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Environmental variables affecting an arid coastal nebkha

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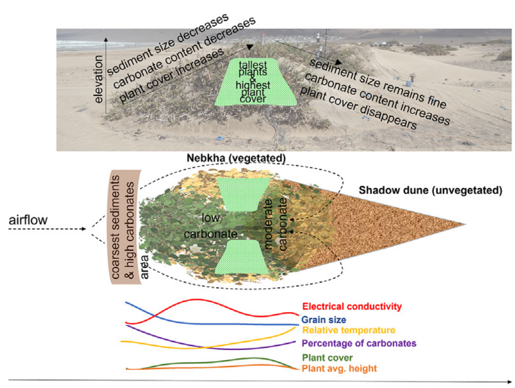
HIGHLIGHTS

- A range of environmental variables affecting a coastal arid nebkha are investigated.
- Distance from the sea acts as a proxy for shelter and abiotic conditions gradient.
- Larger percent of plant cover correlated with finer sediment and lower temperatures.
- The tallest plants were towards the back of the nebkha on the flanks.
- Spatial patterns in sediment characteristics indicate complex secondary airflows are important.

GRAPHICAL ABSTRACT



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ABSTRACT

Foredunes in arid coastal dune systems comprise nebkhas, which originate by interactions between vegetation and aeolian sedimentation. While continuous foredunes in temperate climates have been widely studied, knowledge of interactions between biotic and abiotic drivers in foredunes formed by nebkha is still scarce. With the aim of exploring variables affecting arid foredunes, a range of morphological, sedimentological, and vegetation characteristics were measured on a single nebkha formed by a *Traganum moquinii* plant located in the foredune of *Caleta de Famara* beach (Lanzarote, Canary Islands). Variables were sampled at 120 plots in a 0.5 × 0.5 m square grid. A two-step process using multiple linear regression (MLR) analyses was developed to characterize 1) the influence that morphological variables and distance from the sea have on plant and sediment patterns on nebkha, and 2) the influence of plants on depositional sediment characteristics. Results indicate close relationships between distance from the sea, plant coverage, and sediment patterns. Empirical results were used to develop a conceptual model that explains the spatial distribution of bio- and geo-morphological characteristics of an arid nebkha foredune.

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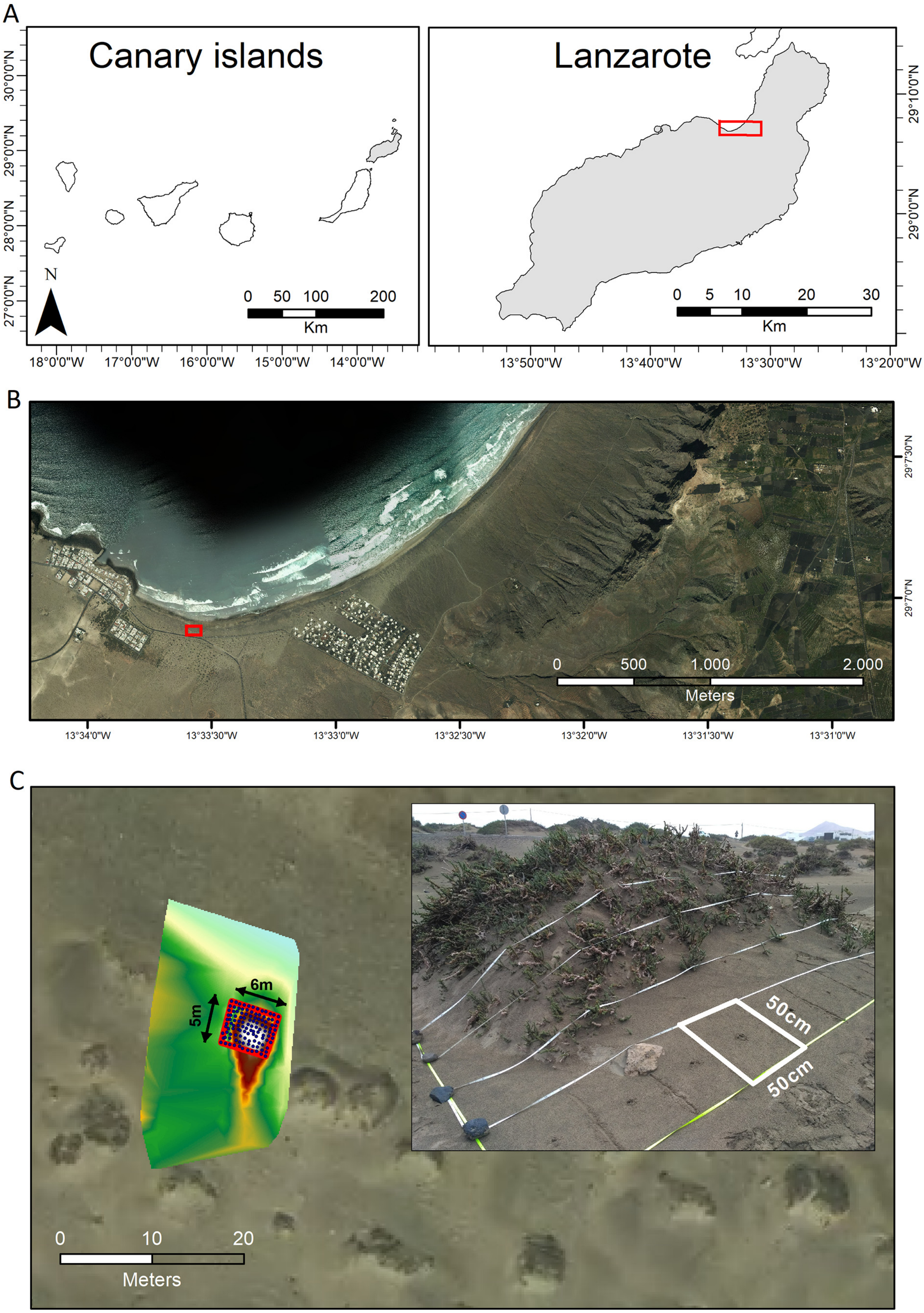
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1. Introduction

