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RESEARCH ARTICLE

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Foredune responses to the impact of aggregate extraction in an arid aeolian sedimentary system

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Abstract

Coastal dunes have long suffered the effects of human interventions that have altered the landscape and operation of these ecosystems. Aggregate extractions have been shown to modify the biogeomorphological processes in aeolian sedimentary systems. The impacts associated to aggregate extraction include the reduction of available sediment and changes to the topography and vegetation patterns, thereby altering the sedimentary dynamics and limiting the recovery capacity of the dunefield. The aim of this article is to analyse the environmental effects produced by historical aggregate extraction in the foredune area of an arid aeolian sedimentary system (El Médano, Tenerife, Spain) through a study of the airflow dynamics and spatial distribution of vegetation, sediment and topographic changes. The methodology was designed with two temporal scales: (i) a long-term approach which compares historical sources and current ones; (ii) a short-term approach through experimental data collection to characterize the present functioning. For the latter, a field study was carried out in June 2021, collecting wind speed and direction data at a height of 0.50 m, sediment data (sand sheet thickness, grain size and sorting), and vegetation data (cover and species richness) at 40 sample points. The main results show that when the anthropic stress ceased the foredune did not follow a natural environmental pattern, and that the way it functions at the present time is determined by the changes induced by the aggregate extraction. Changes include alterations to the topography, the creation of a lagoon, and the generation of an aeolian deflation area and flow acceleration zones with the associated sand transport. This research contributes to an understanding of the environmental consequences of aggregate extractions on the foredunes of arid aeolian sedimentary systems and can enable the relevant authorities to make better-informed decisions that help the management of these ecosystems.

KEYWORDS

airflow dynamics, arid coastal dunes, biogeomorphological processes, environmental patterns, human impact

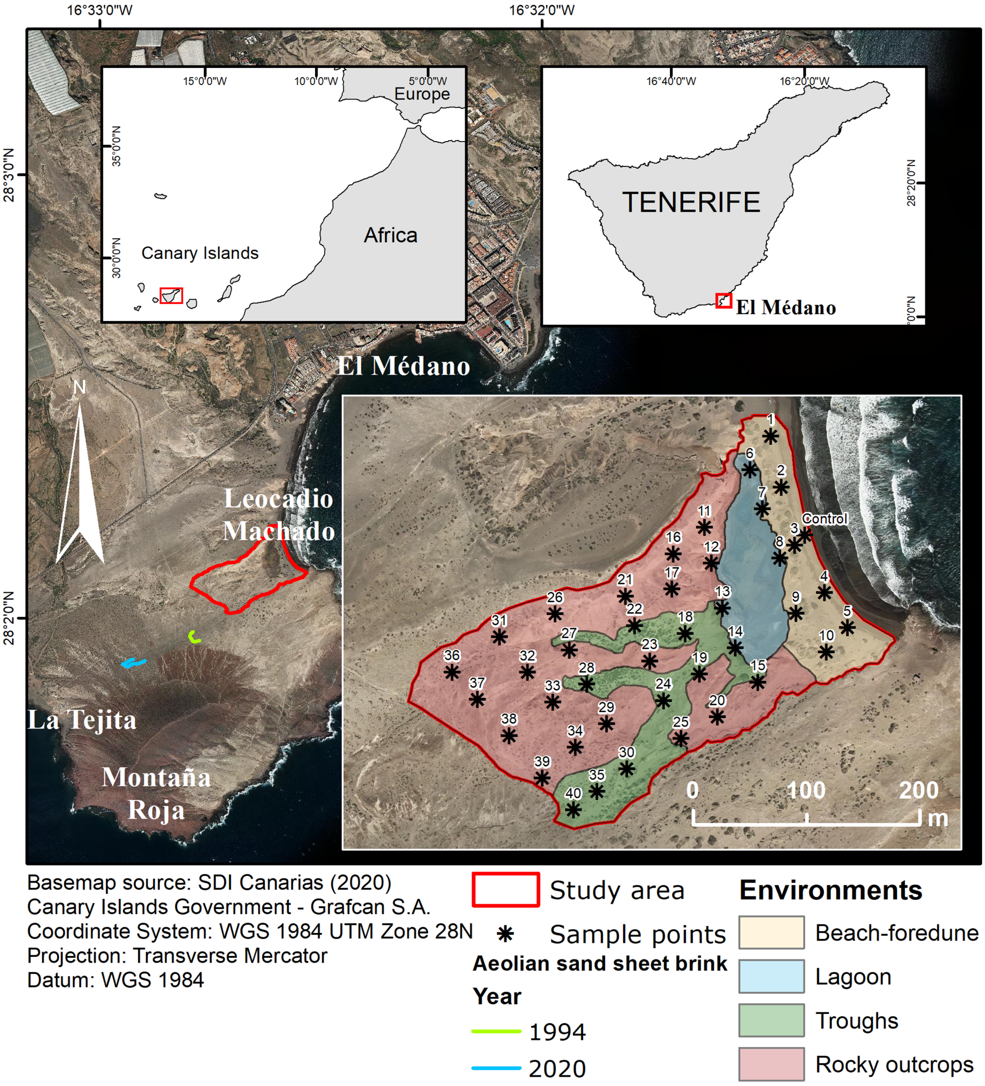
1 | INTRODUCTION

Coastal aeolian sedimentary systems have been recognized as an important source of services and resources for the well-being of humankind (Arévalo-Valenzuela et al., 2021; Barbier et al., 2011; Dang et al., 2021; Everard et al., 2010; Lithgow et al., 2013; Miththapala, 2008) that have long been exploited (Kutiel et al., 1999; Martínez et al., 2008; Provoost et al., 2009). In recent decades, human pressure related, directly or indirectly, to urban-tourism development has increased (García-Romero et al., 2016; Martínez et al., 2013). This human pressure has induced environmental changes that have led to the deterioration of coastal aeolian sedimentary systems (Delgado-Fernández et al., 2019; Jackson & Nordstrom, 2011; Paskoff, 1993). All of these as a result of intensive human actions with potential harmful effects linked to an urban-touristic model of coastal dune systems which include, among others, recreational activities (Prisco et al., 2021; Sanromualdo-Collado, García-Romero, et al., 2021), urbanization and infrastructure construction (García-Romero et al., 2019; Hernández-Calvento et al., 2014; Salgado et al., 2021; Smith et al., 2017), and aggregate extraction (Fernández Montoni et al., 2014; Marrero-Rodríguez, García-Romero, Peña-Alonso, et al., 2020; Marrero-Rodríguez, García-Romero, Sánchez-García, et al., 2020). Thus, there has been a reduction in dune size (Hernández-Calvento, 2006), increase in beach erosion processes (Marrero-Rodríguez, Casamayor, et al., 2021), changes in species richness (Hernández-Cordero et al., 2017), the introduction of invasive alien species and the creation of aeolian deflation zones (García-Romero et al., 2019).

Aggregate extraction has several impacts on aeolian systems, such as a reduction of the sediment available for transport and topographic disturbances (Marrero-Rodríguez, García-Romero, Peña-Alonso, et al., 2020), the removal of vegetation, the reduction of species richness and the loss of associated flora and fauna (Duan et al., 2008; Fernández Montoni et al., 2014), induction to instability in natural and artificial slopes, soil erosion and compaction and sediment remobilization (Garriga Sintes et al., 2017), the creation of permanent flooded areas (Marrero-Rodríguez, García-Romero, Peña-Alonso, et al., 2020), among numerous others at system scale (Duan et al., 2008; Fernández Montoni et al., 2014). In addition, the extraction of aggregates modifies the capacity of the system to provide ecosystem services (Marrero-Rodríguez, Peña-Alonso, et al., 2021). However, such effects depend on the type of extraction that is carried out in the system, as in many cases the extraction only affects the surface sand sheet and produces no topographic alterations (Marrero-Rodríguez, García-Romero, Sánchez-García, et al., 2020), whereas in the case of deep extractions topographic disturbances are generated that can lead to a more difficult recovery (Marrero-Rodríguez, García-Romero, Peña-Alonso, et al., 2020). The impacts are also linked to the area where the extraction takes place. Differences appear between extractions inside the system, in the foredunes or in the subtidal zone. In the latter case, important changes in the beach profile can be produced, including damage to underwater meadows that act as a sand reservoir and a buffer against extreme wave events or a reduction of sediment entry into the system (Ley et al., 2007).

