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Decadal monitoring of *Traganum moquinii*'s role on foredune morphology of an human impacted arid dunefield

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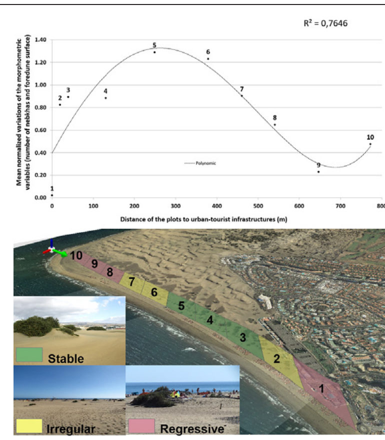
HIGHLIGHTS

- The foredune of an arid dunefield has been analysed from a decadal monitoring.
- *Traganum moquinii*'s role and foredune morphometric variables have been related.
- Foredune has not had homogeneous changes from North to South in the dunefield.
- Three foredune zones detected are explained by eco-antrophogenic processes.
- Relationships in the first line of foredune can be useful for dunefield management.

GRAPHICAL ABSTRACT



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ABSTRACT

Foredunes in arid zones have been little studied, being significantly different than tropical and temperate foredunes. In the case of the foredune of the arid Canary Islands' dune systems, *Traganum moquinii* is the predominant plant species, forms nebkhas and nebkhas fields, and acts as a structuring element in the dune field. In this work, the eco-anthropogenic evolution of the foredune surface, and the morphology and distribution of *Traganum moquinii* species in the Maspalomas dunefield (Gran Canaria, Canary Islands) are analysed, to understand the role that this plant species plays on the foredune's geomorphology and on the biogeomorphological processes altered by human actions. Eight variables were measured in 10 plots at five different times, from the 1960's to the present, through historical aerial photographs and orthophotos, integrated in a GIS. Significant decadal changes in the number and distribution/morphology of *Traganum moquinii* plants and also in the morphology of the foredune are observed, although not in a spatially homogeneous manner, as three different foredune behaviors are observed. The number of nebkhas/number of *T. moquinii* plants, has decreased between 1961 and 2012. The largest changes occurred in the north and south of the study area, and the lowest numbers of nebkhas occur where tourist activities and services are intense. In addition, the distance between *Traganum moquinii* individuals and variables measured in the foredune front (e.g. the diameter of the individuals) have significant relationships. Also, the greater the distance between plant individuals in the foredune front, the greater is the

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distance of *T. moquinii* individual plants in the rest of the plot. The alongshore variations in foredune development are due to natural processes (e.g. natural decline or growth of plants), and human impacts (e.g. carpark and kiosk construction, heavy tourist use). This research could be useful for the management of foredunes in arid regions.

1. Introduction

The Anthropocene is characterized by the alteration of natural processes due to human development (Crutzen, 2006). These alterations have produced problems related to the operation of coastal dune systems (Nordstrom et al., 2000) leading to an increase dune system vulnerability (Fernández and Neves, 1997). While coastal dunes have historically been exploited for the extraction of their resources and animal grazing, in recent decades human pressures have increased due to urban, tourist and industrial development or other activities (Martínez et al., 2013a). This development has accelerated the degradation and, in some cases, the destruction of dune fields around the world (Paskoff, 1993; European Environmental Agency, 2006; Jackson and Nordstrom, 2011; Martínez et al., 2013a, 2013b; Santana-Cordero et al., 2016).

A foredune is an aeolian sedimentary landform generated by aeolian sand deposition in vegetation on the backshore of beaches. Its genesis, morphology and dynamics depends on (among other things) the types of plant species present (grass, herb, shrub), the plant density, distribution and cover, and its temporal and spatial development (Hesp, 1991, 2002; Biel et al., 2019). This is a key landform for the operation of the dune system as, for example, the foredune provides several ecosystem services, such as the provision of protection from storms (Avis and Lubke, 1996; Ley-Vega de Seoane et al., 2007), habitats (Hernández-Cordero et al., 2015a), regulation of coastal erosion, and maintenance of the sedimentary balance of dune fields (Everard et al., 2010).

The formation, dynamics and evolution of the foredune depends on many factors, such as the sediment supply (Psuty, 1988, 2004; Sherman and Bauer, 1993; Aagaard et al., 2004), the rate and magnitude of sediment transport (Nickling and Davidson-Arnott, 1990; Bauer and Davidson-Arnott, 2002; Davidson-Arnott et al., 2005; Bauer et al., 2009; Namikas et al., 2010; Delgado-Fernández, 2011), surfzone-beach type and interactions (Short and Hesp, 1982; Carter, 1988; Carter and Wilson, 1990; Hesp and Smyth, 2016), wind flow (Rasmussen, 1989; Walker et al., 2006), and vegetation cover (Moreno-Casasola, 1986; Hesp, 1988; Lancaster and Baas, 1998; Martinez et al., 2001; Miot da Silva et al., 2008; Hernández-Cordero, 2012). Since foredunes are located at the rear of a beach, they can range from quite stable to highly dynamic (Hesp, 2002), and vary considerably in vegetation cover from scattered nebkhas, to nebkha fields, to large, continuous ridges (Hesp, 1981; Arens, 1996; Arens et al., 1995; Levin et al., 2008; García-Romero et al., 2019b).

The vegetation of the foredune zone in the dune systems of arid regions (such as the study area of this paper) displays differences with respect to that of temperate and tropical systems. In arid systems, the vegetation usually consists of low density shrubs, and the relative sparseness does not give rise to semi-continuous or continuous foredune ridges parallel to the coastline as in temperate and tropical zones. Instead, nebkhas and nebkhas fields typify the foredune zone (Hesp and Walker, 2013; Hernández-Calvento et al., 2014; Hernández-Cordero et al., 2019). Some plant communities of these Canaries systems are recognized as habitats of European interest, as in the specific case of the nanophanerophyte *Traganum moquinii*. In addition, the role of *T. moquinii* is very important because it is the main plant species that generates the foredune, formed by discontinuous nebkhas, in these Islands and other places of northwestern Africa (Hernández-Cordero et al., 2015a). As *T. moquinii* is widely distributed on the northwest coast of Africa, from Morocco, along the W. Sahara coast, to Mauritania (Charco, 2001), and in the Canary and Cape Verde islands, the present paper can be a useful tool to develop management measures for the conservation of these plant communities, especially in those areas were tourist development is still in early stages.

The development of human activities around these Canaries dunefield (installation of resorts, infrastructures and beach services, and beach user's activities) have induced significant alterations in the *T. moquinii* plants and, consequently, in the number of nebkhas and in the original structure of the foredune. In the north of Playa del Inglés, Gran Canaria (study area, Fig. 1), the main problem has been the occupation of the foredune by urbanization (Fig. 2) (Hernández-Cordero et al., 2017), while in the south it has been the actions on the plants by beach users (Hernández-Calvento et al., 2014), which could have hindered the colonization by new *T. moquinii* plants (Hernández-Cordero et al., 2015b). In the central zone of the foredune no human actions have been detected that could have significantly affected the natural system, although there are also tourist services in this area, which are permanent throughout the year, and beach users also have deleterious actions on the plants.

Based on this background, this paper starts from the hypothesis that the anthropogenic actions on these plant individuals and, consequently, on the foredune of this system, could be detected through a spatio-temporal analysis in which it might be possible to detect environmental patterns according to the anthropogenic levels of disturbance in the foredune zone. Thus, the main objective of this paper is to analyse, from a 2D long-term perspective, the environmental changes and relationships between the morphological and distributional characteristics of *T. moquinii*, and the morphological and geometric changes of the foredune zone. This research paper is organized by the following sequence: i) to describe the methodology utilised to determine foredune changes (*T. moquinii* plants and foredune morphology); ii) to detect the evolutionary paths of the foredune system; iii) to analyse of the various factors driving historical and spatial changes in the aeolian system and especially on the foredune.

