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Biogeomorphological responses of nebkhas to historical long-term land uses in an arid coastal aeolian sedimentary system

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A B S T R A C T

Coastal dunes have received growing attention in recent years because of the ecosystem services they provide and the high anthropic pressure that they have historically been subjected to and continue to endure. Such pressure especially affects arid dune fields where any changes are more noticeable due to their natural dynamics. The aim of this paper is to analyze the relationship between the degradation of an arid aeolian sedimentary system (El Médano, Tenerife, Spain) due to historical long-term land uses and its subsequent biogeomorphological evolution. The methodology combines historical sources (historical documents, aerial and common photographs and oral sources) and current ones (orthophotos, LiDAR data and field work). In order to analyze the response of the system to these uses, 8 plots were chosen in which 3 different historical land uses had resulted in the total or partial elimination of the vegetation and landforms. Biogeomorphological variables were measured on 461 nebkhas in these plots. The main results show that the historical land uses studied in this paper (*aerodrome*, *aggregate extraction* and *crop cultivation*) modified the entire system, with changes observed in the topography, vegetation cover and sediment availability for transport. Changes in topography and distance from shore were important factors in its recovery capacity. This research contributes to our understanding of the different aeolian sedimentary dynamics that can be detected in the same dune field (especially with nebkha landforms) and is of particular importance for making appropriate environmental management decisions to facilitate the recovery of the ecosystem.

1. Introduction

The study of coastal dunes has attracted growing attention in recent years because of the importance of the ecosystem services they provide (Miththapala, 2008; Everard et al., 2010; Barbier et al., 2011). However, human uses and direct/indirect anthropogenic pressure have led to their rapid degradation in recent decades (Paskoff, 1993, 2001; Jackson and Nordstrom, 2011; Delgado-Fernandez et al., 2019).

The coastal aeolian systems of the planet have been exposed to a process of anthropic degradation related to traditional activities such as grazing, obtaining firewood or agriculture (Tsoar and Blumberg, 2002; Kutiel et al., 2004; Levin and Ben-Dor, 2004; Provoost et al., 2011) and to recent uses such as aggregate extraction, the construction of urbanizations and tourist infrastructure, and recreational uses (Nordstrom and McCluskey, 1985; Nordstrom, 1994; Nordstrom, 2004; Smith et al., 2017; García-Romero et al., 2019b; Delgado-Fernández et al., 2019). All these uses have induced environmental transformations whose consequences have been, among others, changes in landforms and aeolian sedimentary activity (dune stabilization) (Cabrera-Vega et al., 2013; Hernández-Cordero et al., 2018), reductions of pioneer plants in mobile dunes and species richness (Kutiel et al., 1999; Curr et al., 2000; Dolnik et al., 2011; Faggi and Dadon, 2011), sediment remobilization (Arens et al., 2013), accelerated erosion processes (García-Romero et al., 2016; García-Romero et al., 2019b), alteration of the direction and speed of wind flow (Hernández-Calvento et al., 2014; Smith et al., 2017; García-Romero et al., 2019a), and on occasions surface reduction (Hernández-Cordero et al., 2018). It can be argued, therefore, that most of the surviving ecosystems are an expression of their resilience and that their evolution after the land uses is not restricted to the recovery of the original functions and characteristics but to the adaptation and reorganization of the components of the landscape to the post-disturbance situation (Kombiadou et al., 2019).

Knowledge of the evolution of land uses, vegetation, landforms and environmental dynamics facilitates reconstruction of the historical trajectory of these ecosystems (Bürgi and Gimmi, 2007), as well as to understand the mechanisms of response to the different disturbances. In addition, historical data can help to improve the accuracy of predictive models of ecosystem or species response to such impacts (Gimmi and Bugmann, 2013). Historical reconstruction is therefore a useful tool

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that can be employed to facilitate the implementation of management strategies that foster ecosystem resilience (Fritschle, 2009; Grossinger et al., 2007; Villagra et al., 2009), to confront new anthropic disturbances caused by climate change (Petit and Prudent, 2010) or changes in land use (Jackson and Nordstrom, 2011), and to deal with changing environmental factors such as a reduced sediment contribution (Pye and Blott, 2012; Hernández-Calvento et al., 2014). An awareness and understanding of the historical processes that have taken place can contribute to reducing the vulnerability of these ecosystems to new impacts (Peña-Alonso et al., 2018) through the application of management measures adapted to the dynamics of socio-ecological processes (Garnasjordet et al., 2012).

