establish what role it truly plays. But potentially, feedback is observed between plant colonization and sedimentary stabilization / erosion as the constructed area has increased. A greater construction of the hotel area triggered a reduction of the local wind speed, and a decrease in aeolian sediment transport, favoring the vegetation encroachment and therefore the dunefield stabilization. These feedbacks produce on the one hand the alteration of the natural environmental conditions, and on the other hand, introduce new unknowns related to the biodiversity and geodiversity of the landscape. To better understand these feedbacks an approach examining the adaptation of diversity indices such as those proposed by Shannon (1948), Shannon and Weaver (1949) or Ferrer-Valero et al. (2017) in the transgressive dunesfield of Maspalomas might be useful.

5.3. Topographic changes and erosional landforms in the aeolian shadow zone

Net erosion dominated over net accretion in site 2 as a direct consequence of the decrease in wind speed by more than 50%, as well as the blocking/restriction of sediment input by wind because of construction on top of El Inglés terrace (Hernández-Calvento et al., 2014). Erosion is common in dune systems where some type of human impact has occurred, regardless of the issue studied (e.g. Tsoar and Blumberg, 2002; Wiedemann and Pickart, 2004; Hilton et al., 2006; El Banna and Frihy, 2009; Kiss et al., 2009; Bochev-van der Burgh et al., 2011; Jackson and Nordstrom, 2011). In this study area, erosion in site 2 is a direct consequence of the presence of buildings and infrastructure. In this case, a well-delimited area where erosion is significant can be detected, corresponding with the location of the erosive landforms detected since 2003 (Figures 4, A and 6) and the re-mobilization of sand deposits. Accretion was also measured in site 2 and was locally related with the presence of vegetation, in line with previous studies (Hesp, 1991; 2013). Finally, there are other areas where the sediment has been fixed, a process that should be considered normal, because this is an aeolian shadow area. The observed erosional landforms have been subject to some mobility and change, despite relatively lower winds in this section of the dune field. This is potentially indicative of some localized wind acceleration or wind ´hot-spots´ (García-Romero et al., 2017) leading to sediment erosion in an area that is otherwise subject to low wind flows and limited sediment transport (Hernández-Calvento et al., 2014; Smith et al., 2017). Interestingly, these erosive landforms are all at a very similar distance downwind from the buildings.

Future analyses at this location should incorporate detailed records of wind variables collected at a high temporal and spatial resolution in this area, to allow detailed quantification of airflow processes involved in the evolution of this erosional and/or stabilizing landscape. This would permit identifying the reasons for the existence of erosive landforms at the same distance downwind of the buildings/infrastructure. It is possible to speculate that streets between the buildings on the top of El Inglés terrace act as wind corridors that channel the airflow, locally increasing wind speed in the shadow zone. In fact, this hypothesis is reinforced by checking how these processes do not occur in areas located behind the higher-rise buildings (Mir-Gual et al., 2015). Also it is possible to speculate that the blowouts or the other erosive landfoms appear due to the topographic influence of the infrastructure (Garés and Pease, 2015). The increase in the area of the erosive landforms and deflation zones with exhumed roots of herbaceous plants at this distance from the buildings, could be an indication that currently, and in the future, a large deflation zone will appear rather than a stabilized zone as has been indicated up to now (Hernández-Calvento et al., 2014; Hernández-Cordero et al., 2015a). This may depend on the functioning of the shrub vegetation.

6. Conclusions

This work presents a study of the environmental changes on a portion of a transgressive dunefield and the biogeomorphological processes produced in an aeolian shadow zone detected and formed downwind a high terrace completely changed due to tourist infrastructure development between 1986 and 2003. Thisconstruction altered the aeolian sedimentary input to the region and created an aeolian shadow zone in the dunefield. Climate change, and particularly rainfall variations do not appear to have had any real effect in driving the changes observed. The effect of the touristic development has been to drive changes in the local wind field and hence the direction of dune movement and migration. The changes in the sedimentary dynamics have also altered dune migration directions with dunes turning more towards the W-NNW than previously, and reduced the volumetric input of sediments into the Maspalomas dune system. In addition, there has been a reduction in the number and length of dune brinks and a displacement of the dune brinks to the south, well downwind of the aeolian shadow zone. For these reasons, the Maspalomas dunefield has been significantly environmentally altered due to the development of a human-induced aeolian shadow zone. If these trends continue, or change to other paths (e.g. expansion of the deflation areas), ecosystem services such as tourism and the protection against storms and possible tsunami provided by the dunes would be adversely affected.

With respect to the biogeomorphological processes within the aeolian shadow zone of the Maspalomas dunefield, the following processes and spatio-temporal changes have been observed:

Vegetation trends

1. The vegetation has experienced an increase in cover, density and number of plant communities.
2. The most successful colonizing plant community is *Cyperus capitatus*-*Ononis tournefortii*, comprising herbaceous species. The case of *Cyperus capitatus* is relevant, since it is the only species detected in this area that reproduces from rhizomes. In other dune environments, due to this rhizomatous characteristic, its reproduction is conditioned by clonal growth, and seed production is unimportant.
3. Other plant communities, comprising shrub and tree species, namely *Tamarix canariensis* and *Launaea arborescens* communities, also play an important role in colonization of the dunefield in the study area.

Topographic changes

1. There is an aeolian sedimentary deficit caused by the urban tourist buildings located on the top of the El Inglés terrace blocking the aeolian sedimentary transport pathway, and reducing overall wind energy and sediment transport in the study area.
2. Although the sedimentary deficit has been detected throughout the study area, there are areas of accretion associated with deposition within vegetation, as well as other stable areas. Since 2003, when the top of the terrace had been totally covered by buildings, three erosional landforms have developed. All three of them are located at a similar distance from the new urban development area.
3. These three erosional landforms correspond to a *trough blowout* and two deflation zones currently characterized by surfaces covered with exhumed roots.

4. The increase of the vegetation is related to the sedimentary deficit, which facilitates the growth of plant species. This process is possible since the sand cannot cover the vegetation, and deflation leads to the presence of groundwater closer to the surface.
5. The groundwater table can be detected in the lowest elevations of the study area, and therefore, there is a strong relationship between plant colonization and topography.
6. Plant colonization within about 400 meters of the building/infrastructure development is lower than further downwind, coinciding with the presence of erosional landforms and zones with higher water tables.

Acknowledgements

This work is a contribution of projects CSO2013-43256-R and CSO2016-79673-R (National R & D & I Plan) co-financed with ERDF funds and a PhD contract of the Canary Islands Agency for Research, Innovation and Information Society and by the European Social Fund (ESF). The authors also thank Dr. Pablo Máyer Suárez for providing processed rainfall data.

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