Aggregate extraction in aeolian sedimentary systems of the Canary Islands (Spain) for the construction of urban and touristic facilities began in the 1960s (Ferrer-Valero et al., 2017; Marrero-Rodríguez, García-Romero, Peña-Alonso, et al., 2020; Marrero-Rodríguez, García-Romero, Sánchez-García, et al., 2020; Santana-Cordero et al., 2016). In the case of El Médano (Tenerife island), while land uses transformed the entire ecosystem, the extraction of aggregates seems to have been the activity with the greatest impact on the aeolian sedimentary system (Marrero-Rodríguez, García-Romero, Peña-Alonso, et al., 2020). Topographic modification due to sediment extraction generated a flooded area as excavations took place below sea level. While the response of the system itself in other areas where different historical land uses were carried out (e.g., an aerodrome and crop cultivation area) has resulted in a current look and functioning closer to the ideal status described in the scientific literature, the erratic distribution pattern of nebkhas and plant species generated in the aggregate extraction area does not respond to the characteristic distribution of this type of aeolian sedimentary system (Marrero-Rodríguez, García-Romero, Peña-Alonso, et al., 2020). Moreover, the sediment budget was drastically reduced due to the extraction (Gobierno de Canarias, 2004). However, although these authors studied nebkha distribution and the biogeomorphological processes altered by land uses, there has been very little research on the functioning of such systems after aggregate extractions have ceased. The research carried out to date has focused on the recovery of the associated vegetation (Baasch et al., 2012; Duan et al., 2008; Fernández Montoni et al., 2014; Price et al., 2005) or on evaluating the restoration projects carried out (Clemente et al., 2004; Lithgow et al., 2013). Therefore, there is a gap in the scientific literature regarding the functioning of areas with topographic alterations induced by aggregate extractions, and in particular the foredune zone. Foredunes play an important role in dune systems, firstly because they act as sand collectors, generating the first dunes within small or relatively small groups of plant individuals located parallel to the beach (Hesp, 2002), and secondly because they provide multiple ecosystem services, comprising erosion control, spaces for recreation, educational and research values, habitats for a wide diversity of plant and animals and cultural services (Arévalo-Valenzuela et al., 2021; Everard et al., 2010; Marrero-Rodríguez, Peña-Alonso, et al., 2021; Martínez et al., 2013; Mendoza-González et al., 2021; Richardson & Nicholls, 2021).

As sand is indispensable for construction and urbanization, the demand for aggregate extraction has grown exponentially in many aeolian sedimentary systems in developing regions (Gavriletea, 2017), as was the case of the Canary Island in the last decades of the 20th century, before the prohibition of extracting sand from the dune systems (Marrero-Rodríguez, Casamayor, et al., 2021; Marrero-Rodríguez, Peña-Alonso, et al., 2021; Santana-Cordero et al., 2016). Knowing the effects of aggregate extractions and the response capacity of impacted environments is key to minimize and mitigate the environmental impacts of this activity, even more so when the extractions are carried out in fragile ecosystems like arid coastal aeolian sedimentary systems (Cabrera-Vega et al., 2013; Peña-Alonso et al., 2018). The evolution and response environments after disturbances are not only restricted to recovery of the original functions, but to the adaptation to the element to the new situation (Kombiadou et al., 2019). Thus, the main aim of this work is to analyse the response process of the arid aeolian sedimentary system of El Médano after the cessation of this activity, especially in an area affected by the historical



Basemap source: SDI Canarias (2020)
Canary Islands Government - Grafcan S.A.
Coordinate System: WGS 1984 UTM Zone 28N
Projection: Transverse Mercator
Datum: WGS 1984

FIGURE 1 Location of the study area, environment identification and position of the field experiment sampling points [Color figure can be viewed at wileyonlinelibrary.com]

extraction of aggregate located on the foredune. For this purpose, two temporal approaches are employed: (i) a long-term analysis to identify topographical changes from historical and current sources, including oral interviews with technicians; (ii) a short-term experiment to characterize the present functioning of the system through the analysis of the airflow dynamics and the spatial distribution of vegetation and sediment. The ultimate objective of this research is to help to understand the environmental consequences of aggregate extractions on the foredunes of arid aeolian sedimentary systems and to contribute to the decision-making process to make better-informed management decisions.

2 | STUDY AREA

The aeolian sedimentary system of El Médano (28°02′07.7″N; 16°32′35.7″ W) is located on the southern coast of Tenerife. Three main historical land uses were identified in different areas of the aeolian sedimentary system of El Médano: an old aerodrome, and aggregate extraction and a crop cultivation area (Marrero-Rodríguez, García-Romero, Peña-Alonso, et al., 2020). The study area includes the sector of this system affected by the extraction of aggregates for construction. The 68,613 m^2 of the extraction area extends from the backshore towards the interior of an aeolian sedimentary system comprising an irregular polygon of approximately 360 m × 190 m depending on the morphology of the terrain (Figure 1). In this zone, between the years 1964 and 1977, a volume of 200,000 m^3 of sand were extracted for public and private constructions (Gobierno de Canarias, 2004).

The study area retains few characteristics of its pre-extraction appearance, with the beach being the only landform that has endured before and after extraction (Figure 2). The main features of the study area are a foredune with *Traganum moquinii* which were planted in a restoration project with the aim of protecting the intertidal lagoon that was also generated during the extraction process. Towards the interior we find small gullies and troughs, as well as notable rocky outcrops which are also a result of the extraction process. At the south of the study area, it is identified a sand sheet whose brink is advancing landwards to La Tejita beach (small green and blue lines in Figure 1). This sand tongue suggests a sediment input from the Leocadio Machado beach and the presence of aeolian sedimentary dynamics transporting these sediments inland in a heterogeneous way across the foredune.

The sediments are a mixture of biogenic and terrigenous sands that are produced by the erosion of palaeodunes, along with marine contributions as well as contributions from local ravines during episodes of intense rainfall. These sediments enter from the Leocadio Machado beach and are blown into the system by the

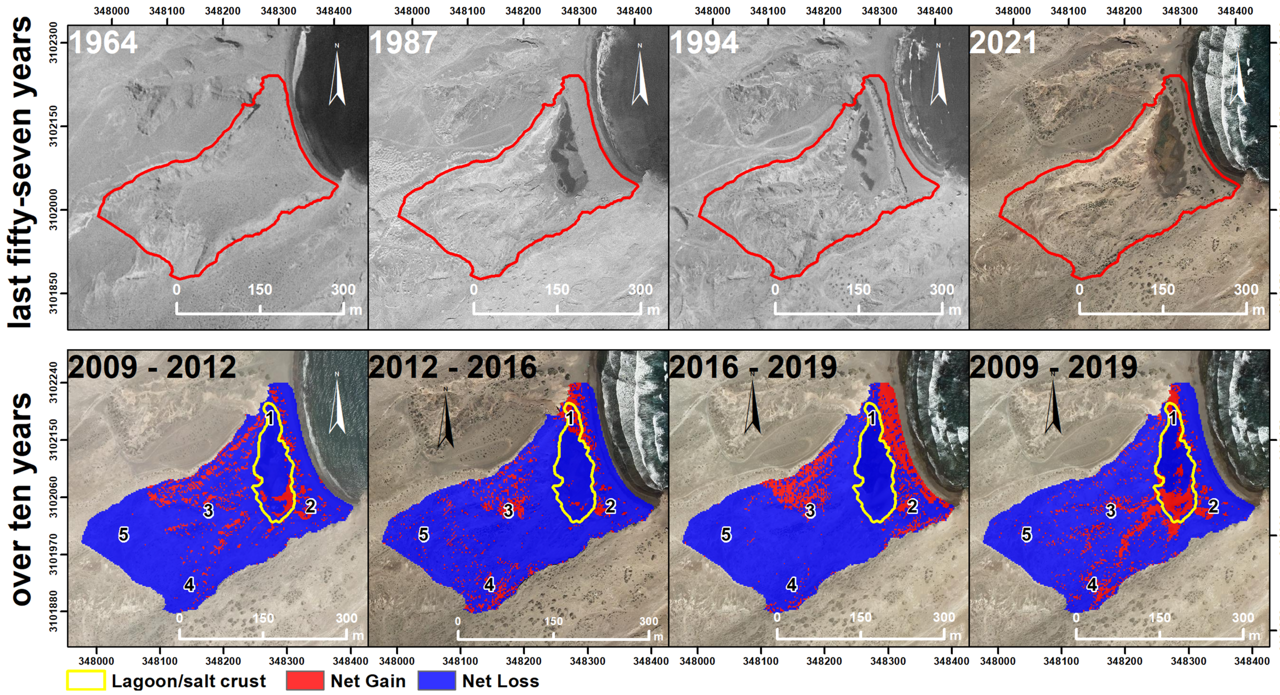


FIGURE 2 Top: Evolution of the study area (aggregate extraction) from 1964 (before extraction begins) to 2021 (orthophotos source: SDI Canarias (Canary Islands Government-Grafcan S.A.). Bottom: Topographic evolution over 10 years (2009–2019) obtained through DoDs and showing Cut Fill results [Color figure can be viewed at wileyonlinelibrary.com]

prevailing east-northeast (ENE) winds, generating nebkhas and shadow dunes (Marrero-Rodríguez, García-Romero, Peña-Alonso, et al., 2020).