2. Study area

The dunefield of Maspalomas is located in the south of the island of Gran Canaria (Canary Islands, Spain), constituting a Special Natural Reserve with an area of 403.9 ha (Fig. 1). Within the reserve lies the Maspalomas dune field, which occupies 360.9 ha and covers a quaternary delta (Hernández Calvento, 2006; Hernández-Cordero et al., 2015b). This system constitutes a transgressive dunefield, according to the Hesp and Walker (2013) classification, and has a mean migration rate of 8 m/year (2003–2006) for up to 12-meter-high dunes (Pérez-Chacón et al., 2007). The sources of sediments are mainly marine, with the sand containing a high proportion of organogens (forams, shells molluscs, seaweed meshes). The terrigenous composition corresponds to fragments of volcanic materials contributed by the Island ravines and the erosion of marine cliffs (Mangas et al., 2012). The sediments are input into the system at El Inglés beach (on the east), where the first aeolian landforms are formed in the foredune zone. They are transported into the system by the trade winds, blowing from the *E*-NE, as active (free) dunes, and finally exit the dunefield to the sea via Maspalomas beach (in the south) (Hernández Calvento, 2006). Mean annual rainfall is 81 mm (1952–2008, AEMET and Hydraulic Service of Las Palmas data) and the mean annual temperature is 21 °C (1997–2007), with a dry period throughout the year (Hernández-Cordero et al., 2015b).

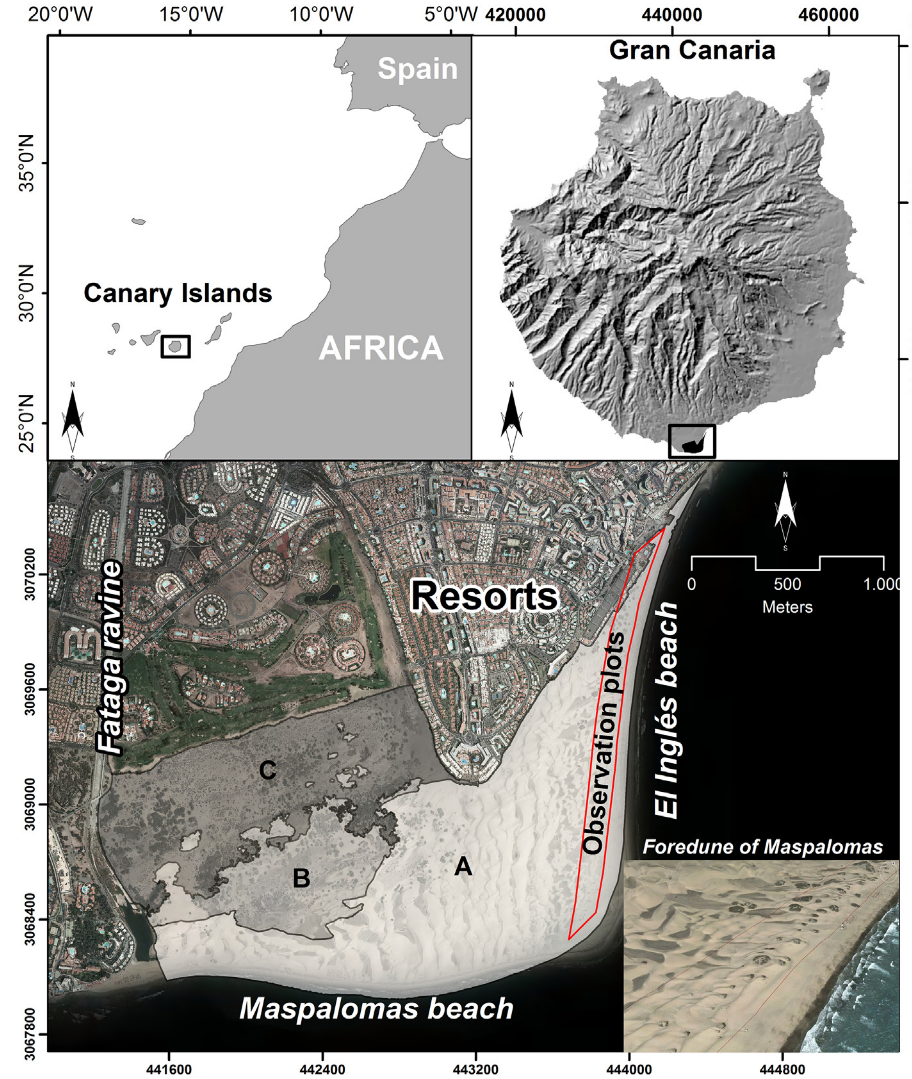

Fig. 1. General view of the Maspalomas dunefield with the three main zones and the location of the foredune zone where observation plots were located. A. active area where the foredune and observation plots are located; B. semi-stabilized area; C. stabilized area.
(Modified from Hernández-Cordero et al. (2015b).)

The most important tourist center of Spain (Domínguez-Mujica et al., 2011), has been constructed around this system, since the 1960's. The beach and dunefield, and the admirable climate, are the major tourist attractions. The construction of large urban and tourist facilities has altered the dune system leading to geomorphological and vegetation changes (Cabrera-Vega et al., 2013; Hernández-Calvento et al., 2014; García-Romero et al., 2016; Hernández-Cordero et al., 2017; Smith et al., 2017; García-Romero et al., 2019a), partially due to the modification of the regional wind flow and local Internal Boundary Layer (IBL) and, in consequence, the aeolian sediment dynamics (Nordstrom and McCluskey, 1984; Nordstrom and Jackson, 1998, Smith et al., 2017). In this dune system, tourism use is constant throughout the year, without any low use period for the system to recover from the impacts generated by services and users (Cabrera-Vega et al., 2013).

The dunefield comprises three separate zones (Hernández-Cordero et al., 2015b). Firstly, an active area (Fig. 1, A), from the coast to the inner area, which has the following landforms: the beach, the foredune, barchan dunes, sand sheets, deflation surfaces, barchanoid and transverse ridges and interdune depressions. Secondly, a semi-stabilized area (Fig. 1, B), with deflation surfaces, barchan dunes and sand sheets or nebkhas; and thirdly, a stabilized area (Fig. 1, C), with stabilized dunes and interdune depressions. A total of 19 plant communities have been detected in the dunefield including *Cyperus capitatus-Ononis tournefortii*, *Tamarix canariensis*, *Launaea arborescens*, *Suaeda mollis* and *Traganum moquinii* communities (Hernández-Cordero et al., 2017).

In the Maspalomas dunefield the *T. moquinii* plants occupy two main areas: some wet interdune depressions (slacks) between the mobile dune ridges closest to the coast, and the area of sediment input to the Maspalomas dune system in El Inglés beach, forming the foredune, which is the area studied in this paper (Hernández-Cordero et al., 2015b). The height of the foredune at Maspalomas varies between 1 and 5 m and is formed by isolated nebkhas formed in *T. moquinii* plants (Hernández-Cordero et al., 2012). *T. moquinii* adult individuals have heights ranging between 1.3 and 3 m, but some may reach 5 m. Small interdune depressions, and on occasions, sand tongues (parabolic-shaped, unvegetated, arcuate ridges) are present between the nebkhas, which vary spatially and temporally depending on the dynamics of the aeolian processes (Viera-Pérez, 2015). These dynamics has been altered in the last decades due to a reduction in the number of *T. moquinii* plants caused by infrastructure building and by the pressure of beach users, as well as other natural or anthropogenic processes, such as storm wave erosion (Hernández-Calvento et al., 2014; Hernández-Cordero et al., 2012) or light pollution (Viera-Pérez et al., 2019), among others. A priori, these changes have not been homogeneous spatially and temporally; thus, the function of *T. moquinii* on the foredune has changed depending on the degree of alteration.