In arid dune systems, the degradation process due to different historical land uses has led to the elimination of vegetation and associated landforms through sediment remobilization, as has happened for example in the Canary Islands (Spain) with particular reference to nebkhas (Marrero-Rodríguez et al., 2019). Meanwhile, more recent land uses and the abandonment of traditional ones have led to the stabilization of sand sheets as the result of the plant recolonization processes (Tsoar and Blumberg, 2002; Kutiel et al., 2004; Marrero-Rodríguez et al., 2020). In other studies, recent land uses, associated especially with urban-tourism development, have been attributed with causing alterations to wind dynamics and a lower sand input, with a consequent reduction or disappearance of mobile dunes or an increase in deflation surfaces and stabilized dunes (Hernández-Calvento et al., 2014; Smith et al., 2017; García-Romero et al., 2016, 2019a, 2019b).

In the Canary Islands, coastal mobile dunes have been transformed into nebkha fields over the last 60 years due to the abandonment of traditional uses (Santana-Cordero et al., 2016a; Marrero-Rodríguez et al., 2020). Due to their specific properties, nebkhas represent patches of high water and nutrient availability for plants and can affect plant diversity (El-Bana et al., 2003), which depends on the vegetation fixing the sand. Nebkhas play an important role in stabilizing surface sand sheets, preventing their erosion and facilitating the settlement and survival of new plants (Brown and Porembski, 1997; Blank et al., 1998; El-Bana et al., 2002a; El-Bana et al., 2003). Vegetation additionally increases terrain roughness (King et al., 2006), which in turn lowers the wind speed and, therefore, affects its transport capacity and its capacity to erode the aeolian sedimentary system.

Arid coastal dune systems can change over relatively short periods of time (Hernández-Cordero et al., 2006) and are therefore a natural laboratory to investigate dune disturbances. The response of dune systems after erosion or remobilization processes has been well studied in reference to hurricane effects (Morton et al., 1994; Houser and Hamilton, 2009), uses that modified sediment transport such as grazing or obtaining firewood (Kutiel et al., 2004; Levin and Ben-Dor, 2004), landform transformation (Tsoar and Blumberg, 2002) or ecological restoration projects (Xu et al., 2018). However, the analysis of the recovery process of landforms and the recolonization of vegetation after the cessation of land uses which have affected them has been less studied. This is because in many cases the systems have been partially or totally urbanized (Santana-Cordero et al., 2016b), with the constructions often