The climate is characterized by its aridity. The annual average rainfall is 83 mm and annual average temperature is around 21°C (García Casanova et al., 1996), so vegetation is scarce due to the arid conditions. The effect of the sand extraction generated flooded areas and rocky outcrops where, so far, local species have not shown signs to adapt to these environmental conditions and cannot settle and survive, which also contributes to the scarce vegetation. However, *Traganum moquinii* can be found in the foredune and inland, along with psammophytes in the throughs and areas with a certain volume of sand.

The study area is part of an area that was declared a Nature Reserve of National Interest (Law 12/1987, of 19 June, on the Declaration of Natural Spaces of the Canary Islands) in 1987 before its reclassification in 1994 as a Special Nature Reserve (Law 12/1994, of 19 December, on Natural Areas of the Canary Islands). However, the associated planning instrument for the protection of the area (Gobierno de Canarias, 2004) was not definitively approved until October 2004 (Marrero-Rodríguez, García-Romero, Peña-Alonso, et al., 2020). In addition, the area has had protected status since 2000 as a result of the European Union (EU) Habitats Directive of that year.

3 | METHODS

The methodology involves two approaches with different temporal scales: (i) a long-term approach which compares historical sources and current ones; (ii) a short-term experiment to characterize the present functioning of the study area.

3.1 | Long-term approach

3.1.1 | Aggregate extraction zone and foredune evolution

An analysis of the historical evolution of the study area was carried out using airborne information sources that include aerial photographs, current orthophotos and LiDAR (light detection and ranging) flight data (Table 1). This allowed observation of the evolution of the aggregate extraction process and the foredune. The historical aerial photographs (1964, 1987 and 1994) were used to observe the evolution of the foredune and the lagoon/salt crust that appeared after the cessation of aggregate extraction (Figure 2, top row). The 2021 orthophoto was used together with the last available digital elevation model (DEM) for the Canary Islands from 2019 to delimit the different environments in the study area (beach-foredune, lagoon, troughs and rocky outcrops) (Figure 1) on the basis of visual criteria through photointerpretation (colour and texture) and using slope change analyses. This information was corroborated during the field campaign described in Section 3.2.

DEMs of difference (DoDs) were calculated over 10 years from 2009 to 2019 (2 m/pixel) and are shown using ArcMap's Cut Fill tool (Figure 2, bottom row). Although the dates of the DEMs do not coincide, it was considered preferable to work with all the available information with the highest precision in order to analyse the trends over the past few decades. The DEMs and DoDs were cleaned, corrected and calculated using Geomorphic Change Detection (GCD) software (Wheaton, Brasington, Darby, Merz, et al., 2010; Wheaton, Brasington, Darby, & Sear, 2010). DoD error (%): 2009–2012 (accumulation: 22.42; erosion: 26.08); 2012–2016 (accumulation: 20.35; erosion: 18.93); 2016–2019 (accumulation: 20.27; erosion: 19.52); 2009–2019 (accumulation: 20.15; erosion: 24.41).

TABLE 1 Inventory of cartographic sources used in this research

Type (source)	Year	Scale	Spatial resolution (m)	RMS[a] (m)
Historical aerial photographs	1964[b]	1:30000	1	1.05–2.05
	1987[b]	1:18000	0.4	1.25–2.05
	1994[b]	1:18000	0.4	1.25–2.05
Orthophotos	2021[b]	[d]	0.2	< 1
LiDAR flight data (DEM)	2009[c]	—	2	—
	2012[b]	—	2	—
	2016[c]	—	2	—
	2019[b]	—	2	—

[a] RMS, root mean square.

[b] SDI Canarias (Canary Islands Government-Grafcan S.A.).

[c] National Geographical Institute (Spain).

[d] Flight with ground sample distance (GSD) of 22.5 cm/píxel.

3.1.2 | Interviews with technicians

Five interviews were carried out in the form of semi-structured conversations (Fogerty, 2007) to learn about the environmental restoration project carried out in the study area in the 1990s. The interviewees were technicians who managed the study area or biologists who carried out fauna and vegetation inventories in the area at that time.

3.2 | Short-term approach

The field experiment was carried out in June 2021, and data related to wind dynamics, sediment and vegetation were collected at 40 sample points. The information gathered included wind speed and direction at 0.50 m, sand sheet thickness, vegetation cover and species richness. At these sample points, sediment samples (approximately 200 g) were taken at a depth of 0 to 10 cm for subsequent sorting and grain size analysis.

3.2.1 | Sediment and vegetation data

Sediment and vegetation data were obtained for the 40 sample points (Figure 1, insert). Sand sheet thickness was recorded to a maximum of 20 cm depth. Samples were taken at the 32 points where sediment was available. The sand samples were taken to the laboratory of the Applied Physics Department of the University of Las Palmas de Gran Canaria. The beach-foredune and lagoon samples were washed with distilled water to remove salt crusts that could obstruct the sieving process. The granulometric analysis was carried out by dry sieving a representative portion of the sample of 100 ± 20 g at intervals of 1/2Ø. The sieves ranged between 8 mm and 0.045 mm. The granulometric parameters (mean grain size, sorting, kurtosis and skewness) were obtained through the GRADISTAT program (Blott & Pye, 2001). The maximum error established was 2%. When this threshold was exceeded the sieving process was repeated, and the mean error of the set of analysed samples was 0.12%.

Vegetation cover and species richness was visually estimated and recorded in plots of 6 m × 6 m at the 40 sample points. This threshold distance was selected in accordance with Alonso-Bilbao et al. (2007), as the distance along which the wind flow is influenced by a plant obstacle in an arid dune system, as for example the shrub species *Traganum moquinii*. Eleven species were recorded (Table 2): *Argyranthemum frutescens*, *Atriplex glauca*, *Launaea arborescens*, *Kleinia neriifolia*, *Limonium pectinatum*, *Lotus sessilifolius*, *Polycarpaea nivea*, *Salsola vermiculata*, *Schizogyne sericea*, *Tetraena fontanesii* and *Traganum moquinii*.

3.2.2 | Wind data

The wind data were obtained using 10 mobile stations consisting of an anemometer-vane-datalogger system with wireless communication (Domínguez-Brito et al., 2020; García-Romero et al., 2019). To discriminate between wind flow conditions, the array of 40 sample points was strategically positioned according to the morphology of the terrain, creating an 8 × 5 mesh that covered the area of aggregate extraction (Figure 1, insert). Four simultaneous sample runs were performed from the beach to the inner zones. Data were collected at each location for 40 min. Wind speed and direction collected in the data logger each 2 s were averaged every 30 s, ensuring that the entire area was affected by the same wind flow over a given period. These 30-s average wind speeds were normalized with respect to the corresponding average wind speed of the control station of the same simultaneous sample run (Delgado-Fernandez et al., 2013). This normalization allowed a comparison of the temporal variability of the wind speeds and to eliminate differences in wind speed variations due to changes in the sample points, thereby enabling inclusion of the complete study area and data comparisons (García-Romero et al., 2019). The input wind direction during the field experiment varied between 45° and 90°, in accordance with the prevailing ENE winds described in Marrero-Rodríguez, García-Romero, Peña-Alonso, et al. (2020).

4 | RESULTS AND DISCUSSION

The results are structured in accordance with the two approaches carried out. The first one is an analysis of the temporal evolution (long-term approach) of the study area, which shows the changes detected in the last 57 years. The second one (short-term approach) allows an

TABLE 2 Characteristics of plant species present in the study area (modified from Marrero-Rodríguez, García-Romero, Peña-Alonso, et al., 2020 and based on García Casanova et al., 1996, Hernández-Cordero, Hernández-Calvento, & Pérez-Chacón Espino, 2015, Hernández-Cordero et al., 2017 and Hernández-Cordero et al., 2019)

Species	Origin	Plant type/life form	Environment	Protection status
Argyranthemum frutescens	Endemic to Macaronesia	Shrub/nanophanerophyte	Xerophilous: semi-arid habitats; rocky coast.	None
Atriplex glauca	Wide geographic distribution	Herb/chamaephyte	Halophilous: rocky or sandy coasts; sand sheets and nebkha fields	None
Kleinia neriifolia	Endemic to Macaronesia	Shrub/nanophanerophyte	Xerophilous: arid and semi-arid habitats; rocky coasts.	None
Launaea arborescens	Wide geographic distribution	Shrub/nanophanerophyte	Xerophilous: arid and semi-arid habitats; sand sheets and nebkha fields; stabilized dunefields	None
Limonium pectinatum	Endemic to Macaronesia	Herb/chamaephyte	Halophilous: rocky coasts	None
Lotus sessilifolius	Endemic to the Canary Islands	Herb/chamaephyte	Xerophilous: arid and semi-arid habitats; sand sheets and nebkha fields	None
Polycarpaea nivea	North Africa and Canary Islands	Herb/chamaephyte	Halophilous: rocky or sandy coasts; sand sheets and nebkha fields	None
Salsola vermiculata	Wide geographic distribution	Shrub/nanophanerophyte	Xerophilous: arid and semi-arid habitats; sand sheets and nebkha fields; stabilized dunes	None
Schizogyne sericea	Endemic to Macaronesia	Shrub/nanophanerophyte	Halophilous: rocky coasts; sand sheets and nebkha fields	None
Tetraena fontanesii,	North Africa and Canary Islands	Shrub/nanophanerophyte	Halophilous: rocky coasts; sand sheets and nebkha fields	Protected
Traganum moquinii	North Africa and Canary Islands	Shrub/nanophanerophyte	Halo-psammophilous: sand sheets and nebkha fields; foredune of dunefields; dune slack	Protected and vulnerable status

understanding of the current operation of the study area (old aggregate extraction).