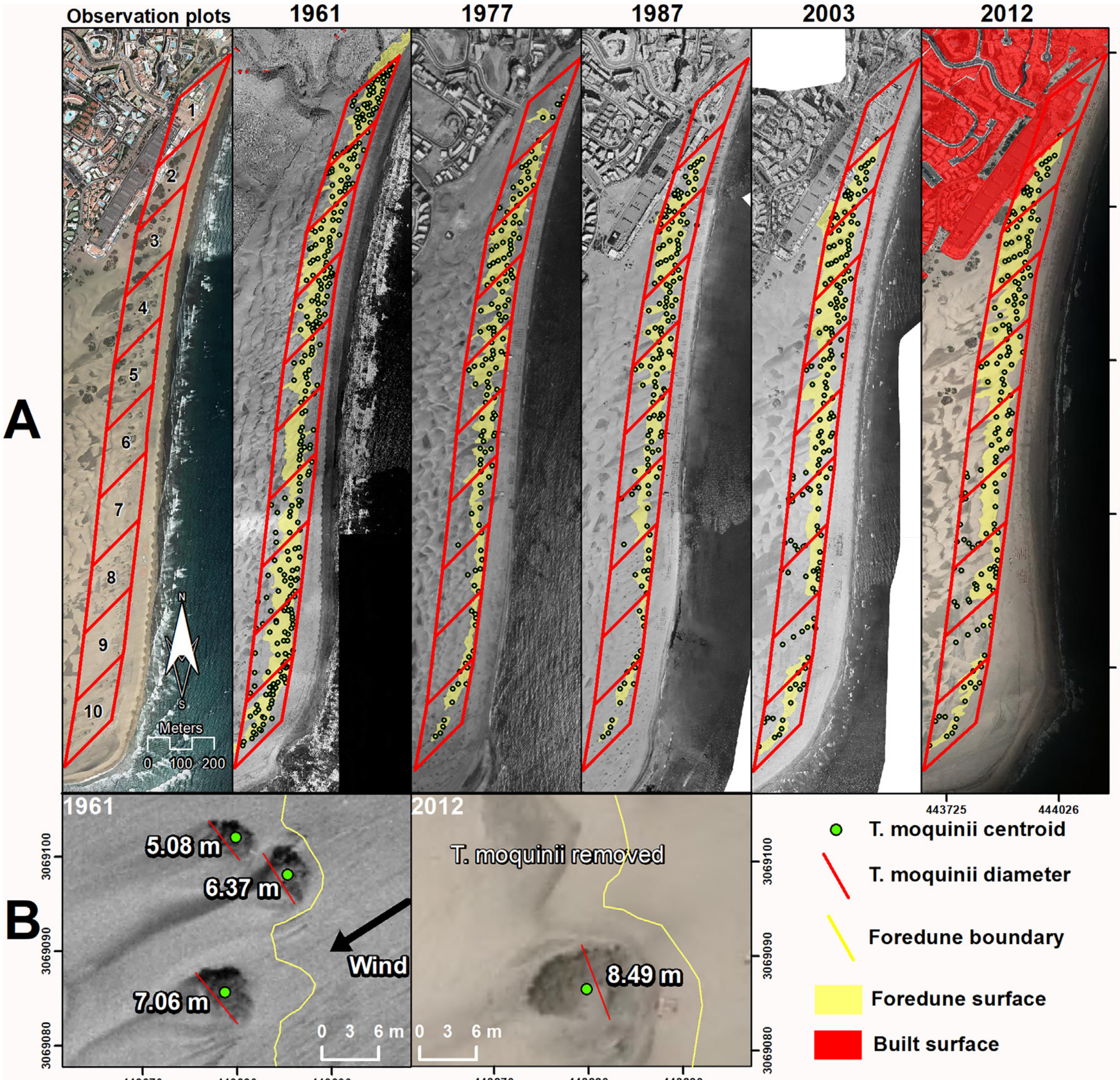

Fig. 2. Identification and evolution of the *Traganum moquinii* plants and foredune surface. A. Plots, *T. moquinii* plants (green circles) and foredune surface for each year. The built environment is shown in red in the 1961 (insignificant) and 2012 (significant) images. B. Some visual results with high spatial resolution of the variables measured in the experiment on *T. moquinii* plants in the line 1 (e.g. diameter of *T. moquinii* individuals (m)). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

3. Methodology

The foredune was divided into 10 plots (Fig. 2). In each of these a series of variables of the distribution and morphology of *T. moquinii* and the foredune were measured, using digital orthophotos and historical aerial photographs. The variables were analysed statistically in order to examine their relationships.

3.1. Information source

The information sources used were orthophotos and historical aerial photographs from 1961, 1977, 1987, 2003 and 2012 (Table 1). The orthophotos of 1961 and 2012 were consulted through the WMS service of the Canary Islands' SDI (Grafcan, S.A.-Government of the Canary Islands), while the 1987 and 2003 ortophotos are provided by the Grupo de Geografía Física y Medio Ambiente (IOCAG-ULPGC). Aerial photos of 1977 were georeferenced from control points using GIS. Although historical aerial photographs of the 1990s are available, they were discarded because reliable information on the characteristics of the flights were unavailable.

3.2. Observation plots

The 10 observation plots (Fig. 2, A) are distributed from north (plot 1) to south (plot 10). They have dimensions of 200 × 200 m and are oriented in a northeast-southwest direction (45°–225°), corresponding

Table 1
Aerial photographic data.

Date	Scale	Spatial resolution (m)	RMS (m)	Delineation error (m)
1961	SDI WMS service	0.12	[a]	0.12
1977	1:6500	0.15	1.54	1.3
1987	[a]	0.15	[a]	0.15
2003	[a]	0.15	[a]	0.15
2012	SDI WMS service	0.25	[a]	0.25

The reference system for these photographs is UTM (28-N) with the WGS84 datum. The delineation error was calculated according to Robinson et al. (1987).
[a] Missing data.

Table 2
Measured variables related to morphology and geometry (foredune) and distribution/morphology of *T. moquinii*.

	Variables	Methods
Foredune	Number of nebkhas (in each plot) (*NN*)	According to the total number of *Traganum moquinii* plants.
	Foredune surface (m^2) (in each plot). Response morphologic variable (*FS*)	Calculated for the polygons digitalized from visual interpretation, using GIS.
Traganum moquinii	Vegetation density (in each plot) (*D*)[b]	According to Mostacedo & Fredericksen, 2000[a]
	Number of *T. moquinii* individuals in line 1 (*B1*)[b]	Visual interpretation
	Mean diameter of *T. moquinii* individuals in line 1 (m) (*D1*)[c]	Calculated for wider diameters with orientation NE-SW, based on lines digitized from visual interpretation, using GIS
	Mean distance between *T. moquinii* individuals in line 1 (m) (*DB1*)[b]	Using geoprocessing tools in GIS

[a] $Dh = \frac{10000}{(\overline{D})^2}$, where: *Dh* is density by hectare (in our case is the surface of the plot) and $\overline{D}$ is the average distance between central points (between *T. moquinii* individuals).
[b] Variables related to number and distribution of *T. moquinii*.
[c] Variable related to morphology of *T. moquinii*.

with the effective winds (Hernández Calvento, 2006) and the orientation shown by the shadow dunes formed leeward of plants in the whole series of aerial photography and orthophotos used. The eastern limit of the plots corresponds to the individuals of *T. moquinii* located closer to the coastline throughout the years studied.

Individuals of *T. moquinii* were identified in each of the observation plots from photointerpretation, using the maximum resolution offered by the sources. The centroid of each specimen was digitized with a point geometry stored in shapefile format in GIS (Fig. 2, B). With this criterion we aimed to objectively identify plant individuals regardless of the source's resolution.