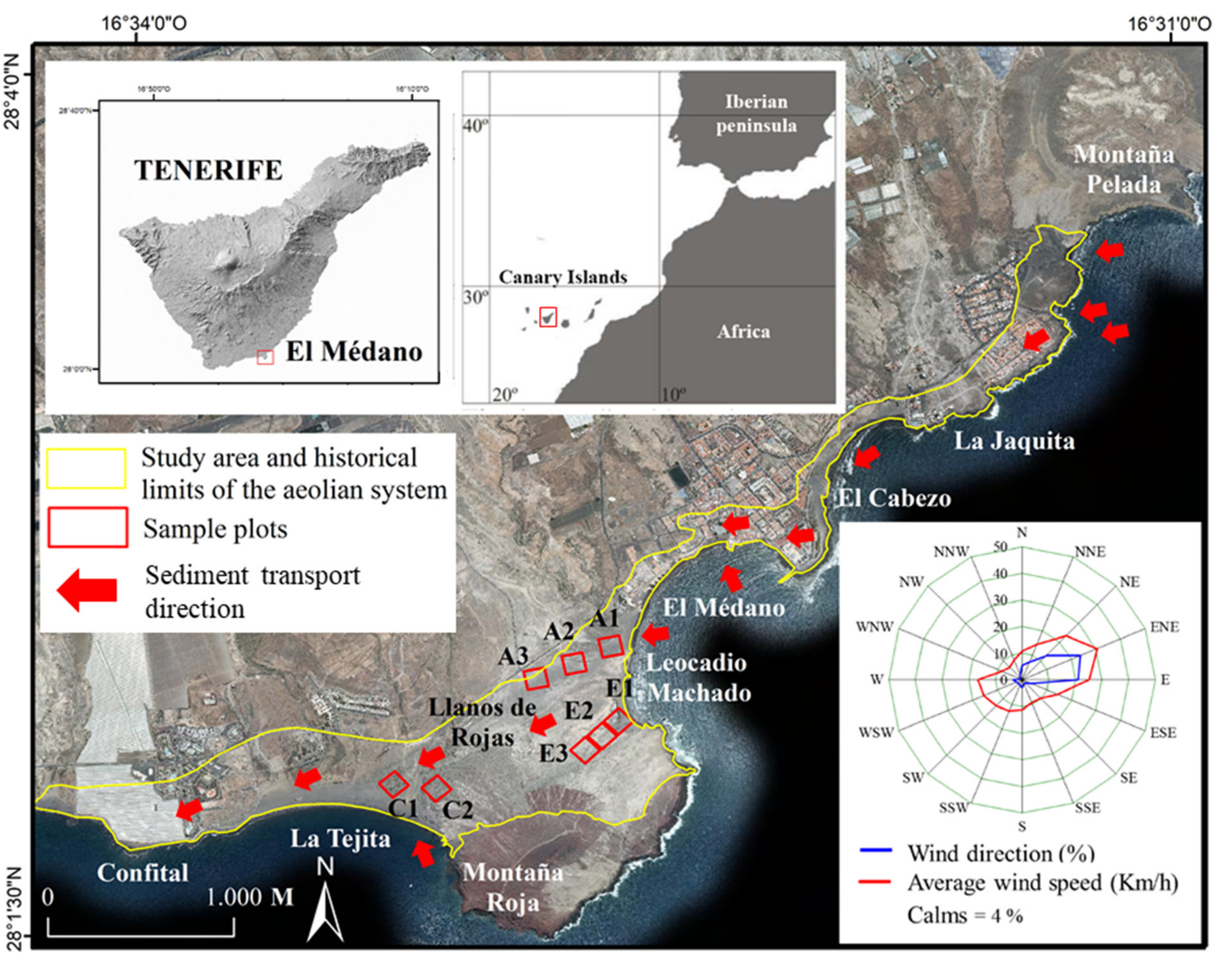

Fig. 1. Location of the study area and historical limits of the aeolian system of El Médano. Bottom right-hand corner: mean wind direction and speed in the study area between 1980 and 2008.
Aerial photo source: SDI Canarias (Canary Islands Government-Grafcan S.A.).

occupying the areas where the sediment enters the aeolian sedimentary system (García-Romero et al., 2016). This makes it impossible to measure biogeomorphological variables from the coastline inland and, using this information, study how the system has responded to the cessation of the historical land uses. In view of all the above, the aim of this article is to analyze the transformation process of an aeolian sedimentary system situated in El Médano (Tenerife, Canary Islands, Spain), with particular emphasis on historical land uses. The subsequent process of plant recolonization and the development of associated landforms (especially nebkhas) after the cessation of the different land uses that are identified in the study is also analyzed. A further aim is to determine the land uses that generated the greatest impact on the foredune and, therefore, on the rest of the system. The final aim is to identify the different biogeomorphological gradients between the coastline and the interior of the aeolian sedimentary system.