The principal mode of foredune development in arid environments is nebkha (Hernández-Cordero et al., 2019; Hesp et al., 2021a; Hesp and Walker, 2013). Nebkhas (aka nabkha, coppice dunes, phytogenic mounds) are individual aeolian landforms formed by sand accumulation around and within discrete vegetation (Cooke et al., 1993; Hesp and McLachlan, 2000). The vegetation might comprise herbs, grasses, shrubs or trees, and in the Canaries typically comprises *Traganum moquini* shrubs. Nebkha foredunes are fragile ecosystems, naturally fragmented, that play an important functional role as they regulate sediment transport inland (Hernández-Cordero et al., 2015) favoring the formation of other landforms such as shadow dunes, barchan dunes and barchanoid ridges (Domínguez-Brito et al., 2020; Hernández-Cordero et al., 2012; Hesp, 2002; Hesp and Smyth, 2017; Yang et al., 2019). The presence of nebkha induce microenvironmental and vegetational spatial heterogeneity in natural landscapes (El-Bana et al., 2002; Zuo et al., 2009). Nebkha morphology is directly related with the size and growth habit of the plant that forms it (Charbonneau et al., 2021; Du et al., 2010; El-Bana et al., 2002; Hesp and McLachlan, 2000; Lang et al., 2013; Toranjzar et al., 2015), and sediment characteristics can vary spatially depending on the plant species and their morphology and density (Kidron and Zohar, 2016; Lee et al., 2007; Li and Ravi, 2018; Xiaohong et al., 2019). Individual nebkha may also show variations in geomorphological and ecological factors at a sub-metre scale, such as soil characteristics, nutrient content, water availability, and vegetation cover. The protection provided by the nebkha cover against sand abrasion (Quets et al., 2017) can also account for variation in nebkhas, and this can depend on plant growth characteristics, sand sources, degree of salt spray inundation, or wind conditions (El-Bana et al., 2007; Hesp and McLachlan, 2000). This microenvironmental spatial heterogeneity can promote the deposition of plant seeds and localize soil nutrients that lead the growth and diversity of species, turning nebkhas into “fertility islands” (El-Bana et al., 2002; Hesp and Smyth, 2019; Schlesinger et al., 1996).

Unlike inland nebkhas, the zonation of coastal dunes, in addition to sand deposition, is conditioned by the influence of the sea, which is reflected in a marked gradient of environmental stress, regardless of the geographical area in which they are located (Doing, 1985). The interaction of biotic processes and abiotic heterogeneity explains the spatial pattern of vegetation (Badreldin et al., 2015). In addition to water availability and nutrient scarcity, the most restrictive abiotic factors for plants are substrate mobility (sand burial and sand erosion), and salinity due to salt spray and seawater flooding (Barbour et al., 1985; Clark, 1986; Hesp, 1991; Kumler, 1997; Maun, 2009; Randall and Scott, 1997; Rozema et al., 1985). Distance from the sea can be used as a proxy for the variability of these abiotic factors, that, in general, are harshest close to the sea and gradually reduce inland (Du and Hesp, 2020; Green and Miller, 2019; Hesp, 2002; Rajaniemi and Allison, 2009; van der Valk, 1974a). These characteristics affect the distribution and abundance of vegetation and plants traits (García-Mora et al., 1999; Hesp, 1991; Luo and Zhao, 2019; Maun, 1998; Moreno-Casasola, 1986), as only species adapted to the harshest environment can germinate, grow and survive near the coast (Ehrenfeld, 1990; Green and Miller, 2019). Once pioneer species with high tolerance to harsh coastal conditions colonize an area, a mechanism of retention of sand and reduction of salinity is created that favors the establishment of new species, ecological competition and plant succession (Barbour et al., 1985).

Many researchers have investigated the formation, distribution and spatial patterns of sediment and vegetation in inland nebkhas, as well as in the foredune of temperate areas (Du et al., 2010; Hesp, 1989; Kidron and Zohar, 2016; Li and Ravi, 2018; Luo et al., 2016; Quets et al., 2017; Ruz et al., 2017; Toranjzar et al., 2015; Xiaohong et al., 2019; Yousefi Lalimi et al., 2017; Zuo et al., 2009). The relationship between environmental characteristics, vegetation patterns and geomorphological processes has allowed the development of conceptual models of coastal dunes in temperate areas (e.g., Hesp, 2002; Kim et al., 2008; Kim and Yu, 2009; Short and Hesp, 1982). However, there is a lack of integrative studies in arid coastal dunes and no current similar conceptual modelling of sedimentation and the interactions between biotic and abiotic factors.

Coastal vegetated dunes are relevant to human society because they play an important role in protecting the coast against storms (Feagin et al., 2015, 2019). Thus, an improved understanding of natural nebkha landforms and their functioning is also relevant for their protection (Luo and Zhao, 2019) and facilitates the identification of anthropogenic disturbances (Kim and Yu, 2009). These are common in arid dune fields in the Canary Islands (Cabrera-Vega et al., 2013; García-Romero et al., 2016; Hernández-Cordero et al., 2012, 2019) due to intense urban-tourist development (García-Romero et al., 2021; Hernández-Cordero et al., 2018; Peña-Alonso et al., 2018b; Viera-Pérez et al., 2019) and to the importance of these spaces as a source of recreational and aesthetic services (Peña-Alonso et al., 2018a; Sanromualdo-Collado et al., 2021).

This article presents a novel approach which explores in detail the spatial patterns of morphological, sedimentological and vegetation characteristics on a typical natural nebkha located in the foredune of *Caleta de Famara* beach (Lanzarote, Canary Islands), and examines relationships between those characteristics and nebkha development. Results on morphological, sediment and plant variables are combined to explain how spatial patterns inside a nebkha are interconnected and how they condition the growth and development of nebkhas in arid foredunes. Based on these empirical data, a new conceptual model is proposed as a step towards a better understanding of coastal nebkhas in arid environments.