3.3. Variables measured

The variables measured as well as the method used, are shown in Table 2. Due to the morphological and ecological characteristics of *T. moquinii*, which is distributed openly and reaches significant heights similar to trees (heights: 1.3–5 m) (Hernández-Cordero et al., 2012), the calculation of the vegetation density used is that proposed by Mostacedo and Fredericksen (2000).

Line 1, or the first line, refers to the *T. moquinii* individuals (and nebkhas) located on the front of each plot, closest to the coastline. These individuals are the first obstacle in the aeolian transport pathway from the beach, and then they accumulate sand and form nebkhas, and it is possible that they interfere in the distribution of the rest of *T. moquinii* individuals in each full plot. In addition, these individuals are exposed to natural marine and anthropogenic processes.

3.4. Statistical analysis

First, to determine the possible differences in the foredune of Maspalomas and the consequences on the *T. moquinii* individuals as species, a classification by clusters was made (Ward's method with Euclidean distance squared) where only the evolution of the morphological and geometric variables of the foredune (number of nebkhas and foredune surface) were used because are response variables as will be used later (linear mixed models), especially the foredune surface.

Second, the relationship between the variables of *T. moquinii* plants was analysed in order to understand their importance in the distribution and evolution of this species. This analysis was made from the different groups of plots obtained in the cluster studied using a Pearson correlation. The use of the Pearson correlation coefficient has been considered adequate when the variables present a visually appreciable linear relationship. This should allow the elucidation of variables that have a significant relationship in each of the groups whose evolution and behavior of *T. moquinii* has been different in the last few decades.

Finally, the variables measured from the 1960's to the present allowed us to analyse the evolution of *T. moquinii* plants, the nebkhas and foredune zone associated with them. This was conducted in order to evaluate the relationship between *T. moquinii* morphological variables and the morphological and geometric variables of the foredune area (number of nebkhas and foredune surface). For this reason, we have considered using statistical analyses for examination of multiple predictors simultaneously, such as linear mixed models, to account for temporal autocorrelation. The models were fitted of the form:

$$FS_{ij} = \beta_0 + \beta_1 NN_{ij} + \beta_2 D_{ij} + b_{0i} + \varepsilon_{ij} \quad (1)$$

Using as predictors the variables measured in line 1, the next model is used:

Table 3
Temporal evolution of the *T. moquinii* variables.

Variables	Years	Plots									
		1	2	3	4	5	6	7	8	9	10
Density (*D*) (in each plot)	1961	239.82	117.07	85.50	122.12	63.56	118.52	53.08	60.01	99.86	229.52
	1977	59.25	50.58	62.86	68.33	54.64	94.22	23.17	45.96	75.38	48.14
	1987	6.06	97.60	65.94	79.02	66.68	78.33	25.05	44.74	50.70	48.90
	2003	6.21	96.81	73.08	76.81	48.49	95.87	68.84	85.03	55.94	48.38
	2012	6.21	101.90	73.08	80.92	48.49	91.40	48.74	124.21	42.68	48.38
Number of *T. moquinii* individuals in line 1 (*B1*)	1961	13	6	9	13	10	11	10	6	13	20
	1977	5	7	9	7	9	10	6	6	7	8
	1987	1	5	8	7	7	8	5	7	6	7
	2003	1	5	7	9	10	9	7	9	4	7
	2012	1	5	8	9	7	8	5	9	5	6
Mean diameter of *T. moquinii* individuals in line 1 (m) (*D1*)	1961	8.55	10.48	10.40	7.78	8.87	6.95	7.49	5.93	4.16	3.32
	1977	10.44	13.56	12.65	12.39	11.31	8.18	8.99	8.78	7.25	6.32
	1987	11.82	13.34	13.17	11.52	11.57	8.86	10.64	6.69	5.36	6.25
	2003	10.88	13.29	13.01	11.45	13.12	9.91	8.32	7.59	6.59	5.83
	2012	11.11	13.59	15.66	12.08	13.64	8.44	9.82	8.12	5.45	7.05
Mean distance between *T. moquinii* individuals in line 1 (m) (*DB1*)	1961	10.35	20.41	12.74	9.79	15.42	15.44	13.83	21.50	9.99	10.32
	1977	20.64	16.38	11.18	13.90	15.15	13.04	25.96	16.96	11.73	22.94
	1987	0.00	18.17	9.91	14.66	17.32	15.60	26.90	18.70	16.94	22.22
	2003	0.00	17.78	12.17	11.52	14.64	15.55	22.11	9.31	15.54	21.50
	2012	0.00	20.34	11.95	11.27	21.23	15.65	25.13	8.98	17.45	26.68

$$FS_{ij} = \beta_0 + \beta_1 DB1_{ij} + \beta_2 B1_{ij} + \beta_3 D1_{ij} + b_{0i} + \varepsilon_{ij} \quad (2)$$

where FS_{ij} is the response morphologic variable (the foredune surface). In model (1) NN_{ij} is the number of nebkhas or number of *T. moquinii* individuals in the plot in the year *i* at the plot *j*, and D_{ij} is the density of *T. moquinii* in the year *i* at the plot *j*. In model (2), $DB1_{ij}$ is the mean distance between nebkhas or mean distance between *T. moquinii* individuals in line 1 in the year *i* at the plot *j*, and $B1_{ij}$ is the number of *T. moquinii* in line 1 in the year *i* at the plot *j*, finally $D1_{ij}$ is the mean diameter of the *T. moquinii* plants in line 1 the year *i* at the plot *j*. These are fixed factors in the model. Year has been introduced in the model as a random factor as the observed years are a random sample of all possible study years. The term b_{0i} represents random annual variation in the mean foredune surface. b_{0i} is assumed to follow a normal distribution with zero mean and variance σ_0^2. ε_{ij} are the residual terms, and are also supposed to follow a normal distribution with zero mean and variance σ_ε^2. Heteroscedasticity between observation plots was also taken into account and has been modeled using a different variance per plot as shown in Pinheiro and Bates (2000), so that $(\varepsilon_{ij}) = \sigma_j^2$. Parameters in the linear mixed model has been estimated by using the library nlme (Pinheiro et al., 2017), in the statistical software environment R (R Core Team, 2016). The significance of these parameters in the models has been tested by a *t*-test. Goodness of fit of the model has been assessed