2. Study area

The aeolian sedimentary system of El Médano is located on the southern coast of the island of Tenerife, in the municipality of Granadilla de Abona (Fig. 1). The sediments are the result of a mixture of sands from inland sources of local ravines and marine contributions in which organogenic and inland sands are mixed. The marine contributions are transported along the coastal drift to the rocky ledges of Montaña Pelada, El Cabezo and Montaña Roja, which impede them from continuing their journey. Once they have been deposited, the wind dynamics take over, giving rise to the genesis of different landforms including climbing dunes and dunes associated to vegetation (Criado et al., 2011). Finally, the action of the dominant ENE wind (Fig. 1 insert) transports the sand to the leeward sector, where the marine dynamics intervene again redistributing the sediments. On the beach of Montaña Pelada, the sediments ascend through the ravine until they reach the road and the houses, and during episodes of intense rainfall, they are returned to the beach. In the past, at Montaña Roja, sediments ran along a sandy corridor approximately 1.6 km long in a NE-SW direction, with Leocadio Machado beach acting as a sediment input sector and the SW sector of La Tejita and El Confital as a leeward sector where the sediment is again exposed to marine dynamics (IGME, 1972). However, the SE of La Tejita sector also acts as a sediment input zone. This is mainly due to the presence of Montaña Roja which also acts as a vortex that alters the circulation of the winds (from NE-SW to SW-NE) that push the sediments inland. This can be observed in the climbing dune located in the SW of Montaña Roja or in the direction of the shadow dunes of La Tejita. It is likely that, in the past, this same process occurred in other sectors of the coast such as La Jaquita and El Cabezo today transformed by urbanization.

The climate is characterized by aridity, with an annual average rainfall of 83 mm and annual average temperature of around 21 °C (García-Casanova et al., 1996). The vegetation that corresponds to these conditions is shrubby with poor cover and is adapted to the conditions of salinity and sediment mobility, although there are important inland variations where plant communities associated to ravines, rocky outcrops and areas of strong flooding appear. Of particular importance in the study area are the different so-called Habitats of European Interest. These habitats are as follows: 1210 Annual vegetation of drift lines; 2110 Embryonic shifting dunes; 92D0 Southern riparian galleries and thickets; and one priority habitat, 2130 Fixed coastal dunes with herbaceous vegetation. The system is partially urbanized in the form of the town of El Médano and scattered buildings towards Montaña Pelada.

3. Methodology

The methodological process has two main stages: i) characterization of the historical evolution of the system and the identification of historical land uses that significantly altered the system; ii) statistical analysis of the relationship between current nebkha characteristics and the detected historical land uses. In this second stage, the gradients that are detected in the measured variables (ratio between the variation of the value of a nebkha characteristic and its distance to the coast) are analyzed in depth to determine any difference between land uses in terms of biogeomorphological recovery/development.

3.1. Historical characterization and identification of land uses

The procedure to analysis the historical evolution of the studied dune system was carried out from an historical ecology perspective, using the historical information sources commonly used in such an approach.

3.1.1. Documentary sources and historical bibliographic references

An analysis was made of numerous historical documents of differing origin collected in the municipal archive of Granadilla de Abona and the archive of the Tenerife Friends of Nature Association (ATAN - Asociación Tinerfeña de Amigos de la Naturaleza) - who have drawn up restoration plans and fought through the courts to protect the area - as well as different historical bibliographies (De Olive, 1885; López-Soler, 1906; Escolar Serrano, 1984). Historical field photographs were also used to visualize and determine the state of the system in the past. These were found in private archives, ATAN's photographic collection and the collections of the Foundation for Ethnography and the Development of Canary Crafts (FEDAC). In addition, the *Jable* search tool of the University of Las Palmas de Gran Canaria Library was used to find and review relevant articles in the local press and to obtain information from the records of the Official Gazette of the Canary Islands Government regarding licenses for the extraction of aggregates.

3.1.2. Historical aerial photographs, orthophotos and LiDAR data

These sources (Table 1) were used to contrast information from historical documents and interviews, to spatially determine environmental/land use changes and the creation of urban nuclei, and to delimit the historical area of the aeolian sedimentary system. The historical aerial photograph of 1964 (1:30,000) was georeferenced in a geographic information system (GIS) through checkpoints and was used, along with the rest of the aerial documents, to obtain spatial information on land cover (uses, vegetation and landforms). Light detection and ranging (LiDAR) measurements taken in 2009 and 2015 were also used to obtain digital elevation models (DEM) with a 1 m spatial resolution. Volumetric changes were calculated from these DEMs using the geomorphic change detection technique developed by Wheaton et al. (2010a, 2010b). The DEM of difference (DoD) error (%) of the erosion: 25.18 and the accumulation: 24.86 (Fig. 6).

3.1.3. Wind data

Wind variables (mean wind speed and direction and percentage of calms) were calculated from data recorded at a weather station

Table 1
Aerial photographs, orthophotos and LiDAR data used.