2. Study area

The *Caleta de Famara* beach-dune system (29°06′55″N, 13°33′36″W) is located in the north of Lanzarote Island (Canary Islands, Spain), within the Chinijo Archipielago Natural Park (Fig. 1A). Weather conditions are constant throughout the year, with average annual temperatures of 21.1 °C and mean annual rainfall below 111 mm (AEMET 1981–2010). Prevailing winds are ENE, NE and NNE (Hernández-Cordero et al., 2019). *Caleta de Famara* beach (Fig. 1B) provides the main sediment supply to its adjacent dune field system, and to the *El Jable* sand sheet to the south of it (Cabrera-Vega, 2010). The dune field is approximately 0.45 km^2 and comprises nebkha dunes that range from 1 to 15 m wide and may reach 3.5 m high (Alonso et al., 2011).

Data was collected on a single nebkha representative of the nebkha forming the foredune system, at a landwards distance of 65 m from the high tide limit. The nebkha was typical of the medium size range of the system measuring 6 × 5 × 1.9 m in width, length, and height, respectively and similar to others, its longitudinal axis was oriented 18° N, roughly parallel to the NNE trade winds (Fig. 1C). Like all nebkha in this system, the dune was formed in one plant species, *Traganum moquinii,* which covered 60% of its surface. A shadow dune of 10.5 m in length extended downwind from the leeward top of the nebkha. *T. moquinii* is a shrub that strongly depends on sediment supply, and that grows in an upward direction from buried brunches (Viera-Pérez, 2015). It is also the main dune-building species of foredunes in the Canary Islands (Hernández-Cordero et al., 2015, 2019) and northwest Africa (Hernández-Cordero et al., 2019; Hesp et al., 2021b). Its marine and climatic conditions, plant growth patterns, natural fragmentation, and the presence of nebkha and shadow dunes, makes the foredune of the *Caleta de Famara* representative of arid regions foredunes generally (Hernández-Cordero et al., 2012). Finally, the system is exposed to moderate human pressure (Peña-Alonso et al., 2018b) due to the proximity to urban areas, its popularity, and the presence of stone windbreaks

Fig. 1. A) Location of the Caleta de Famara (Lanzarote) beach-dune system. B) Aerial view of the Famara coastline showing some of the urban developments to the east and west of the beach-dune system, and with the red square indicating the selected nebkha; C) Digital elevation model (DEM) and close up of the studied nebkha divided into measuring plots. Source of orthophoto: IDECanarias, GRAFCAN, S.A.-Government of the Canary Islands, (2018). Coordinates UTM (28 N). Ellipsoid WGS84. Datum REGCAN95.

constructed by recreational users in the foredune (locally referred to as 'goros'). The selected nebkha was one of the few located far enough away from stone windbreakers to be considered as the standard example of the medium size nebkha of the foredune non impacted directly by human activities.

3. Methods

3.1. Field survey

Data was collected between 18th and 20th October 2018. The nebkha was divided into 120 plots measuring 0.5 × 0.5 m (Fig. 1C). The shadow dune was excluded from the study area due to the absence of vegetation (Fig. 2). The center of each plot was surveyed with RTK-GPS (Trimble R4) (Łabuz, 2016) to create a digital terrain model (DTM) and to extract elevation (m), aspect (°), and slope (°) of each plot (Moore et al., 1991). Aspect was grouped in 8 directions of 45° (N, NE, E, SE, S, WS, W and NW).

For each plot, plant percentage cover was visually estimated, and maximum and average height of aerial parts of the plant were measured. No additional plant species other than *T. moquinii* were observed in any of plots. Soil temperature was measured in the center of each plot with a digital thermometer with probe (±0.2 °C) at a depth of 1 cm, as well as ambient temperature required to make corrections. Finally, sediment samples (approx. 200 g) were taken at a depth of 0–10 cm for subsequent laboratory analysis.

3.2. Laboratory analysis

Electrical conductivity (mS cm^{-1}), grain size (mm) and percentage of carbonates (%) of sediment samples were analyzed in the laboratory. Electrical conductivity (EC 1:5; Rhoades, 1993) was measured using an electric conductivity meter prior to washing the samples with distilled water and oven drying at 60 °C. The accumulation of salt in the sediments reveals the scarcity of precipitation, so the electrical conductivity of the soil can be used as a proxy measure of how salt spray from the sea is spatially distributed on the nebkha.

Grain sizes were obtained by separation of the different fractions in an electromagnetic sieve and their subsequent weighing. The sieves ranged between 2 mm and 0.063 mm, at 1Φ intervals. The weights of fractions retained on each sieve were incorporated into the GRADISTAT program (Blott and Pye, 2001) and interpreted by the Folk and Ward (1957) method to determine the mean grain size. Errors derived from sieving did not exceed 0.35% in any sample.

The percentage of carbonates in each sample was determined following the volumetric method by Bernard's calcimeter (Guitián Ojea and Carballas, 1976). Three replicas of each sample were made, using weights between 0.25 and 0.35 g. The presence of carbonates is used to determine the sources of sediment, being carbonate content related to marine biogenic sources (Alcántara-Carrió et al., 2010; Bernárdez et al., 2012; Calhoun et al., 2002).

3.3. Data analysis

With a graphical purpose, in order to make the point data more continuous to be represented by maps, spatial data were interpolated using ordinary kriging (Fig. 3), which has been widely applied to map spatial patterns in soil properties in dunes (Kim and Yu, 2009; Kim and Zheng, 2011; Yang et al., 2019).

Pearson's correlation coefficients were determined to analyze linear relationships between pairs of variables. Multiple Linear Regression analysis (MLR) was performed to predict the distribution of sediment and vegetation properties. MLR analysis are widely used in ecology to describe the influence that certain factors (biological and environmental) have on

Fig. 2. Front (A), east (B), west (C) and back (D) views of the nebkha and the shadow dune.