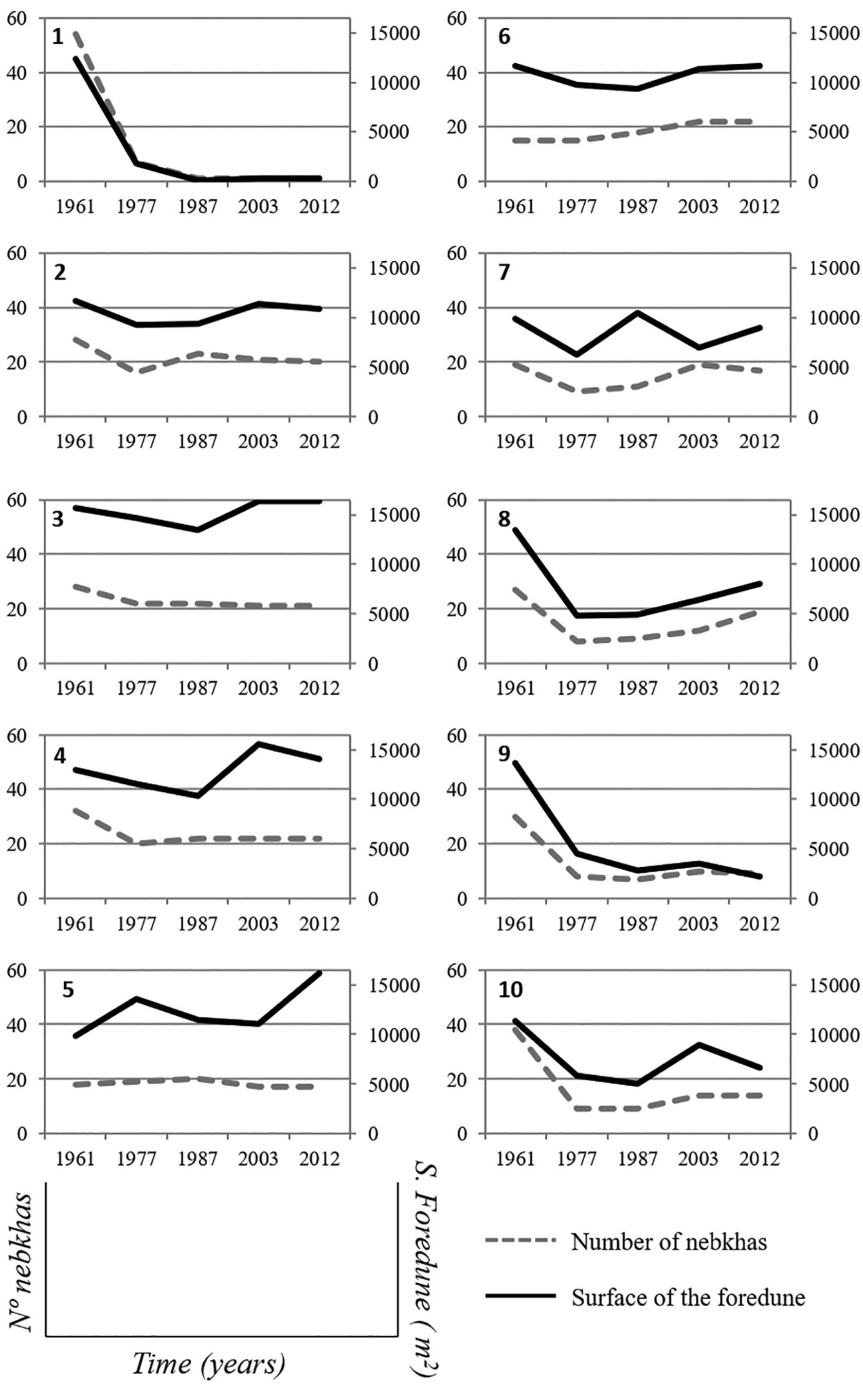

Fig. 3. Evolution in the number of nebkhas and changes (m^2) in the foredune surface since 1961 to 2012 in each observation plot extending from the north (Plot 1) to the south (Plot 10).

by using the Shapiro-Wilk test for testing normality (Shapiro and Wilk, 1965) of both the within group errors and the random effects of the model. Other assumptions of the model (independence between within-group errors and homogeneity of the random effects covariance matrix) have been checked by the graphical tools in the library *nlme*. The significance level for all tests has been 0.05. The models' estimation is shown in Table 3. Data have been removed in some cases to calculate models (1) and (2), especially related to plot 1 because the changes detected have no other explanation than the alteration because the plot has been occupied by construction (see Fig. 2). For this reason, the DF in model (1) is 36, and in model (2) is 39.

4. Results

4.1. Decadal evolution of the variables measured

4.1.1. Evolution of the foredune surface and number of nebkhas

The data indicate significant differences in the evolution of the foredune, both spatially and temporally (Fig. 3). First, the number of nebkhas (grey line) and, therefore, the number of individuals of *T. moquinii*, has decreased between 1961 and 2012. The largest changes are detected in plot 1 (north of El Inglés beach), and in plots 9 and 10 (south). The most stable plot over time is plot 5, located in the central area. The number of nebkhas declined in plots 2, 3 and 4 between 1961 and 2012, and, in contrast, plots 7 and 8 experienced an increase in the number of nebkhas since 1987. Plot 6 is the only plot, which had a low decrease of number of nebkhas between 1961 and 1977, and then increasing in numbers progressively since then.

As for the surface covered by the foredune (black line) (i.e. the area occupied by nebkhas, shadow dunes and inter-nebkha parabolic-shaped tongue dunes (aeolian landform described by Viera-Pérez (2015))), plot 5 has increased in surface area since 1961 (Fig. 3). Plot 1 is the only one that has experienced a reduction in the area of the foredune. The same is observed in plots 8, 9 and 10, although these plots have had periods of increased surface area also. Plots 2, 6 and 7 have in common that the surface area of the foredune decreased slightly with respect to 1961. In addition, all plots have had periods of stability or even increased their surface area. Finally, plots 3 and 4 experienced a decline in foredune area until 1987, showing a recovery since then.

4.1.2. Evolution of the number and distribution of T. moquinii, and associated nebkha

In general terms, there are significant changes in the morphological variables of *T. moquinii* over the last decades in practically all the plots, although the differences also depend on their location (Table 3). One example is the vegetation density, and it has decreased in all the plots with respect to the 1960's except plot 8. In plot 8 the number of individuals in line 1 (the foremost line of nebkha) increased, while the mean distance between them decreased. The mean diameter of *T. moquinii* in line 1 also increased in all plots. In terms of mean distance and density, in plot 1, individuals disappeared (Fig. 2, A and B). However, in plots 2, 3 and 8 the mean distance between individuals decreased while the mean density increased.

4.2. Maspalomas' foredune mode and consequences on the T. moquinii variables

4.2.1. Spatial geomorphological differences in the foredune

The cluster analysis examining the evolution of the variables related to the geomorphology of the foredune (number of nebkhas and foredune surface), indicates the existence of three groups of plots or three foredune zones (Fig. 4).

4.2.1.1. Group 1: plots 2, 6 and 7. This group is located in the north (plot 2) and in the central area of the study area (plots 6 and 7). These plots are characterized by variations in the geomorphological characteristics of the foredune. Thus, plots 2 and 7 show a decrease in the number of nebkhas and the surface of the foredune, while plot 6 in 2012 shows an increase in the area of the foredune while the number of nebkhas has remained similar to 1961.

4.2.1.2. Group 2: plots 3, 4 and 5. The plots of this group are located in the north and center of El Inglés beach. These are plots that have had greater stability since 1961, although plots 3 and 4 show a small decrease between 1961 and 1987. However, these are plots that have increased in the area of foredune in the last few years (2003–2012).

4.2.1.3. Group 3: plots 1, 8, 9 and 10. This group of plots is located in the north (plot 1) and south (plots 8, 9 and 10) (as also seen in Fig. 5). They are the plots that have shown a larger decrease in the number of nebkhas and in the surface of the foredune area.

4.2.2. Understanding intraspecific competences through T. moquinii individual's evolution and distribution on the Maspalomas foredune

The results of the Pearson test of the variables in the three groups obtained through cluster analysis are shown in Table 4.

In group 1, the density has a negative correlation with the distance between the individuals of *T. moquinii* in the first line (where the 'first

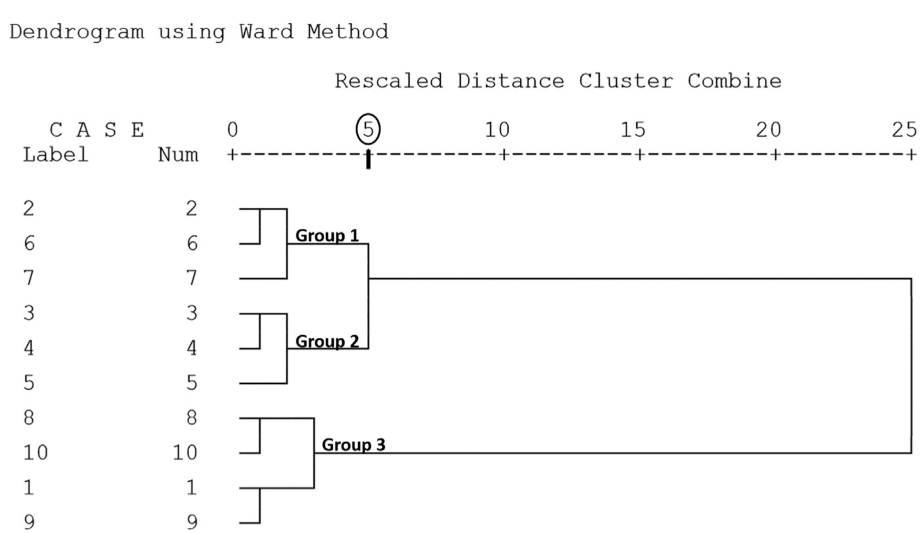

Fig. 4. Dendrogram from cluster analysis using the Ward method. Variables related to geomorphology of the foredune (number of nebkhas and foredune surface) are used. Three groups occur inside of distance 5.