Type (source)	Year	Scale	Spatial resolution (m)	RMS[a] (m)	Delineation error (m)
Historical aerial photographs	1964[c]	1:30,000	1	1.05–2.05	6.2
	1987[c]	1:18,000	0.4	1.25–2.05	3.7
Orthophotos	2018[c]	[b]	0.1	< 1.5	0.1
LiDAR (DEM)	2009[d]	–	1	–	–
	2015[d]	–	1	–	–

The delineation error was calculated according to Robinson et al. (1987).
[a] RMS = root mean square.
[b] Flight with GSD de 22.5 cm/píxel.
[c] SDI Canarias (Canary Islands Government-Grafcan S.A.).
[d] National Geographical Institute (Spain).

owned by AEMET (State Meteorology Agency in Spain) and situated in Reina Sofía airport 2.5 km northwest of the study area (Fig. 1).

3.1.4. Field work

Two field campaigns were carried out in September of 2018 and January of 2019. In the first campaign, the objectives were to conduct interviews, take repeat field photographs, and to contrast in the field information acquired in the interviews and from the analysis of aerial photographs. With respect to the oral sources, three interviews were conducted to collect information on human uses. The interviews were based on a semi-structured conversation between an interviewer and an interviewee with an open script following the oral history methodology of Fogerty (2005). The interviews were carried out with people born between 1942 and 1948, tourism-based camel owners and port workers. During these campaigns, the locations of disused lime kilns and bunkers were identified, as well as the locations of other activities, including areas used until relatively recently for the extraction of aggregates and areas currently in use for wastewater discharges. Areas with *Traganum moquinii* plant communities were also identified since this plant plays an important role in the development of the foredune. The locational data was recorded with GPS for later incorporation into a GIS and used to identify the plants in the historical aerial photographs following the methodology used by Hernández-Cordero et al. (2012).

Based on the information obtained from the historical sources and mapping the different historical land uses in GIS, eight plots (100 × 100 m) were selected for the purposes of this study along three transects in areas affected by different land uses: an old *aerodrome* (A1, A2 and A3), an *aggregate extraction* area (E1, E2 and E3) and a *crop cultivation* area (C1 and C2) (red squares in Figs. 1 and 4). The possibility of using control plots was discarded because anthropic impacts have affected practically the entire system. Plot orientation follows as closely as possible the line of sediment transport. Ideally, the C1 and C2 study plot positions would have been situated and orientated slightly differently, but due to the impact of the transit of people over a large number of trails and the location of an old car parking area, these positions were the only feasible areas where it was possible to locate the plots and allow a study of the biogeomorphological responses related to crops and, in this way, obtain sufficient statistical data for the study. These historical land uses and therefore the plots were selected for three reasons: i) the effects of the land uses in question stretched from the foredune right into the aeolian system; ii) the areas are now free of any land use; and iii) unlike the built-on land, there are variables in these areas that can be measured to know the current nebkha characteristics. In the field work undertaken in January of 2019, data related to nebkha landforms (Fig. 2) were collected, including morphological variables: *height* (m), *longitudinal axis* -or *length*- in the direction of the sedimentary dynamics and shadow dunes (m), and *transverse axis* -or *width*- perpendicular to the longitudinal axis (m); variables related to the vegetation which form these landforms: percentage of *vegetation cover*, *species richness* (number of species per nebkha) and presence of *T. moquinii*; plant status variables (presence/absence) in accordance with Ley et al., 2007 as indicators of i) wind effect: *exhumed roots*, *dry front* and *dry plants*, ii) marine incidence: *dry front and dry plants*.

T. moquinii is singled out as a vegetation variable because this plant plays a key role in the foredune formation process and, therefore, in the operation of the entire dune system. The individuals of this plant can grow up to 5 m tall, creating an aeolian shadow that can sometimes extend up to 20 m in length (Alonso et al., 2007; Pérez-Chacón et al., 2007), and hence functioning as a sediment trap that induces the formation of dunes. This shrub barrier in the sediment input area regulates the transit of sediment inland, slowing their advance and generating the set of permanent dunes that creates the foredune (Hernández-Cordero et al., 2012).