4.1 | Evolution of aggregate extraction zone (long-term approach)

Oral interviews with technicians indicated that the foredune was rebuilt by piling up rubble and stones (Figure 2, 1994) left behind from the extraction process. Remains of *Cymodocea nodosa* collected from the beach were also added. Subsequently, *Traganum moquinii* specimens were planted to improve its appearance. The main objective was the protection of the coastal lagoon that had formed during the extraction process and which had become a nesting area for birds.

Figure 2 (last 57 years) shows the observations made through orthophotos and the background that gave rise to the analysis undertaken in this research. It can be seen that in 1964, prior to the anthropic impact, there was a beach-foredune system and, more importantly, no lagoon. According to Marrero-Rodríguez, García-Romero, Peña-Alonso, et al. (2020), aggregate extraction took place from the 1970s until 1987 (the year the study area and its surroundings were granted protected status as part of the Montaña Roja Special Nature Reserve). This resulted not only in the elimination of sediment, vegetation and aeolian landforms, but also in the appearance of a lagoon due to the extraction drilling. However, in 1994 the formation of a foredune with unusual traits can be detected, breaking the patterns and models related to foredune initiation and formation described by Hesp (2002). Thus, instead of the expected foredune initiation described for arid environments, formed by isolated nebkhas around vegetation and the subsequent formation of shadow dunes that can converge inland to form tongue dunes, that are the first almost continuous dunes; the foredune formed in 1994 was a continuous ridge between the beach and the lagoon which was far away to the natural look of natural foredunes in arid environments (García-Romero et al., 2021; Hernández-Cordero et al., 2012; Viera-Pérez, 2015). The interviews revealed that this was a restoration process of artificial origin and not a spontaneous response of the system as speculated by Marrero-Rodríguez, García-Romero, Peña-Alonso, et al. (2020). This reinforces the idea that the foredune in the study area was not formed as a consequence of the extractions made below sea level (where the lagoon appears), the subsequent disruption to the original slope and the elimination of the surface sand sheet, as has occurred in other ecosystems with similar characteristics (Fernández Montoni et al., 2014; Price et al., 2005). Finally, it is observed that from 1994 to 2021 (27 years), the (artificial) foredune has practically not developed either longitudinally or transversely in a natural way (Figure 2, 10 years Cut Fill). In this sense, the foredune's restoration method, based on the construction with rubble and stones (that is an artificial structure made by rigid elements) could limit the natural development of the foredune, and even might have turned it in an obstacle for the aeolian sedimentary dynamics, generating disruptions in a similar way that buildings do (Hernández-Calvento et al., 2014; Poppema et al., 2021; Smith et al., 2017). It is observed that the sedimentary dynamics could be deviating to the south (zone 2, Figure 2, Cut Fill 2009–2012, 2016–2019 and 2009–2019) due to the detected accumulations (in red) in this zone. This coincides with the identified sand sheet advancing inland from the Leocadio Machado beach to La Tejita beach (Figure 1), which suggests that there is a sediment input from the sea that is forced to the south of the system by the sedimentary dynamics, due to the effects of the human interventions on the study area. In general, the study area is erosive (in blue) except for zones 1, 2, 3 and 4 (Figure 2, bottom row, in red).

4.2 | Current operation of aggregate extraction zone (short-term approach)

4.2.1 | Vegetation and sediment spatial distribution

The beach-foredune (Figure 3, A), with a surface area of 10,680.85 m^2, has sediments characterized by poorly sorted medium sands (Figure 4B–D) and the vegetation cover is determined by the presence of *Traganum moquinii* in the foredune. *Traganum moquinii* responds to sand burial by accelerating its growth (Hernández-Cordero, Hernández-Calvento, & Pérez-Chacón Espino, 2015; Viera-Pérez, 2015), and therefore can generally be found in embryonic dunes and in the foredune (García-Romero et al., 2021). However, young individuals do not appear in this sector. In the lagoon sector (7,579.83 m^2) (Figure 3, B and C) there is a high availability of fine and medium sands which could be transported by the wind. However, the existence of the flooded area and the important salt crust prevent the transport of these sediments inland. In this area, the sand sheet reaches a thickness greater than 20 cm (Figure 4A). The high number of pyroclasts present in samples 13 and 14 show that the lagoon acts as a collector into which the ravines of Montaña Roja drain; however intense precipitations in the area are very scarce (García Casanova et al., 1996), and so runoff dragging the accumulated sediments would also be very occasional. Vegetation is almost non-existent in this area, with *Tetraena fontanesii* only appearing in the limits of the flooded area as it is tolerant of high saline conditions and puddling of the roots in seawater.

Nebkhas, shadow dunes and ripples appear mostly in the south sector where troughs (12,332.56 m^2) allow sediment accumulation (Figure 3, D). Sediment thickness in this sector reaches over 20 cm (Figure 4A). Sediments are fine sands transported by the wind as they are moderately well sorted (Figure 4, brown circle). The vegetation cover reaches a maximum of 50% (Figure 5). The main species in this sector are *Tetraena fontanesii*, *Launaea arborescens*, *Salsola vermiculata* and *Traganum moquinii*. All of them tolerate burial by aeolian sedimentary activity. However, unlike *Traganum moquinii*, the rest of the plants tolerate burial by a limited volume of sand, dying when the speed of sand accumulation exceeds the growth rate and threshold of the plant (Hernández-Cordero, Pérez-Chacón Espino, & Hernández-Calvento, 2015). In the trough located in the extreme south, the sediments have a larger average size because they do not cross the lagoon during their transport landwards, and because the higher wind speeds in this zone have blown away and transported the finest portion of the sediment. In addition, the sorting is better because they are transported by the wind continuously as there is less vegetation cover and they are not affected by runoffs from Montaña Roja.

The troughs present in the rest of the study area show a more limited sedimentary activity (Figure 3, E). The thickness of the sediment varies between 10 cm and 20 cm (Figure 4A) and they are

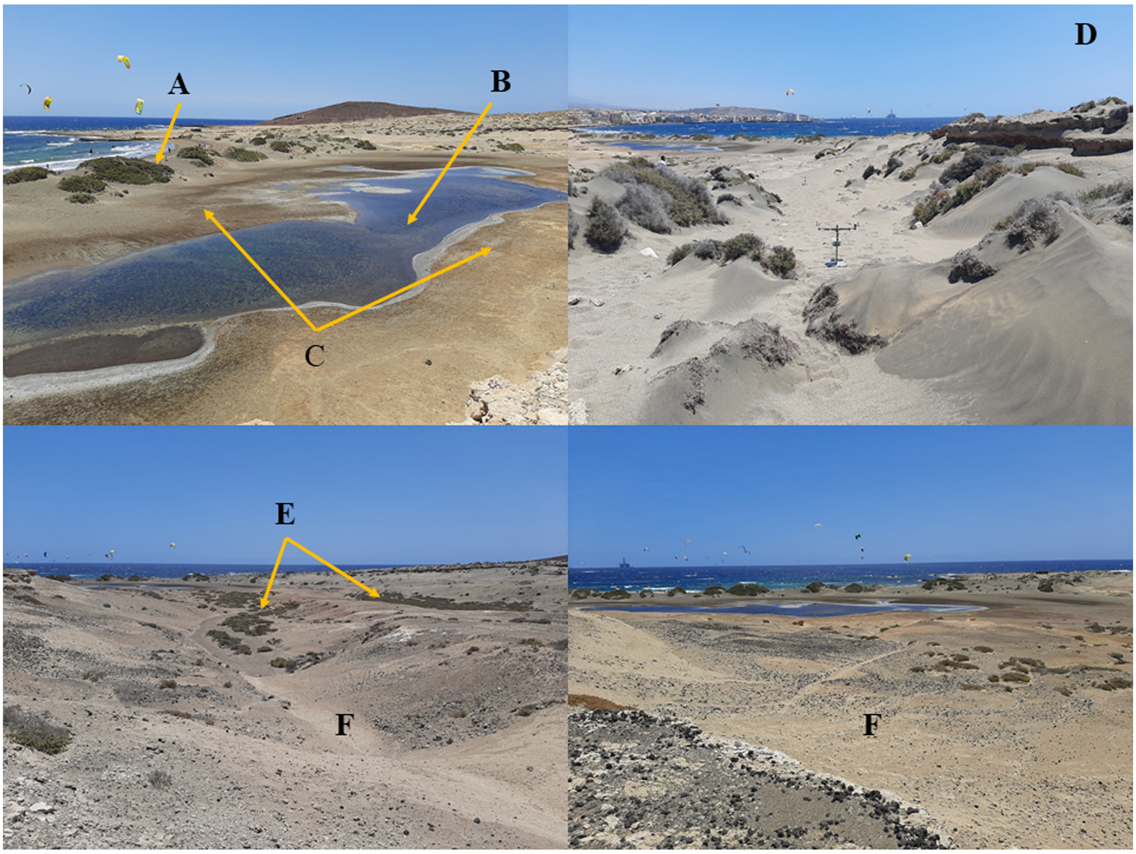


FIGURE 3 Environments present inside the area affected by the extraction of aggregates. A: beach-foredune; B: permanently flooded lagoon sector; C: sector flooded in high tides that presents an important saline crust; D: troughs with accumulation of sand, sparse vegetation and active aeolian landforms (ripples, nebkhas and shadow dunes); E: troughs without active aeolian landforms and high density of vegetation; F: aeolian deflation zones without vegetation or sand accumulation [Color figure can be viewed at wileyonlinelibrary.com]