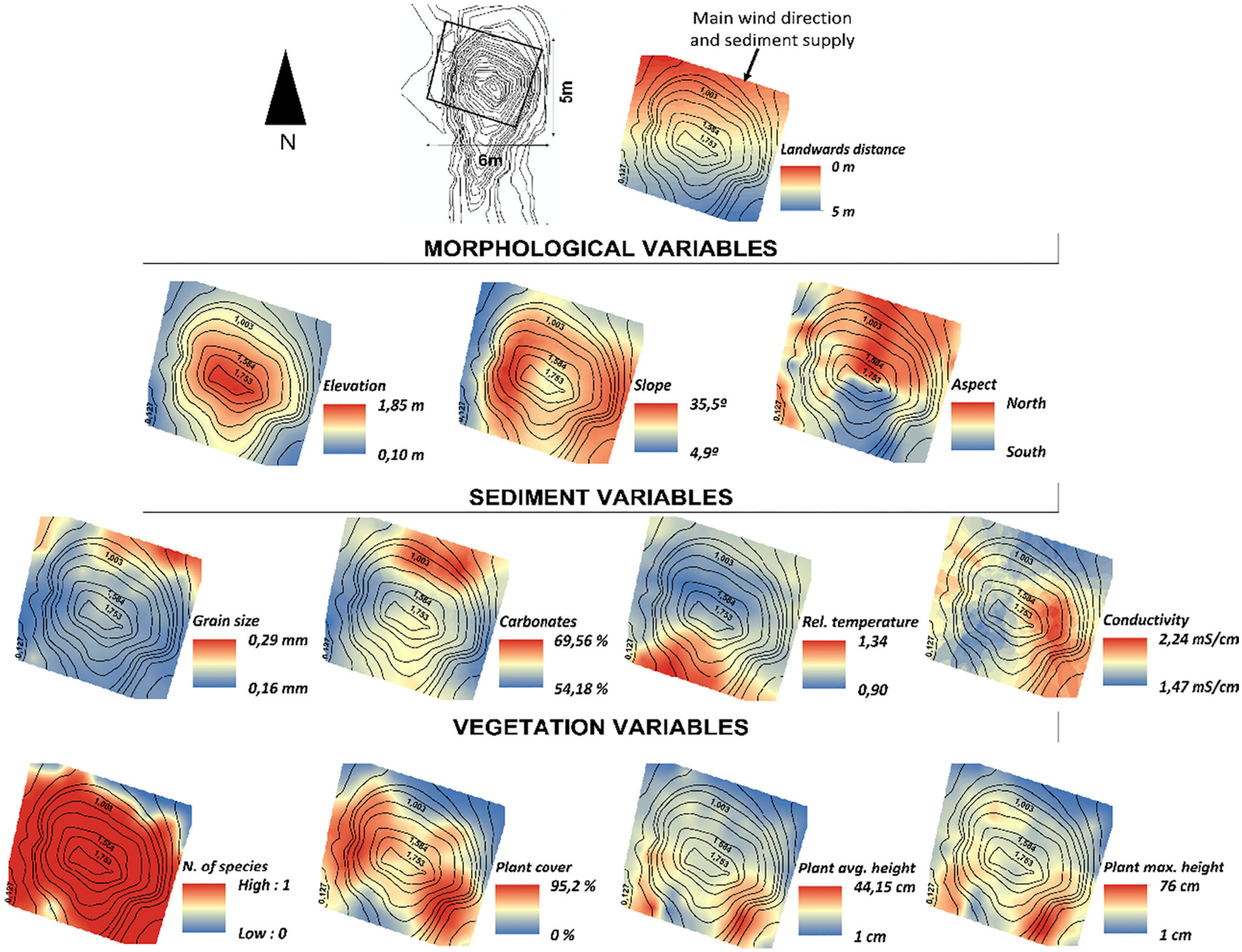

Fig. 3. Spatial distribution of variables. Kriging interpolation from 120 survey points.

different aspects of ecology (James and Mcculloch, 1990). To perform the MLR analysis, the set of variables was divided in two groups: 1) a first group including morphological variables (elevation, aspect and slope) and landwards distance from the dune toe (to explore the role played by proximity to the sea); 2) a second group including sediment properties (electrical conductivity, grain size, percentage of carbonates and relative temperature) and vegetation characteristics (plant cover, average height and maximum height).

MLR analyses were applied in two stages: in the first MLR analyses (MLR-1), morphological variables were used as independent variables to determine the most significant relation between them and sediment and vegetation characteristics (namely plant cover and average height, because plant maximum height was deemed redundant for statistical analyses). In the second MLR analysis (MLR-2), plant cover was introduced as an independent variable to explore its predictive capacity on sediment characteristics. Plant height was excluded at this stage due to its high correlation with plant cover.

The average height of the plant was selected as a representative variable of the plant height, and the variable corresponding to the plant maximum height was excluded from the models as it was considered redundant. The goodness of fit of the MLR obtained was determined by using the Shapiro-Wilk test for testing normality of the residuals (Shapiro and Wilk, 1965). Table 1 includes the list of all variables analyzed in this study.

4. Results

Spatial patterns of measured variables are included in Fig. 3, with overall morphology and landwards distance from the dune toe at the top,

Table 1
Groups of variables measured in this study at each of the 120, 0.5 × 0.5 m nebkha plots. Morphological (sediment) drivers acted as independent (dependent) variables in both MLR analyses 1 and 2, while vegetation related characteristics changed from dependent to independent.