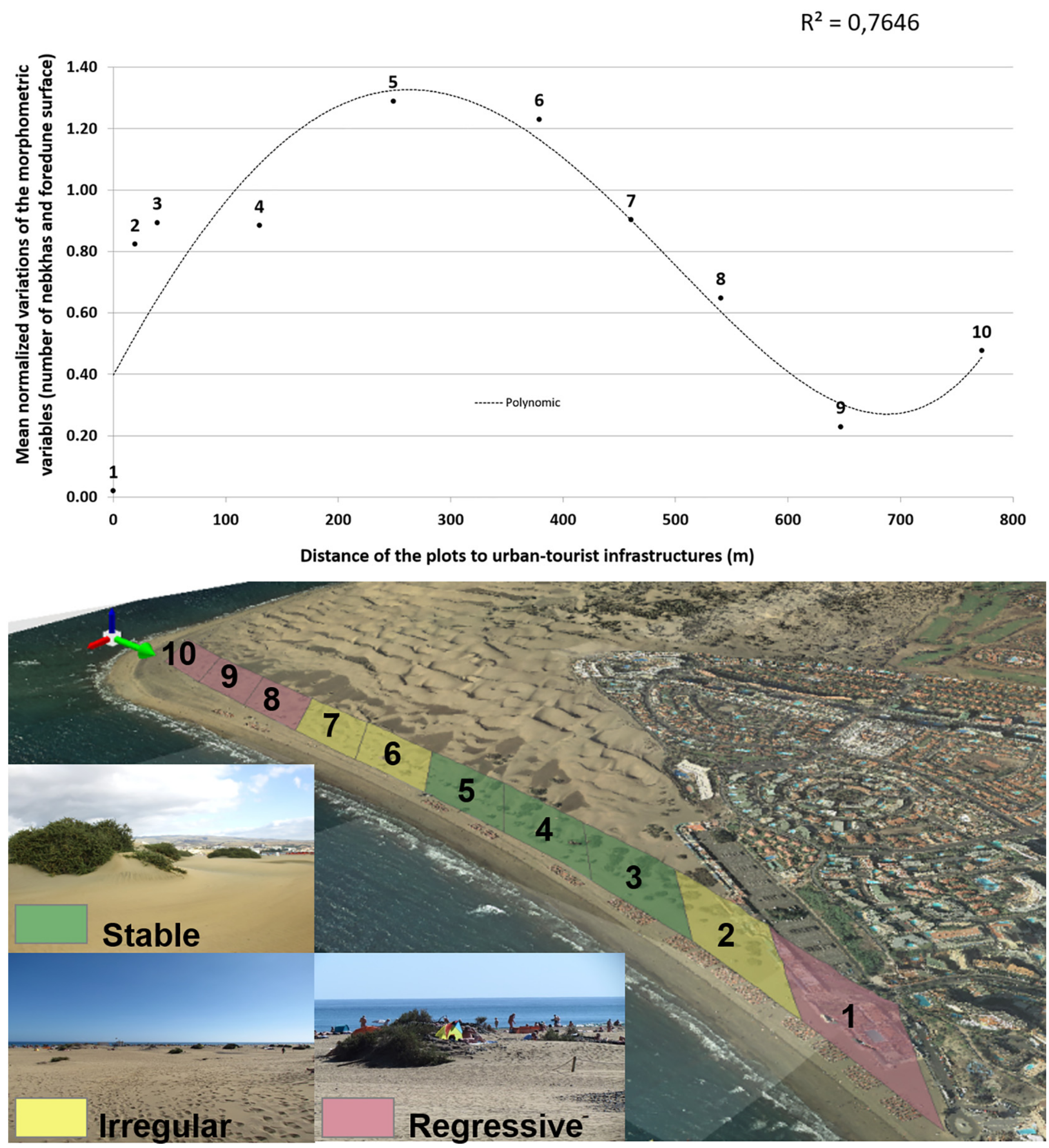

Fig. 5. Relationship between the variation of the morphology and geometry variables studied and the distance to the urban-tourist infrastructures of each plot. The numbers refer to the observation plot. The green region has the greatest distance from relatively higher tourist activity/infrastructure. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

line' is the line of nebkha closest to the backshore). The distance between individuals of *T. moquinii* shows a positive correlation with the distance between individuals in the first line of the plot. The number of *T. moquinii* individuals in the first line has a strong negative correlation with the distance between individuals and the diameter of the *T. moquinii* specimens in the first line.

In group 2, density is the variable with the highest correlation, as it is positively correlated with the density and number of individuals of *T. moquinii* in the first line, and negatively with the distance between individuals of *T. moquinii* in the first line, and with the diameter of the specimens of this species in the first line. The distance between individuals of *T. moquinii* is positively related to the distance between individuals of this species in the first line, and negatively with the density in the first line. The number of plants in the first line has a negative correlation with the diameter of the individuals in the first line.

In group 3 the density correlates positively with the number of *T. moquinii* individuals and with the density in the first line. The distance between individuals of *T. moquinii* correlates positively with the distance between individuals of this species in the first line and negatively with the diameter of the specimens of *T. moquinii* in the first line. The number of individuals in the first line has a negative correlation with the diameter of the individuals. Finally, the diameter of the individuals of *T. moquinii* in the first line correlates negatively with the distance between them in the first line.

4.3. Relationship between T. moquinii's variables and foredune surface

The equations obtained for models (1) and (2) show that the different variables are significant according to the p-value (Table 5). In model (1), the number and density of nebkhas variables are related in each plot with respect to the response variable or foredune surface. In this case, there is a direct relationship between both variables due to the low values obtained in the residual variability $\sigma_0 = 0.3544$ and $\sigma_\varepsilon = 1385.56$. In addition, the *p*-values are also low values with 4.98E−11 in the number of nebkhas and 0.01751 in the density. This indicates that when one nebkha unit increases, the foredune surface increases by 548.8 m^2, and when the density increases one unit, the foredune surface decreases by 39.12 m^2. This density equation is influenced by the distance between the *T. moquinii* individuals or nebkhas, because

Table 4
Pearson test of the variables in three groups obtained through cluster analysis. Correlations between *T. moquinii* variables.