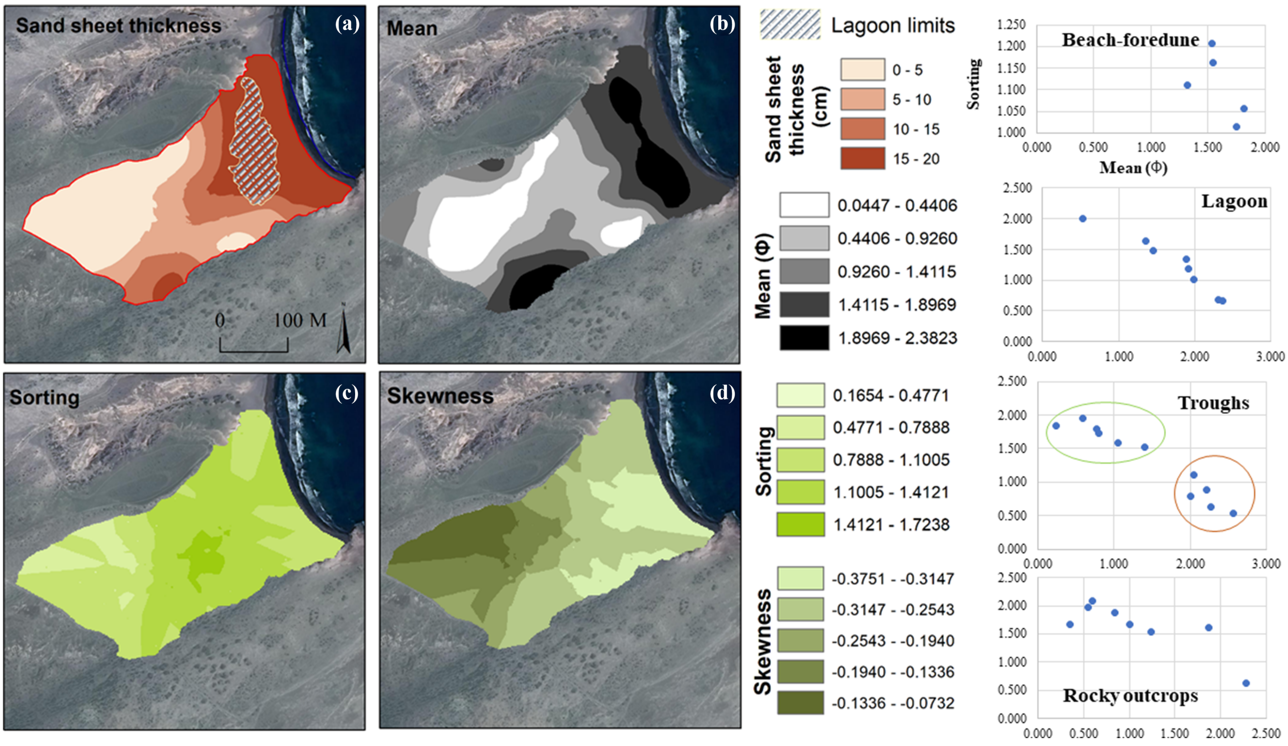
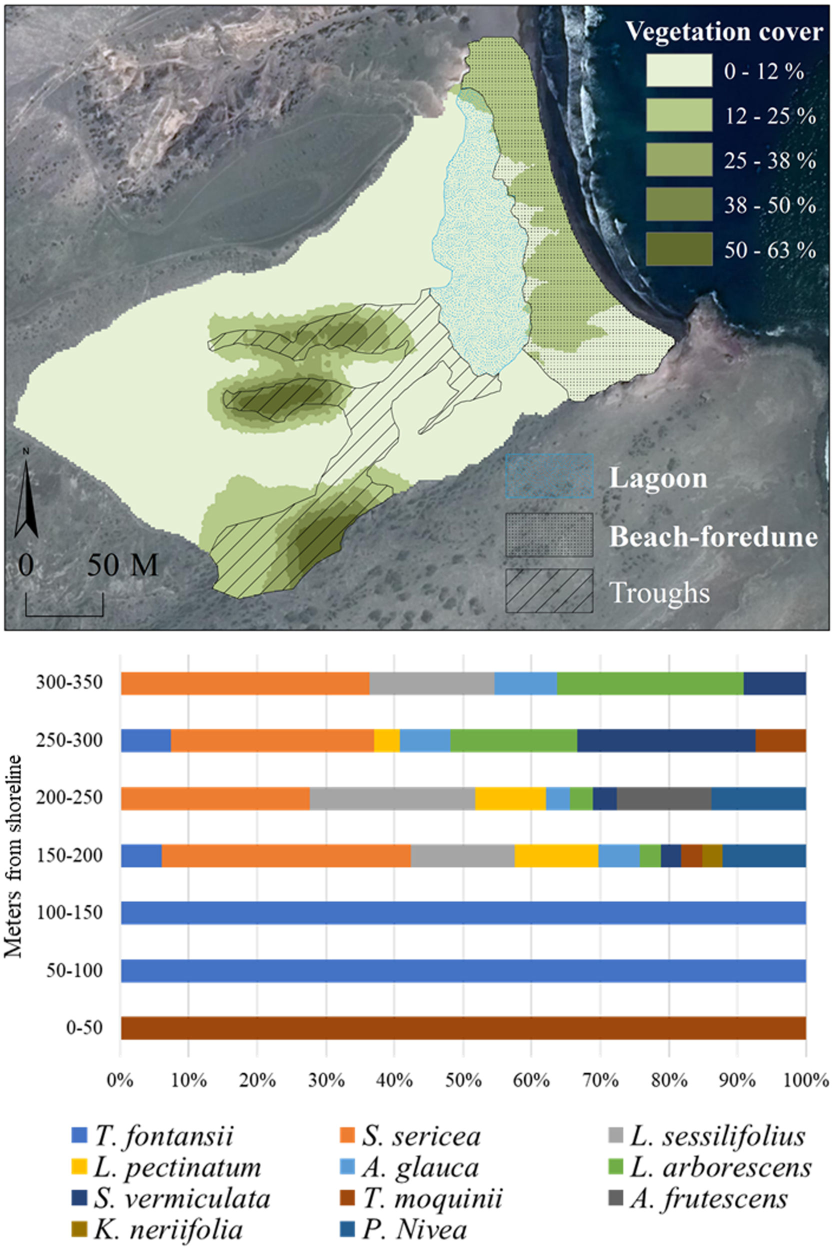


FIGURE 4 (A) Sand sheet thickness, (B) mean grain size, (C) sorting and (D) skewness in the aggregate extraction area. Sorting and mean grain size values represented in graphs on the right by environment present in the area. Green circle: troughs with vegetation cover between 50% and 70%. Brown circle: troughs with vegetation cover under 50% [Color figure can be viewed at wileyonlinelibrary.com]

FIGURE 5 Vegetation cover and species distribution from the shoreline [Color figure can be viewed at wileyonlinelibrary.com]



mostly coarse and poorly sorted sands (Figure 4, green circle). The sediments of the central troughs are finer than those of the troughs located in the southern sector of the study area, as coarse sands are likely to fall into the lagoon when they are transported by the wind. These troughs can also experience sediment transport during runoff, as the samples present pyroclastic fragments from Montaña Roja. The vegetation cover (Figure 5) is very high (between 50% and 70%) and the species present are *Schizogyne sericea*, *Lotus sessilifolius*, *K. neriifolia*, *Atriplex glauca*, *Lasioglossum pectinatum* and *Argyranthemum frutescens*. These plants do not tolerate burial by large volumes of sand and some of them, including *K. neriifolia* and *Argyranthemum frutescens*, do not tolerate substrate mobility. Therefore, active aeolian landforms are almost absent, although sporadic nebkhas associated to *Schizogyne sericea* and *Lotus sessilifolius* can be found.