Group	Morphological	Vegetation	Sediment
Variables	Plot elevation (m)	Plant cover (%)	Relative temperature (C°)
	Plot aspect (°)	Average plant height (m)	Electrical conductivity (mS cm^{-1})
	Plot slope (°)	Maximum plant height (m)	Mean grain size (mm)
	Landwards distance (m)		Percentage of carbonates (%)
MLR-1	Independent	Dependent	Dependent
MLR-2	Independent	Independent	Dependent

morphological characteristics in the second row, sedimentological variables in the third row, and vegetation variables at the bottom. The nebkha was cone -or pyramidal-shaped with a maximum elevation of 1.85 m relative to its base (Fig. 3, morphological variables row). The steepest slopes were found on the sides (E and W), with the landwards side showing relatively gentle slopes due to the presence of the shadow dune (Fig. 2). Grain sizes were relatively homogenous throughout the nebkha except for larger average sand sizes around the dune toe (Fig. 3, sediment variables row). This was also the area where most carbonates tended to concentrate, suggesting that the finer sand grains were blown landwards while the coarser sand grains and carbonates (e.g., shells) remained at the back-beach and lower stoss slope. Carbonate content and plant cover displayed an almost opposite trend (Fig. 3, 2nd map in the sediment and vegetation variables rows, respectively). In general, plant cover increased landwards and was highest towards the two sides of the nebkha. However, although plant cover first increased cross-shore along the central axis towards the crest, it then decreased towards the leeside of the nebkha where the shadow dune was. This leeside area with no plant cover displayed relative higher carbonate contents in comparison with the vegetated flanks. Soil temperatures (Fig. 3: Spatial distribution of variables. Kriging interpolation from 120 survey points, sediment variables row) were naturally highest on the leeside where there was no vegetation cover, and the dune was facing south (likely aided too by the reversing vortices in this region, and wind-sheltering effect provided by the vegetation in front). Conductivity was highest towards the sides with a peak on the eastern slope (Fig. 3, sediment variables row, last). The nebkha was covered by only one species (Fig. 3, bottom row), and plant height (both average and maximum) tended to peak towards the end of the two nebkha flanks, with the tallest plants found on the eastern leeside.

Table 2 shows results of the Pearson's analysis between all pairs of variables. Landwards distance from the sea showed the highest correlation with vegetation variables. Slope and aspect also displayed positive relationships with vegetation variables ($r^2 > 0.7$). Landwards distance was positively correlated with conductivity ($r^2 = 0.21$) and temperature ($r^2 = 0.55$), and negatively correlated with grain size and percent carbonates (r^2 of -0.64 and -0.29, respectively), in line with results in Fig. 3 pointing to the accumulation of coarser and more carbonate material at the dune toe. In terms of vegetation and sediment variables, the strongest (and negative) correlations were found between grain size and all three vegetation variables ($r^2 < -0.55$), indicating a spatial relation between increases in plant cover and maximum and average plant heights, and finer sediment sizes. Vegetation characteristics and percent of carbonates were also inversely related, but coefficients were lower compared to those for grain size ($r^2 < -0.23$). Sediment conductivity was positively correlated with all three vegetation variables ($0.20 < r^2 < 0.38$) and was relatively more strongly related with plant cover. This is in line with Fig. 3 and points to the role played by *T. moquinii* in preventing the loss of surface moisture. Soil temperature also decreased with plant cover and slightly increased with plant average height. It is worth noting that surface elevation did not show any significant correlation with measured plant height, grain size, carbonate content, and soil conductivity. Surface elevation only seemed positively correlated with plant cover ($r^2 = 0.38$) and negatively correlated with temperature ($r^2 = -0.23$). Albeit significant, these relatively low r^2 indicate the need to explore the role of nebkha surface elevation further and in combination with the spatial trends observed in Fig. 3 (see Section 5 Discussion). Finally, elevation also seemed weakly correlated with maximum plant height ($r^2 = 0.18$) but not average plant height hence suggesting that plant height could be better explained by other variables such as distance from the sea and shelter.

The MLR-1 analysis showed that combinations of morphological variables can significantly explain vegetation and sediment spatial patterns (Table 3). Distance from the sea explained a substantial amount of variability and was significant in all regression curves. Since distance from the sea was measured landwards from the dune toe, this variable is also a proxy for 'shelter', which is further discussed in Section 5 Discussion. The curve describing plant average height as a function of landwards distance from the sea had the highest correlation value ($r^2 = 47.88\%$). However, the results of the Shapiro-Wilk test (*p*-value <0.05) rejected the hypothesis of normality in the residuals of the curve, pointing to disparities between this curve and observed values. This is in line with patterns described in Fig. 3 (bottom row), where increases in plant average height can be observed towards the south along the dune sides, but not towards the south along the dune central axis (leeside of the dune crest) where plant cover was limited or even absent. In terms of sediment characteristics, the highest correlation ($r^2 = 43.00\%$) was found for the grain size curve as a function of distance from the sea and slope. This is in line with trends observed in Fig. 3 (sediment variables row) indicating that coarser sediments tended to accumulate at the dune toe area, while finer sediments tended to be transported landwards and concentrate on the steeper slopes (found on the E/W sides of the nebkha).

The MLR-2 analyses, which included vegetation characteristics as independent variables revealed the role that vegetation played on the spatial distribution of sediment characteristics (Table 4). All curves increased their coefficients of correlation when plant cover was added as an independent variable. Moreover, the Shapiro-Wilk test guaranteed the normality of the residuals, suggesting good fits between the curves and actual observations. For example, if the MLR-1 curve for grain sizes suggested an increase of fine sediment landwards and 'upwards' (i.e., along steeper slopes), the new MLR-2 curve suggested that fine sediment sizes also tended to concentrate in areas with relatively larger vegetation cover (which were, in line with the previous paragraph, also found on the E/W sides of the nebkha).

From all dependent variables analyzed, soil relative temperature had the largest r^2 value (69.15%) when it came to describing it as a function of landwards distance, surface elevation, aspect, and plant cover (Table 4; Fig. 3, middle row). Higher temperatures were found landwards and in slope units facing south, especially those with limited plant cover.