Groups	Variables	Density	Dist_Traganum	No. Traganum_line 1	Diameter_line 1	Dist_Traganum_line 1	Density_line 1
Group 1. 2, 6, 7 N = 15	Density	1	−0.944[**,a]	0.267	0.064	−0,574[*]	0.407
	Dist_Traganum		1	−0.305	−0.068	0,683[**]	−0.511
	N° Traganum_line1			1	−0.725[**]	−0.730[**]	0.817[**,a]
	Diameter_line 1				1	0.177	−0.334
	Dist_Traganum_line1					1	−0.956[**,a]
	Density_line1						1
Group 2. 3, 4, 5 N = 15	Density	1	−0.966[**,a]	0.531[*]	−0.568[*]	−0.595[*]	0.635[*]
	Dist_Traganum		1	−0.375	0.493	0.651[**]	−0.640[*]
	N° Traganum_line1			1	−0.648[**]	−0.431	0.477[a]
	Diameter_line 1				1	0.121	−0.129
	Dist_Traganum_line1					1	−0.936[**,a]
	Density_line1						1
Group 3. 1, 8, 9, 10 *N* = 20	Density	1	−0.036[a]	0.886[**]	−0.394	−0.033	0.746[**]
	Dist_Traganum		1	0.170	−0.602[**]	0.911[**]	0.022
	N° Traganum_line1			1	−0.670[**]	0.143	0.728[**,a]
	Diameter_line 1				1	−0.521[*]	−0.358
	Dist_Traganum_line1					1	−0.191[a]
	Density_line1						1

[**] Correlation is significant at the 0.01 level (bilateral).
[*] The correlation is significant at the 0.05 level (bilateral).
[a] The correlation is discarded because the density calculation is related to the average distance between the individuals of *T. moquinii* on the plot or on line 1 and the number of *T. moquinii* on the plot or in line 1.

when the distance between them increases, the foredune is more fragmented and as a result, the foredune surface decreases.

Model (2) (Table 5) shows relationships between the variables DB1, B1 and D1 to explain the behavior of the foredune surface, due to the low p-values obtained (9.46E−09, 4.50E−10 and 1.57E−19 respectively). Although high values in the residual variability are found ($\sigma_0 = 1483.116$ and $\sigma_\varepsilon = 4790.96$) these are not valid to predict the foredune surface variable. In this case, if one DB1 unit increases, the foredune surface decreases 182.6 m^2, producing a fragmented foredune. If one B1 unit increases, the foredune surface increases 266.1 m^2 and then, if one D1 unit increases, the foredune surface increases by 744.7 m^2.

5. Discussion

5.1. Biogeomorphological evolution of the Maspalomas' foredune

The analyses of the environmental changes and relationships between the morphological and distribution characteristics of *T. moquinii* and the morphological and geometric changes of the foredune zone through biogemorphological variables, confirms the initial hypothesis, namely, that the anthropogenic levels of use and disturbance around the foredune determines the environmental evolutionary patterns of the foredunes. While this result is similar to some studies conducted in temperate environments (e.g. Nordstrom et al., 2000; Martínez et al., 2013a, 2013b), it is more fundamentally important in arid coastal environments where plant cover is low, only one or very few species are present, therefore we are experiencing on an foredune which has a trend to fragment easily, and the stability and functioning of the foredune zone is so much more fragile.

Table 5
Estimation of the models (1) and (2).

	Variables	Value	Std. error	DF	t-Value	p-Value
Model (1)	(Intercept)	2127	816.4	36	2.606	0.01325
$\sigma_0 = 0.3544$	NN	548.8	59.42	36	9.235	4.98E−11
$\sigma_\varepsilon = 1385.56$	D	−39.12	15.71	36	−2.49	0.01751
Model (2)	(Intercept)	4499	1266	39	3.553	0.001014
$\sigma_0 = 1483.116$	DB1	−182.6	25.15	39	−7.259	9.46E−09
$\sigma_\varepsilon = 4790.96$	B1	266.1	32.28	39	8.243	4.50E−10
	D1	744.7	44.09	39	16.89	1.57E−19

σ_0 and σ_ε: residual variability.

The evolutionary differences in the geomorphological characteristics of the foredune between 1961 and 2012 (number of nebkhas and foredune surface) indicate the presence of three groups, in contrast to Amini et al. (2012) who found 4 zones in a study on concentration, stabilization, height and biological cover on a foredune in North Iran. However, in the case of Maspalomas, the anthropogenic factor is determined by tourist pressure (users, beach services) as opposed to the study area studied by Amini et al. (2012) where the anthropogenic pressure is low. Group 1 comprises irregular dynamics but tended to stability, group 2 has a predominantly stable dynamic, while group 3 shows a regressive evolution, with a significant decrease in the number of nebkhas and in the surface of the foredune. This differential behavior has also been detected in other foredunes around the world, although in non-arid regions, such as in the Doñana National Park (Huelva, Spain), where Vallejo et al. (2006) differentiated five types of foredunes. This variability could be related to two of the three main variables that have been observed in the Emilia-Romagna littoral, in Italy (Corbau et al., 2015): (a) orientation of the coast, and the foredune, with respect to marine and aeolian forces; and (b) human activities. The second variable (human activities) is here stronger than the first one, because El Inglés beach is virtually a straight long beach with almost no change in orientation. According to Hernández-Calvento et al. (2014), the changes on the southern sectors of the foredune are not induced by the orientation, but by the urbanization located in the northern region, which has induced an acceleration of the winds to the south. According to Hernández-Cordero et al. (2017), part of this urbanization (a shopping center and a car park), occupied the foredune in the north of El Inglés beach (Fig. 2), eliminating *T. moquinii* individuals and changing the aeolian dynamics.

The reduction in the number of *T. moquinii* individuals, and therefore the alteration of the foredune, has not generated the formation of blowouts, as sometimes (and quite commonly) occurs in temperate regions (Leatherman, 1976; Godfrey et al., 1979; Ritchie and Penland, 1990; Saunders and Davidson-Arnott, 1990; Hesp, 2002; Mir-Gual et al., 2013). This fact seems to be related to the differences between arid and temperate foredunes. The arid foredune of Maspalomas comprises discontinuous nebkhas, and thus, the effect of degradation of an arid foredune is the reduction of nebkhas, and the formation of deflation surfaces and free (mobile) landforms such as small barchan dunes (less than 1 m high) and sand sheets (Hernández-Cordero et al., 2012; Hernández-Calvento et al., 2014).

In addition, in plots 2, 6 and 7, the disappearance of *T. moquinii*, possibly due to anthropogenic actions, is detected, although in smaller numbers. These results are more evident in the case of plot 2, given its proximity to the urban-tourist area. The majority of beach services have been historically located in the surrounding area of this plot and within its inner area, which has meant, from the mid-1970's and until the late 1980's, the presence of kiosks of 120 m^2, as well as a great number of hammocks and umbrellas. A continuous trafficking of vehicles along the backshore was linked to these services and other tourist activities (security and surveillance), in order to supply services to the beach-going public and tourists (Hernández Calvento, 2006). In regard to plots 6 and 7, the remoteness of the urban-tourist center and the beach facilities was still not sufficient for their conservation. Around these plots, facilities of hammocks and umbrellas have been historically limited, which have made these areas places of attraction for tourists looking for greater naturalness. The lack of basic public services in these areas, such as urinals, has led tourists to use *T. moquinii* plants as improvised urinals, with negative consequences for the plants (Hernández Calvento, 2006). Also, these plants have often served as a base for the construction of windbreaks by tourists, since in this area a higher wind speed is detected, partly due to the influence of the tourist development (Hernández-Calvento et al., 2014). To all these actions is also added the direct effects of human trampling that affects the vegetation (McDonnell, 1981; Fenu et al., 2013; Delgado-Fernández et al., 2019), in this case *T. moquinii*. This has led to the alteration of the plants (broken branches, for example) and the modification of the aeolian sedimentary dynamics around the plants (Hernández Calvento, 2006).

Plot 5 is located in the most unaltered zone, where the number of nebkhas has been maintained in the last decades (Fig. 3) (Viera-Pérez, 2015). Fig. 5 shows a normalized mean of the variation experienced in the morphology and geometry variables in each plot (number of nebkhas and foredune surface) and their distance to tourist infrastructures (access to the beach, resorts, etc.). In the first 150 m, tourist activities and services are intense, hence the relatively lower numbers of nebkha and surface occupied by a foredune. At around 450 m tourist services again increase and nebkha numbers diminish. In the middle zone (250–400 m) tourist activities are relatively low, and the number of nebkhas and surface of the foredune is greater (Fig. 5).