The rest of the study area is formed by aeolian deflation areas where aeolian landforms are absent (Figure 3, F). Vegetation cannot colonize due to the presence of rocky outcrops and because the sand sheet thickness is just 1–3 cm deep (Figure 4A) with very poorly sorted coarse sands (Figure 4B,C).

4.2.2 | Airflow dynamics

The temporal variability of normalized wind speeds at each sample point is shown in Figure 6. Temporal variability in input wind speed (in m s^{-1}) and direction (in degrees) recorded at the control tower showed differences during the experiment (Figure 6B,C). A significant difference can be observed in input wind speed between Run 1 and Run 2, which were faster, and Run 3 and Run 4, which were slightly slower.

In Run 1, there was a noticeable difference in wind speed between the sample points located in the backshore (SP1–SP5), where wind speeds generally reached 70% of the input wind speed, and between the sample points located in the second row, behind the foredune, where wind speeds varied from between 30% and 60% of the wind speed at the control point. With respect to SP10, although it is located in the second row, wind speeds were similar to those in the first row, reaching speeds that exceeded 80% of the input wind speed. In this southern zone of the beach-foredune environment, the foredune more closely resembles the mounded morphology typical of arid

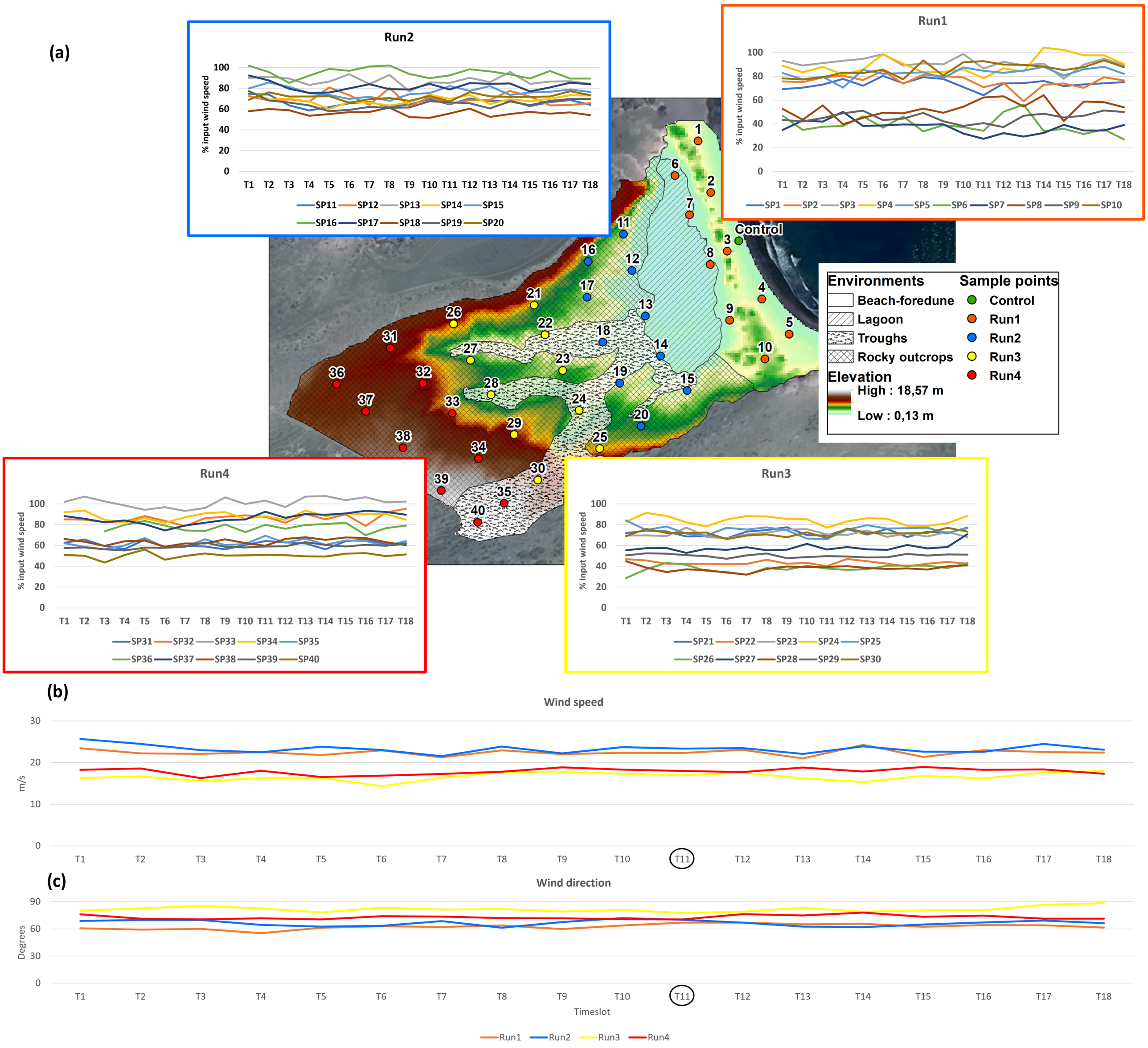


FIGURE 6 (A) Location of sample points and temporal series of normalized wind speeds averaged every 30 s for each simultaneous run. (B) Wind speeds averaged every 30 s at the control tower. (C) Wind directions averaged every 30 s at the control tower. Timeslot T11 is highlighted because it is the input wind flow in Figure 7 [Color figure can be viewed at wileyonlinelibrary.com]

coastal dune systems (Hernández-Cordero et al., 2019; Hesp et al., 2021; Viera-Pérez, 2015), instead of the nearly continuous sand ridge of the foredune in the north. While the foredune in the northern area blocks the wind and reduces its speed when entering the system, the naturally fragmented foredune in the southern area allows the wind to enter between the vegetated mounds, transporting sediment to the rear areas of the foredune and forming nebkhas and shadow dunes that enable the foredune to develop in height and width (García-Romero et al., 2021; Hernández-Calvento, 2006; Hernández-Cordero et al., 2012; Viera-Pérez, 2015).

In Run 2, wind speeds showed homogeneous behaviour, with values above 50% of the input wind speed recorded at the control tower. The surface of the lagoon, without vegetation and landforms, facilitates flow recovery after the deceleration induced by the foredune. The depressed topography and the emergence of vegetation in the mouth of the troughs cause the highest reduction of wind speed in this zone (SP18 and SP19). The wind speed is reduced locally by the presence of vegetation (Arens, 1996; Davidson-Arnott et al., 2012; Hesp et al., 2005; Leenders et al., 2007; Mayaud et al., 2016) that can also act as a sediment trap (Al-Awadhi & Al-Dousari, 2013; Dupont et al., 2014; Xiaohong et al., 2019), maintaining the thickness of the sand sheet. The highest wind speeds in Run 2 were recorded at SP16, located in an elevated rocky outcrop close to the northern scarp, whose topography is likely to be responsible for flow acceleration at this point.

Wind speeds at the sample points recorded in Run 3 varied between 25% and 90% of the input wind speed. Three sample points presented wind speeds under 50% of the input speed. As was the case in SP18 and SP19, wind speeds at SP22 and SP28 were reduced by the presence of vegetation at the bottom of the troughs. Additionally, the reduction of wind speeds at SP26, located as in the case of SP16 in an elevated rock outcrop close to the northern limit of the extraction, could be caused again by the topography of the scarp, but in this case due to a rocky ledge that blocks the wind. The highest

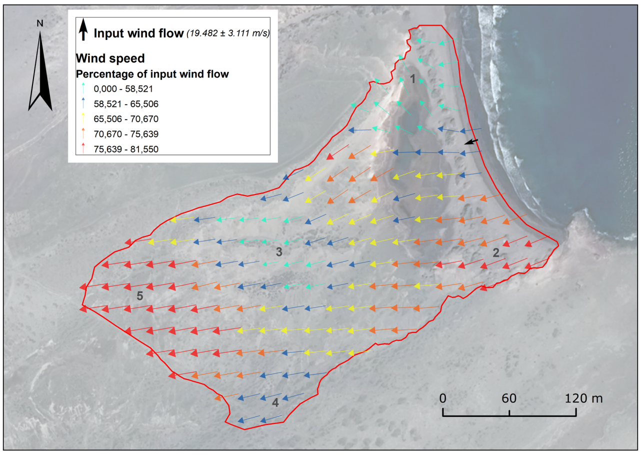


FIGURE 7 Airflow pattern at timeslot T11 (input wind speed = 19.482 ± 3.111 m/s; input wind direction = 71.369 ± 3.918° [Color figure can be viewed at wileyonlinelibrary.com]

wind speeds for this run were recorded at SP24, due to its location at the bottom of a denuded trough where the wind is channelled in the absence of vegetation to slow down the airflow.

In Run 4, acceleration was clearly observed at SP33, where airflow presented wind speeds higher than the input speed (> 100%). This sample point is located in an elevated zone near the scarp, where wind is accelerated by flow compression along the gully and a near-surface jet flow forms (Hesp & Hyde, 1996; Hesp & Smyth, 2019, 2016; Piscioneri et al., 2019).