5. Discussion

Empirical data collected from the nebkha were used to summarize relations in a conceptual model shown in Fig. 4. While the model remains

Table 2
Pearson's correlation between variables (** *p*-value <0,01; * p-value <0.05).

	Landwards distance	Slope	Elevation	Aspect
Plant cover	0.43**	0.20*	0.33**	0.31**
Plant max. height	0.67**	0.29**	0.18*	0.30**
Plant avg. height	0.70**	0.23*	–	0.29**
Grain size	−0.64**	−0.31**	–	−0.29**
Carbonates	−0.29**	–	–	–
Conductivity	0.21*	–	–	–
Temperature	0.55**	–	−0.23*	–

	Temperature	Grain size	Conductivity	Carbonates
Plant cover	−0.30**	−0.58**	0.38**	−0.30**
Plant max. height	–	−0.57**	0.20*	−0.24**
Plant avg. height	0.19*	−0.55**	0.28**	−0.23*

Table 3
Multiple Linear Regression analyses (MLR-1) for vegetation and sediment characteristics as dependent variables and morphological characteristics as independent variables.

Dependent variable	R^2 (%)	*p* value	Independent variables	Regression coefficient	Standard error	*t* value	*p* value	Residuals Shapiro-Wilk p-value
Plant cover	25.06	<0.001	Constant	10.833	6.598	1.642	0.103	0.002
			Landwards distance	8.620	1.735	4.968	<0.001	
			Elevation	19.650	5.651	3.477	<0.001	
Plant avg. height	47.88	<0.001	Constant	4.224	1.247	3.388	<0.001	<0.001
			Landwards distance	4.543	0.432	10.504	<0.001	
Grain size	43.00	<0.001	Constant	0.242	0.006	42.409	<0.001	0.082
			Landwards distance	−0.012	0.001	−8.440	<0.001	
			Slope	−0.0005	0.000	−2.387	0.018	
Carbonates	8.84	0.001	Constant	61.749	1.229	50.217	<0.001	0.582
			Landwards distance	−1.120	0.323	−3.465	<0.001	
			Elevation	1.758	1.053	1.670	0.097	
Conductivity	3.78	0.018	Constant	1.660	0.066	25.132	<0.001	0.026
			Landwards distance	0.054	0.023	2.383	0.018	
Relative temperature	40.23	<0.001	Constant	0.995	0.022	44.983	<0.001	0.103
			Landwards distance	0.033	0.003	5.250	<0.001	
			Elevation	−0.059	0.016	−3.545	<0.001	
			Aspect	0.009	0.005	1.900	0.059	

linked to this particular landform, it is worth stressing that the studied nebkha was representative of the nebkha comprising the foredune found at *Caleta de Famara* beach (see Section 2 Study area). This is, however, a pioneer detailed scale (120 plots) comprehensive investigation of morphological, sedimentological, and vegetation patterns on a nebkha foredune, and hence future studies will be needed in order to compare and validate some of the results here.

The interdependence between variables will obviously change over time and with nebkha development or evolution. Once the seed can germinate and the plant emerges, a system of adventitious roots can develop providing water and nutrients for plant growth, accumulating sediments around the plant and forming the nebkha (Lang et al., 2013; Luo and Zhao, 2019). Further interactions with the local dynamics eventually lead to the development of a nebkha such as the one investigated in this study.

In terms of Fig. 4, plant cover was significantly correlated with the rest of the variables (Tables 2, 3) and tended to increase with distance from the sea. The tallest plants were not found on the dune crest but towards the lee sides of the nebkha, in areas with the largest percent of vegetation cover.

Aeolian processes are an important influence on plant height on the flanks. Steep slopes and topographic accelerations promote high wind velocities along the basal unvegetated edges of the vegetated nebkha (Hesp, 1981; Hesp and Smyth, 2017). These are constantly eroded, and sand is transported downwind and/or onto the attendant shadow dune. This means that the side slopes of the adjacent nebkha are maintained at high angles because any sand deposited past the side slope toe (and usually outside the vegetation zone) will typically be removed. Avalanching on these slopes is common. Thus, the highest stems and plant cover is found on the flanks due to the steep slopes, because sand deposition is not uniform across the plant, and maximum central sand deposition occurs as the nebkha evolves.

At the front of the dune, the constant movement of the plant due to the direct effect of incident winds can affect the photosynthetic function of the plant and reduce plant growth (De Langre, 2008). Direct exposure to the wind also leads to greater exposure to salt spray and sand abrasion, which can decrease growth of plants or even irreversibly damage them (Boyce, 1954; Du and Hesp, 2020; Maun and Lapierre, 1986).

Although plant cover generally increased cross-shore from the dune toe landwards (and then tended to decrease once in the leeside), both plant cover and plant average height were relatively lower at the crest compared to the sides (i.e., the increase in plant cover/height was lower across the nebkha central axis, compared to transects along the nebkha flanks). As noted above, deposition in the central region of the plant is maximized, so therefore height of the aerial parts of the plant will be less compared to the sides or flanks.

Reversing flow vortices typical of separated flow in the lee of nebkha (Hesp, 1981; Hesp and Smyth, 2017) are likely responsible for the relative increases in the amount of carbonate content found towards the leeside, where finer sediments can be deposited and retained due to the lower velocities in the separation zone (see conceptualized airflow in Fig. 4).

The presence of plants contribute to the cooling of sand/soil, block and reduce the action of the wind (Arens, 1996; Hesp et al., 2005) and favor the deposition of salt spray (Du and Hesp, 2020), as well as accumulating nutrients and organic matter in the interior areas of a nebkha (Rajaniemi and Allison, 2009). All these patterns were observed in the studied nebkha (Figs. 3, 4).

Table 4
Multiple linear regression analyses (MLR-2) for sediment characteristics as dependent variables and morphological and plant cover independent variables.