5.2. *T. moquinii* and its intraspecific competences on the Maspalomas' foredune

The correlations between variables morphological and distribution of *T. moquinii* could offer information to detect the state of natural equilibrium shown by the foredune. In this sense, the largest number of significant correlations observed in group 2 (plots 3, 4 and 5), indicate that this portion of the foredune could be in an equilibrium state, because it corresponds to plots that have displayed greater stability throughout the study period. In group 1 (plots 2, 6 and 7), as well as in group 3 (plots 1, 8, 9 and 10), a significant number of correlations between the variables are detected, although they exhibit a regressive dynamic as the number of plants has been declining over time.

The results indicate the importance of using variables measured in the first line of the foredune, and, in particular, the distance between the individuals of *T. moquinii* (Table 5; Fig. 5) This distance is a key factor to be taken into account for the proper development of the species. The density in the whole plot, as well as the distance between individuals of *T. moquinii* in the plot, and the number of them in the first line are closely related to the rest of the morphologic variables of this species. These results could be used for ecological restoration of the foredune in those areas where it has been degraded, as has occurred in the south of El Inglés beach, where there has been a fragmentation of the foredune (Hernández-Cordero et al., 2012; Hernández-Calvento et al., 2014). They could also be applied to other arid zone foredunes in cases where restoration is required.

The variable distance between *T. moquinii* in the plots is positively related to the distance that the individuals have in the first line in both groups. This means that the greater the distance between individuals in the first line, the greater is the distance of *T. moquinii* in the rest of the plot. This shows that the distribution pattern of *T. moquinii* in the foredune depends directly on the distance between the specimens of this species in the first line at the backshore. This result is key to the management of this protected natural space, since it is precisely the individuals of the first line which experience greater anthropogenic pressure by users, facilities and services on the beach.

The number of *T. moquinii* in the first line has a close relationship with the diameter of the specimens in the first line. Thus, in the 3 groups the greater the number of individuals in the first line, the smaller the diameter of these individual plants. This result may be related to the competition that exists between individuals in the front of the foredune or by local human impacts, at least in the north of El Inglés beach, where artificial lighting induces inhibition in flower production and, thus, reduced possibilities in reproduction of the *T. moquinii* species. However, individuals exposed to light have greater growth (Viera-Pérez et al., 2019). It should be considered that *T. moquinii* under suitable conditions is a shrub that can reach up to 5 m in height and occupy a large area (Hernández-Cordero et al., 2012), so it needs significant root area for its maximum development. Therefore, when the number of individuals is significant they cannot reach their maximum size. Such competition for resources and space also occurs in shrubs of other species in semi-arid zones (Kambatuku et al., 2011). These variables should be taken into account in order to understand the distribution of vegetation in arid coastal foredunes because in most studies conducted so far (Van der Valk, 1974; Maun and Lapierre, 1986; Hernández-Cordero, 2012, Zhang et al., 2015), the distribution of vegetation is conditioned especially by sediment transport and accumulation.

5.3. *T. moquinii*'s role on the Maspalomas' foredune

The mixed models used in this research for examination of multiple predictors simultaneous, which heteroscedasticity between observation plots is taken into account and has also been modeled using a different variance per plot, have allowed for the first time to analyse statistically the *T. moquinii* role on the geomorphology of the foredune, unlike previous studies such as Hernández-Cordero et al. (2012, 2017) which only show the evolution of the number of *T. moquinii* individuals or the surface occupied by this plant species and is not related to morphology.

T. moquinii shows a relationship with the variables associated with the morphology and geometry of the foredune of Maspalomas, being a structuring element in the formation of accumulation landforms (nebkhas, shadow dunes and tongue dunes), which corroborates the findings of other studies (Hernández Calvento, 2006; Hernández-Cordero et al., 2012; Viera-Pérez, 2015). In general, the number of nebkhas has a (obvious) strong relationship with the plant density of the plot and the distance between the individuals of *T.* moquinii as shown in Figs. 3 and 5. These variables have a natural relationship that favors the formation and conservation status of the foredune (Hesp, 1983). However, it should be clarified that as the number of nebkhas associated with the presence of *T. moquinii* specimens has been used for the calculation of plant density, their relationship is logical.

It is also worth noting the relationship between the foredune surface and the other variables of *T. moquinii* measured such as diameter, number and density of *T. moquinii* plants in line 1. This may explain why the plots of this group are the most stable geomorphologically over time. The correlation between these variables could be indicating a balance in the system, which reinforces the relationship between vegetation and sediment transport, leading to the formation of nebkhas and the foredune itself. As for the variable of the surface of the foredune, this does not have any relation with any variable related to the distribution and morphology of *T. moquinii*, quite the opposite to that which occurs with the number of nebkhas. This behavior can be explained by the fact that it is a plot where a locally greater or significant wind velocity has been detected (Máyer Suárez et al., 2012), and therefore has an accelerated aeolian transport (as also occurs in plot 5). As a result, it might be that wind velocity in this area is a significant and structuring factor, as seen in other case studies (Nordstrom and Jackson, 1993; Davidson-Arnott and Law, 1996; Jackson and Cooper, 1999; Davidson-Arnott et al., 2002; Hesp et al., 2005; Miot da Silva and Hesp, 2010; Corbau et al., 2015). Due to these relationships, future research could examine such relationships further by adding the third dimension through LiDAR and photogrammetric altimetry. In this way, the relationships between the *T. moquinii* species and in this case foredune morphometry, could be analysed using variables such as plant height with respect to variables such as volume (sediment supply) and foredune height.

6. Conclusions

The conclusions that derive from this investigation are the following:

1. The distribution and morphology of the shrub species *Traganum moquinii* has been analysed over a multi-decadal historical time frame, to examine the morphometric function exerted by this species on the foredune of an arid coastal dunefield and the impacts of human activities on foredune functioning. The importance of this analysis is that this plant species is a structuring element in the dynamics of the arid coastal dune systems in the Canary Islands as well as in a significant part of northwest Africa.
2. Overall, the number of nebkhas, and, therefore, the number of individuals of *T. moquinii*, has decreased between 1961 and 2012.
3. 3. The evolution of the nebkha dominated foredune of Maspalomas has not been spatially homogeneous due to eco-anthropogenic processes. This is evidenced by the detection of 3 types of foredune through decadal monitoring, a stable dynamic zone (group 2), a zone with irregular dynamics but tending towards stability (group 1) and a regressive (degenerating) zone (group 3).
4. 4. Where tourist activities and services are intense, relatively lower numbers of nebkha and foredune surface occur. Where tourist activities are relatively low, the number of nebkhas and surface of the foredune is greater.
5. 5. The morphological variables of *Traganum moquinii* studied in the first (foremost) line of the foredune (number of *Traganum moquinii* individuals, diameter of individuals, distance between individuals and density) seem to be the most significant in the spatial distribution pattern of *Traganum moquinii* and sediment accumulation especially for the evolution and development of the foredune further landwards.
6. 6. The relationships between the geomorphological variables of the foredune and the morphological variables of *Traganum moquinii* could be useful information for the environmental restoration of the foredune of Maspalomas in those areas where it has been degraded, as well as for an adequate management of the dune system.

CRediT authorship contribution statement

Leví García-Romero: Data curation, Formal analysis, Investigation, Methodology, Writing - original draft, revisions. **Antonio I. Hernández-Cordero**: Data curation, Supervision, Validation, revisions. **Patrick A. Hesp**: Supervision, Writing - review & editing, revisions. **Luis Hernández-Calvento**: Supervision, Writing - review & editing, Funding acquisition, revisions. **Ángelo Santana del Pino**: Statistical Analysis, revisions.

Declaration of competing interest

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