The sample points located at the south-western vertex of the study area (SP35, SP39 and SP40) showed low wind speeds. Despite being in the more elevated zones of the topography, it is an area moderately sheltered from the ENE winds. Moreover, these sample points were in or near the largest gully, where a population of *Traganum moquinii* specimens can be found offering high vegetation cover and the ability to stop the wind and retain the sediment that gives rise to the formation of characteristic sediment accumulation landforms, such as nebkhas, shadow dunes and ripples (Figure 3, D).

To analyse spatial patterns of the wind data collected at all the sample points during the field experiment, the mean data of timeslot T11 were used as this timeslot had the lowest standard deviation from the input wind direction at the control tower (71.369 ± 3.918°), ensuring that changes in input wind direction were minimum between runs (Figure 7).

In the northern limit of the beach-foredune environment (1), the wind is blocked by the foredune, halving its speed, and limiting the capacity for sediment to enter the system in this zone. The southern limit of the foredune (2), where it is higher and wider and vegetation forms discontinuous mounds that allow the wind and sediment to enter the system and form accumulative landforms leeward, is the main wind and sediment entry zone to the system. The absence of obstacles in the lagoon area permits, to some degree, the recovery of the flow after the interference produced by the foredune. Once the wind has passed the lagoon, the flow dynamics differ according to the characteristics of the environment: (i) the wind over rocky outcrops close to the northern limit of the extraction is highly influenced by the morphology of the scarps that limit the system, with alternating flow acceleration and deceleration zones according to the land relief; (ii) the wind flow channelled through the two central troughs (3), where high vegetation cover exists, is slowed down by the effect of plants and sediment deposits, forming small landforms that thicken the sand sheet in these zones; (iii) the wind flow channelled through the southern trough of the system, which lacks vegetation in its mouth, is accelerated by the effect of the relief and transports sediment to the higher zone of the trough. In this higher zone (4), the wind flow decelerates due to the zone being sheltered from the ENE winds and the presence of large *Traganum moquinii* specimens (Figure 3, D), where sediment leads to the initiation of accumulating landforms, such as nebkhas and shadow dunes.

The highest wind speeds were found in the rocky outcrops located in the northwest zone of the extraction area (5). In these elevated zones, the wind flow channelled through the gullies is accelerated by the rapidly increasing slope which promotes jet flows. This acceleration is enhanced in the elevated flat zones by the absence of vegetation, which prevents the wind flow from slowing down and the sediment from being retained.

4.3 | Aeolian sedimentary transport patterns

The graphical analyses shown in Figure 8 are divided into two parts: (i) the patterns between the normalized wind speed taken in the (short term) experiment with sorting and mean grain size in the different environments (beach-foredune, lagoon, troughs and rocky outcrops), ordered according to their distance from the coastline; (ii) the relationships between sorting and the distance from the coastline of two transects. The first transect is in the centre of the study area from the lagoon and comprises sample points (with sand) 12, 17, 22, 27 and 13, 18, 23, 28. The second transect is formed by the sample points (with sand) which do not practically coincide with the lagoon (i.e., 14, 19, 24, 29, 34 and 25, 30, 35, 40) located in the south of the study area, discarding the sample points at the beach-foredune environment as the intention is to verify sediment behaviour landwards from the lagoon environment and to compare spatial differences.

In the first block (Figure 8, top), the results show two different patterns between wind and sorting/mean grain size. In the first case, the beach-foredune and troughs are environments where, according to the results, aeolian sedimentary transport is related to wind speed, as established by Bagnold (1941) and Fryberger et al. (1992). It was found that grain size tended to increase with the normalized wind speed at the sample points (positive trend), and that sediment selection improved as wind speed decreased (negative trend) or hardly varied, as the case of the beach-foredune environment. This could be attributable to the greater transport effect of stronger winds at the sample points, resulting in fine sediments having a saltation trajectory regardless of their vertical distribution (Farrell et al., 2012), while leaving larger grains at the sample points (Namikas, 2003). This could also explain why sediment with better sorting is found in areas with lower wind speed (opposite case) (Jerolmack et al., 2011). In this regard, in these two environments the results are related to sediment transport patterns described under natural conditions (Lancaster et al., 2002). In the second case, involving environments which are a direct consequence of anthropization as the result of aggregate extraction, namely the lagoon and the rocky outcrops, the patterns are totally changed, showing inverted trends in both sorting and mean grain size. It is thus understood that in these environments the aeolian sedimentary

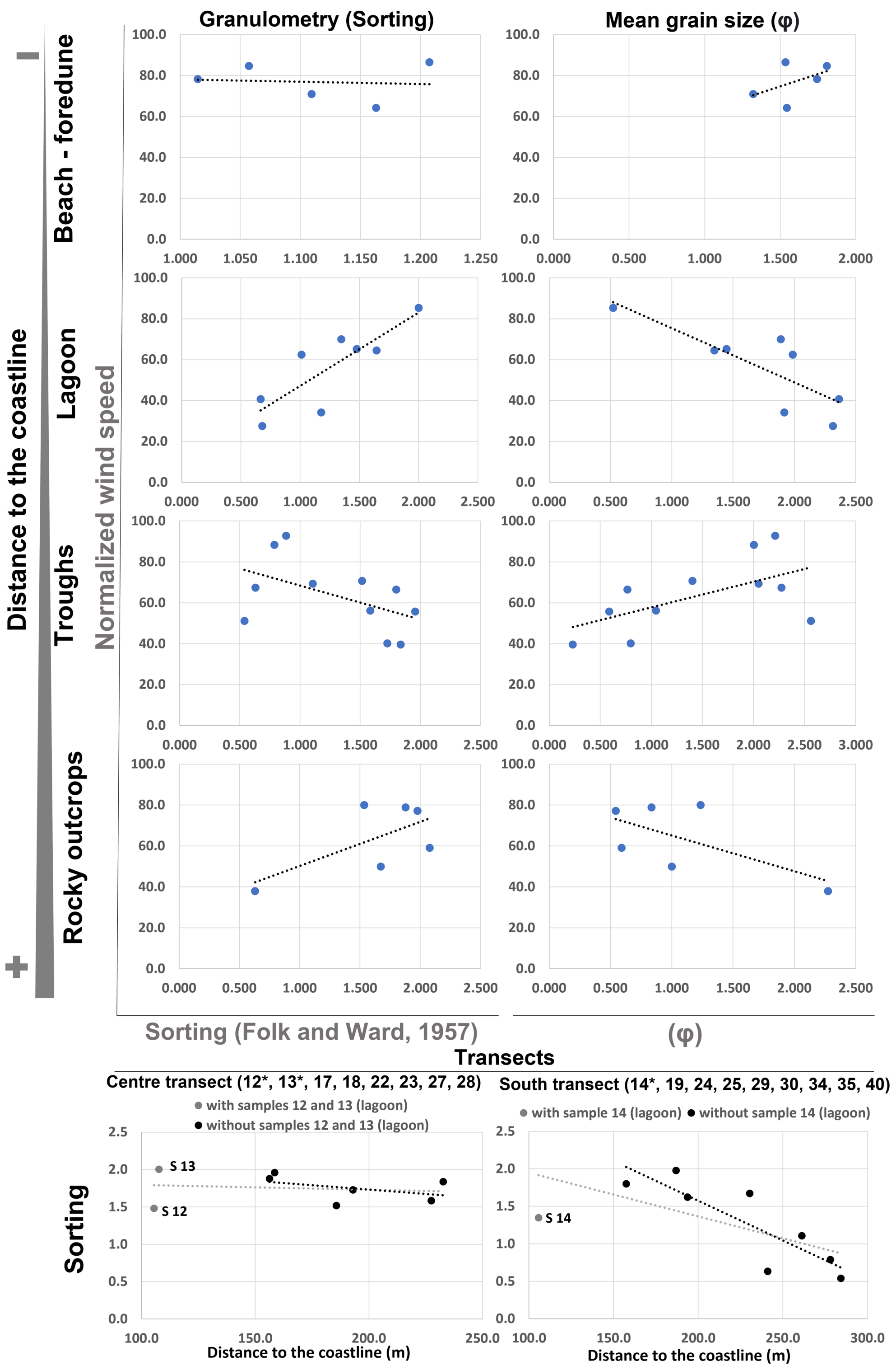


FIGURE 8 Trend patterns between normalized wind speed, distance to the coastline and sedimentary variables. Top: Trend patterns between normalized wind speed and sorting (left), and mean grain size (right) in different environments within the aggregate extraction zone with respect to the coastline. Bottom: Trend patterns between sorting and distance to the coastline in the centre (left) and in the south (right) of the study area. Two situations are shown: (i) with sample points around or within the lagoon (grey points); (ii) without sample points around or within the lagoon (black points) [Color figure can be viewed at wileyonlinelibrary.com]

dynamics have been altered. Aeolian transport into the extraction area, as it moves away from the coastline, encounters two obstacles produced by aggregate extraction (i.e., the lagoon and the rocky outcrops) which do not allow natural aeolian sedimentary dynamics, even when the winds blow at an angle or oblique to the coastline, as Nordstrom et al. (2007) detected in a nourished fine sand beach without obstacles at Ocean City (New Jersey).