Dependent variable	R^2 (%)	*p* value	Independent variables	Regression coefficient	Standard error	*t* value	*p* value	Residuals Shapiro-Wilk p-value
Grain size	53.15	<0.001	Constant	0.246	0.005	43.468	<0.001	0.481
			Landwards distance	−0.009	0.001	−6.334	<0.001	
			Slope	−0.0005	0.0002	−2.455	0.015	
			Elevation	0.007	0.005	1.452	0.149	
			Plant cover	−0.0003	0.00007	−5.229	<0.001	
Carbonates	14.61	<0.001	Constant	62.287	1.203	51.742	<0.001	0.42
			Landwards distance	−0.692	0.344	−2.008	0.046	
			Elevation	2.735	1.071	2.555	0.011	
			Plant cover	−0.049	0.017	−2.982	0.003	
Conductivity	13.7	<0.001	Constant	1.576	0.058	26.98	<0.001	0.438
			Plant cover	0.004	0.001	4.46	<0.001	
Relative temperature	69.15	<0.001	Constant	1.011	0.016	63.339	<0.001	0.058
			Landwards distance	0.048	0.004	10.184	<0.001	
			Elevation	−0.018	0.012	−1.474	0.14	
			Aspect	0.011	0.003	3.198	0.001	
			Plant cover	−0.002	0.0002	−10.477	<0.001	

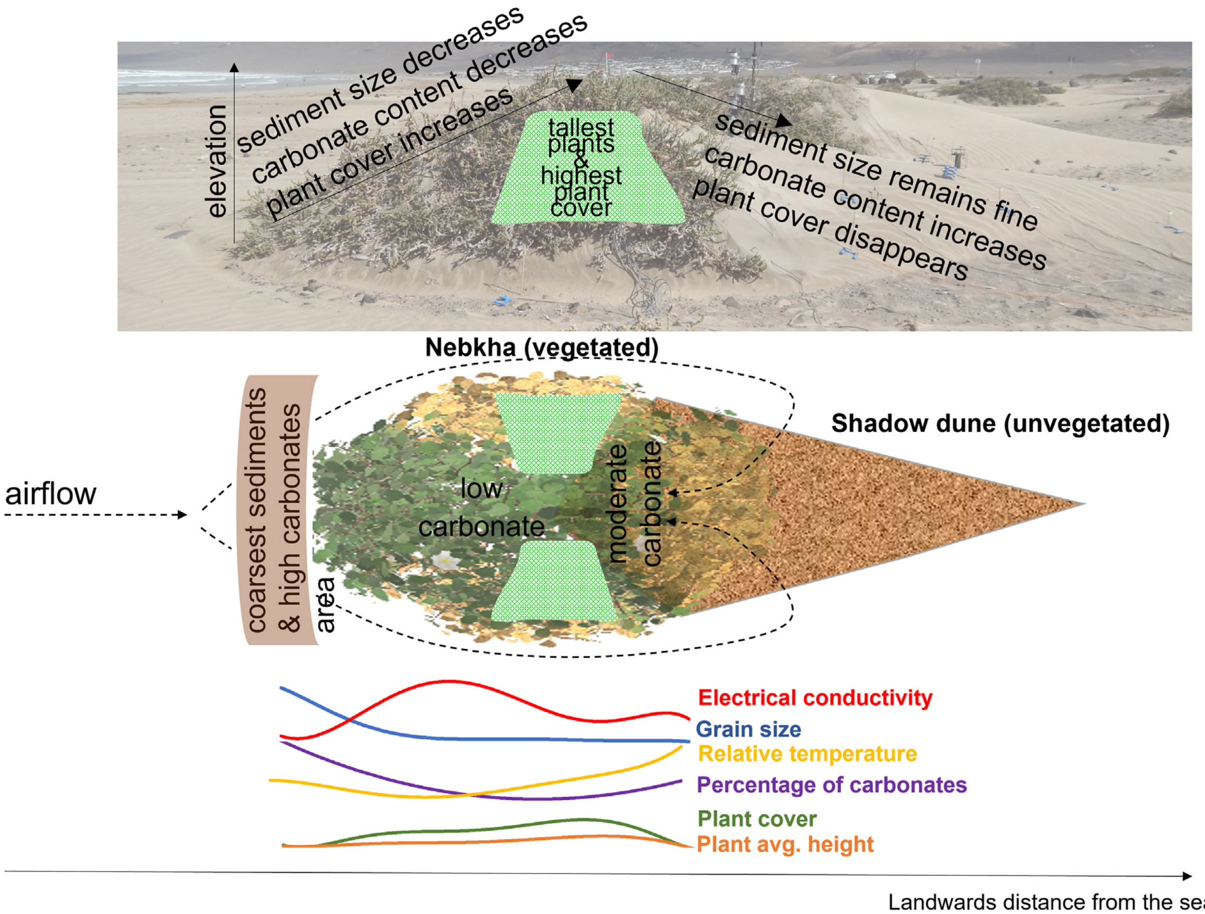

Fig. 4. Conceptual model showing spatial patterns of morphological, sedimentological and plant characteristics at a foredune nebkha. Airflow pattern deduced from field visual observations.

The sediment was composed of grain sizes less than 0.42 mm, which are highly erodible (Chepil, 1953). Sediment sizes were highly dependent on plant presence since coarser grains were only observed in zones without plants (Fig. 3). This coarser sediment was located in those unvegetated zones of the nebkha subjected to high energy wind where erosion occurs (dune toe and flanks), while the finer sand is transported to higher areas of the nebkha and the shadow dune (Al-Awadhi and Al-Dousari, 2013; Al-Dousari et al., 2008; Khalaf and Al-Awadhi, 2012; Xiaohong et al., 2019). The sediment was composed by a mixture of organogenic sediment from the sea with the contribution of terrigenous sediment from the nearby *Riscos de Famara* (Cabrera-Vega, 2010). The carbonate content decreased landwards since its main source was the sea. The coarsest and more calcareous sediment was found in the portions of the nebkha closest to the sea, while finer sediment sizes with lower carbonate contents were found in inner and landwards areas of the nebkha. Sediments with higher carbonate content are lighter and more erodible, so in areas of the nebkha subject to the same wind action, larger sand grains should be more calcareous. More calcareous and lighter grains were thus blown to higher areas of the nebkha (Tables 2, 3; Fig. 4).