The second block (Figure 8, bottom) shows the distribution of the sorting that occurs landwards from the lagoon in the perpendicular transects composed of the aforementioned sample points. In the first case (left), it is detected that there is no selection in the sample points located in the centre of the study area and that cross the lagoon towards the interior. This pattern coincides in the two situations presented, that is, with and without the sample points 12 and 13 that are located around or within the lagoon. However, a different behaviour is detected in the transect located in the south of the study area (right), where the sorting of the sediment produced mainly by the wind is observed. In this case, a negative trend in sorting while distance to coast increased is observed when sample point 14 located around the lagoon is taken; but if this sample point is removed, this trend between the sorting and the distance to the coast becomes even more pronounced.

TABLE 3 Actions during the aggregate extraction period, associated current consequences, and management actions carried out or planned to improve the area

Environments	Actions associated to aggregate extraction	Current consequences	Management actions carried out or planned to improve the area
Beach-foredune	• Topographic modification • Removal of *Traganum moquinii* specimens • Foredune removal	• Reduction of sediment input • Channelization of the landwards wind flow to the south.	• Foredune restoration (executed) • Piling of rubble, stones and accumulation of *Cymodocea nodosa* (executed) • Installation of posts attached with ropes as a fence (executed) • *Traganum moquinii* specimens plantation (executed)
Lagoon	• Topographic modification • Excavation below sea level	• Creation of flooded area • Difficulty for plant recolonization • Limitation of space available for foredune development • Salt crust and flooded area do not allow sediment transport	• Sediment extraction to avoid clogging of the lagoon (planned) • Fenced to prevent user entry (executed)
Troughs	• Topographic modification	• Sand sheet stabilization • Alteration to species richness • Small gullies creation	• Planting local vegetation in bare areas (planned)
Rocky outcrops	• Topographic modification • Excavation down to rock level • Remobilization of sand sheets	• Wind flow acceleration • Difficulty for plant recolonization • Reduction of sediment trapping	• Remobilization with machinery (planned) • Planting local vegetation in bare areas (planned)

In general, it can be interpreted that the current aeolian sedimentary dynamics are altered by the negative extraction effects from the coast to the interior zones, especially by the lagoon. Where the aeolian sedimentary transport occurs in a more natural way, or where a recovery is detected (without forgetting that this area was also altered), is towards the south of the extraction area, forming an aeolian sand sheet which is observed towards the interior of the aeolian sedimentary system (Figure 1).

4.4 | General discussion

Aggregate extraction in the aeolian sedimentary system of El Médano affected and continues to affect the biogeomorphological processes in this area. As reported by Marrero-Rodríguez, García-Romero, Peña-Alonso, et al. (2020), topographic modification and distance to the coast are key factors that condition the capacity of a system to response after the cessation of aggregate extraction. Topographic modifications took place throughout the study area and led to environmental consequences that are still present (Table 3). The management actions and restoration projects that have been carried out have been of little help in terms of the recovery of the system, and in some cases, such as the reconstruction of the foredune, not only were foredune restoration procedures in arid systems not followed, but the actions taken collaborated in the alteration of its functioning. Thus, while management actions like the installation of fences to prevent user entry are currently effective, the reconstruction of the foredune could help the restoration of the system, but it should not have been re-built in a ridge form, pilling up rubbles and stones, blocking the wind in the north and limiting the capacity for sediment to enter the system. In this sense, restoration actions oriented to the formation of a discontinuous foredune comprising nebkhas formed by *Traganum moquinii* specimens and shadow dunes should have been taken. The installation of circular collectors has shown to be effective to the formation and stabilization of large mound dunes, where then large *Traganum moquinii* specimens can be planted to progressively retain sand (Sanromualdo-Collado, Hernández-Cordero, et al., 2021), regulating the sediment input to the inner zones of the system and facilitating the colonization by species less adapted to sand burial. Moreover, even actions oriented to the introduction or relocation of sand could have been considered, bearing in mind that every restoration action must be revised and adapted to the environmental specificizes of the area. Factors like the limits imposed on vegetation due by the arid conditions, the sea water flooding, the new topography after the extraction or the continuous presence of visitors trampling in the zone, among others, complicate restoration strategies based on the spontaneous recovery of the vegetation (Baasch et al., 2012; Duan et al., 2008; Fernández Montoni et al., 2014).

Despite the lesser distance to the coastline meaning a higher recovery capacity of the system (Marrero-Rodríguez, García-Romero, Peña-Alonso, et al., 2020), the effects of the removal of the foredune and its associated vegetation, as well as the excavation below sea level, prevent recovery of the initial conditions even in the closest environments to the coast (beach-foredune and lagoon). Beaches and foredunes are highly productive in terms of sand minerals (Dang et al., 2021), which could be the reason why extraction extended below sea level in this zone, leading to a non-recoverable impact on the system in the analysed time period. The underground filtering of seawater created a lagoon, where no colonization by plants is possible and there is no sediment accumulation (Ley et al., 2007; Marrero-Rodríguez, García-Romero, Peña-Alonso, et al., 2020), which in turn prevents the formation of a natural foredune. The construction of a foredune in front of the lagoon in an attempt to restore the ecosystem and protect the coastal lagoon did not help to recover the initial conditions. The use of rubble, stones and seagrasses resulted in an artificial continuous ridge in the northern limit of the extraction zone that differs considerably from natural foredunes in arid environments (Castro, 1988). The combined action of the lagoon and the artificial foredune acts as an obstacle that inhibits sediment from accumulating in a natural mound-shaped foredune (Arens, 1996). However, as the lagoon has become an important site for seabirds, the previously mentioned Master Plan of the protected area has determined that it must be maintained and conserved as part of the management budget.

The elimination of the surface sand sheet complicated the rooting process of the vegetation, which in turn has contributed to alterations to species richness and plant species distribution. Scarce vegetation also limits sediment retention capacity inside the system (Suter-Burri et al., 2013), as well as the system's ability to recover its initial conditions. Only in zones where vegetation has successfully established itself, such as the bottom of the troughs, has sand thickness increased and accumulation processes taken place. In the case of the southernmost trough, this sediment accumulation has led to the formation of a sand sheet, whose brink is heading toward La Tejita beach, situated to the southwest and outside the study area (Figure 1), following the original northeast–southwest (NE–SW) sand corridor described in Marrero-Rodríguez, García-Romero, Peña-Alonso, et al. (2020). This sediment transport finding was also reported in observations made over 258 days recorded in the 2018 Granadilla Observatory Report (OAG, 2018), which identifies this sand tongue as the zone of maximum sediment flow intensity towards La Tejita beach.

The combination of the coastal lagoon created during the extraction process and the building of an artificial foredune are found not only to be unable to influence the recovery of the system, but also to be affecting wind flow patterns and limiting sediment input to the southern limit of the foredune. However, more detailed research is required in the beach-foredune and lagoon areas to know how these two environments interact and limit sediment input into the system. It would also be interesting to know the amount of sediment available in the submerged part and its characteristics, and whether sediment is accumulating on the beach for subsequent transport to the system. Similar methodologies to the type used in the present study can be applied to areas with historical aggregate extractions shortly after the cessation of the activity in order to evaluate the immediate effects of the extraction and monitor the suitability of any proposed actions.

5 | CONCLUSIONS

The evolution of the aeolian sedimentary system of El Médano in the last 40 years has been conditioned by the environmental response to the historical aggregate extraction carried out in this system. The current functioning of the biogeomorphological elements and processes taking place in the system are strongly conditioned by the human actions associated to the aggregate extraction.

The topographic modifications, including the creation of a lagoon as the result of extractions below sea level, the removal of the sand sheet and the creation of aeolian deflation areas have conditioned the capacity of plant communities to establish themselves in the system and consequently retain sediment to evolve towards the typical conditions of the natural arid aeolian sedimentary systems. The building of an artificial foredune to protect the lagoon and induce the restoration of the system failed in its objective as the structure did not correspond to the natural morphology of arid foredunes. Instead, it caused a change to the nearly homogeneous wind flow pattern and sediment entry expected, restricting it to the southern part of the foredune.

In a scenario of high aggregate demand for construction purposes, the effects of aggregate extraction need to be carefully considered by all concerned parties so that any potential environmental impacts can be minimized, especially when involving fragile ecosystems like arid coastal aeolian sedimentary systems which provide important services and resources for society. This research contributes to a better understanding of the environmental consequences of aggregate extraction on the foredunes of arid aeolian sedimentary systems and offers key information about their response. The results can be used to enable the relevant authorities to make better-informed management decisions and help avoid impacts in these areas.

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DATA AVAILABILITY STATEMENT

The data that support the findings are available on request from the authors.

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