The conductivity of the sediment was high to severe (FAO, 2009; Hardie and Doyle, 2012), due to scarce precipitation. Although soil conductivity tends to decrease from the coastline to the interior of the dune field (Du and Hesp, 2020; Gooding, 1947; Rajaniemi and Allison, 2009), the proximity of the dune to the sea and the absence of intermediate obstacles allowed incoming marine winds to deliver high concentrations of salts to the nebkha. However, within the nebkha, the expected gradient perpendicular to the coast was not observed, but instead there was a greater concentration of salts in the sediment on the NE-ENE side. This area of the dune faced more into the prevailing winds and hence was subject to the greatest trapping and deposition of salt spray (Donnelly and Pammenter, 1983; Goldsmith, 1973; van der Valk, 1974b). This could explain why the sediment conductivity patterns were not correlated with morphological variables and the distance from the sea gradient. In fact, only the landwards distance from the sea appeared as a dependent variable in the MLR-1 curve, and it had a very low significance, probably because the study area was small compared to the scale of the sea-inland conductivity gradient, and salt spray deposition is more uniform across the nebkha foredune zone, and less influenced by near-surface wind flow dynamics.

The temperature of the sediment increased landwards and was highest in south-facing areas of the nebkha, (i.e., on the landward slope and on the shadow dune) where solar radiation due to the suns's orbit was highest and where the cooling of the sediment surface by the incident winds was reduced due to the sheltering effect of the nebkha and low velocity reversing flow conditions.

The introduction of plant cover as an independent variable substantially improved the MLR-2 curves for the spatial distribution of the sediment characteristics. This is in line with multiple studies on the interaction between plants and sediment deposition (Davidson-Arnott et al., 2012; Dupont et al., 2014; Leenders et al., 2007; Mayaud et al., 2016). Wind-sediment-plant interactions were observed cross-shore with larger sediment sizes concentrating in areas of the nebkha facing the sea and the beach in front (i.e., its primary sediment source) and finer sediment sizes towards the interior of the nebkha due to the presence of plants and their effect on slowing the wind and facilitating the deposition of fine sand around them. The increase in plant cover and plant height contributes to the uptake of the finest sediment transported in suspension (Li and Ravi, 2018; Yang et al., 2018), which is deposited in interior and steep areas of the nebkha close to the ridge (Arens, 1996; Hesp, 2002). However, because sediment sizes found in nebkha were fundamentally transported by saltation and intercepted by the plant a few centimeters from the ground (Li and Ravi, 2018; Yang et al., 2018), the influence of the plant on the grain size distribution was better related to the plant cover than with plant height (Table 3). The influence of plants in the retention of fine sediment also had consequences for the distribution of carbonate grains; hence the introduction of plant cover as a dependent variable in MLR-1 increased its fit and significance.

Plant presence was a main control on the spatial distribution of sediment conductivity. Areas with the highest conductivity corresponded to windward zones with large plant cover oriented to the NE-ENE (Fig. 3), where the prevailing winds brought high concentrations of salt spray (Goldsmith, 1973), while leeward zones displayed low salt accumulation (Boyce, 1954; Maun, 2009). High density vegetation meant a greater resistance to wind flow penetration into the canopy (Hesp et al., 2019), so salt deposition was concentrated in the edges of the plant and nebkha.

The presence of the plant also contributed to reducing the temperature of the sediment, with lower temperatures generated in areas with the highest percent vegetation cover (El-Bana et al., 2003; Hesp and McLachlan, 2000). The opposite occurred in the central rear area of the nebkha (Fig. 3), where the low vegetation cover and unvegetated shadow dune equated with greater insolation making this part of the nebkha one of the hottest regions on the nebkha. The results of the relationships between variables suggest that heterogeneity in the geomorphological and sedimentological properties in coastal nebkhas are highly dependent on the heterogeneity induced by vegetation distribution.

6. Conclusions

The emergence, growth and development of coastal nebkhas is a clear example of a functioning biogeomorphological unit which is the result of the interdependence between ecological features, sediment dynamics and attributes and geomorphological characteristics, among others.

Distance from the sea played a role in both sediment and vegetation patterns, while flow dynamics and sediment transport patterns are also important. The interaction of plant cover with flow dynamics was directly related with a higher concentration of finer particles and lower soil temperatures. Areas with no plant cover to the leeside of the dune were related to a concentration of finer carbonate sediments, and higher soil temperatures. The shelter effect of the plant and the nebkha and the distance from the sea also contributes to the heterogeneity in other sedimentological characteristics such as conductivity. This induced heterogeneity in geomorphological and sedimentological properties could, at the same time, influence the plant growth and development.

The conceptual model developed from a spatially detailed dataset consisting of multiple variables in 120 plots over a nebkha entails a novel step to a better understanding of coastal nebkhas in arid environments. However, extensive measurements of other nebkha dunes are needed to test and refine the model further.

CRediT authorship contribution statement

Abel Sanromualdo-Collado: Investigation, Methodology, Investigation, Formal analysis, Data curation, Writing - original draft, Writing – review & editing.

Juan B. Gallego-Fernández: Conceptualization, Investigation, Visualization, Methodology, Formal analysis, Writing - original draft.

Patrick A. Hesp: Conceptualization, Investigation, Methodology.

María Luisa Martínez: Investigation, Methodology, Formal analysis.

Nicholas O'Keefe: Investigation, Data curation.

Nicolás Ferrer-Valero: Investigation, Data curation.

Luis Hernández-Calvento: Conceptualization, Supervision, Writing - review & editing, Project administration, Funding acquisition.

Declaration of competing interest

No conflict of interest exists.

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