In addition, the distance between each nebkha and the coast was calculated from the 2018 orthophoto. The variables were measured in relation to a total of 461 nebkhas and the 13 most commonly found plant species (Table 2). These plants are herbaceous and shrubby species mainly associated with rocky and sandy coasts, as well as arid environments and sand dunes. Therefore, most are species resistant to salt spray, marine flood and/or water scarcity. Currently, there is little information on the response of these plants to sand burial, except for *T. moquinii*. These species respond positively to aeolian sedimentary dynamics, accelerating its growth when buried by sand (Hernández-Cordero et al., 2015a; Viera-Pérez, 2015). *T. moquinii* is a pioneer species that generates embryonic dunes and the foredune, but it is also present in the most advanced stages of plant succession (Hernández-Cordero et al., 2012; Hernández-Cordero et al., 2019). Of the other species, most can develop in aeolian sedimentary systems with little sand volume (sand sheets and nebkhas fields), as *Astydamia latifolia*, *Atriplex glauca*, *Lotus sessilifolius*, *Polycarpaea nivea* and *Tetraena fontanesii*, and/or stabilized dunes of dunefields, as *Launaea arborescens*, *Plocama pendula* and *Salsola vermiculata* (García-Casanova et al., 1996; Hernández-Cordero et al., 2015b; Hernández-Cordero et al., 2019). So far, fieldwork observations indicate that these species are not resistant to the burial of a large volume of sand, dying when the dune increases its height.

Fig. 2. Nebkha field in the study area. A) Lagoon location.

3.2. Relationship between biogeomorphological processes and land uses

Based on the variables described in Section 3.1 with respect to the 461 nebkhas located in the eight study plots, a Spearman's bivariate correlation analysis was performed using SPSS in order to find patterns of dune behavior from the variables considered and the distance to the coast. The Kruskal-Wallis test was applied complemented by Dunnett's test to identify statistically significant differences between the three historical land uses analyzed and thereby enable the specific identification of diverse patterns among the land uses.

Table 2
Characteristics of plants species associated with nebkhas.
(Based from García-Casanova et al., 1996; Hernández-Cordero et al., 2015b, 2017, 2019.)

Species	Origin	Height/Life forms	Environment
Astydamia latifolia	North of Africa and Canary Islands	Herb/hemicryptophyte	Halophilous: rocky or sandy coasts; sand sheets and nebkhas fields
Atriplex glauca	Wide geographic distribution	Herb/chamaephyte	Halophilous: rocky or sandy coasts; sand sheets and nebkhas fields
Cakile maritima	Wide geographic distribution	Herb/therophyte	Halo-psammophilous: sandy coasts; sand sheets and nebkhas fields
Frankenia capitata	Wide geographic distribution	Herb/chamaephyte	Halophilous: rocky coasts
Launaea arborescens	Wide geographic distribution	Shrub/nanophanerophyte	Xerophilous: arid and semiarid habitats; sand sheets and nebkhas fields; stabilized dunes of dunefields
Limonium pectinatum	Endemic of Macaronesia	Herb/chamaephyte	Halophilous: rocky coasts
Lotus sessilifolius	Endemic	Herb/chamaephyte	Xerophilous: arid and semiarid habitats; sand sheets and nebkhas fields
Plocama pendula	Endemic	Shrub/nanophanerophyte	Xerophilous: arid and semiarid habitats; stabilized dunes of dunefields
Polycarpaea nivea	North of Africa and Canary Islands	Herb/chamaephyte	Halophilous: rocky or sandy coasts; sand sheets and nebkhas fields
Salsola vermiculata	Wide geographic distribution	Shrub/nanophanerophyte	Xerophilous: arid and semiarid habitats; sand sheets and nebkhas fields; stabilized dunes
Schizogyne sericea	Endemic of Macaronesia	Shrub/nanophanerophyte	Halophilous: rocky coasts; sand sheets and nebkhas fields
Tetraena fontanesii	North of Africa and Canary Islands	Shrub/nanophanerophyte	Halophilous: rocky coasts; sand sheets and nebkhas fields
Traganum moquinii	North of Africa and Canary Islands	Shrub/nanophanerophyte	Halo-psammophilous: sand sheets and nebkhas fields; foredune of dunefields; dune slack

4. Results and discussion

4.1. The historical land uses of the aeolian sedimentary system

The historical limits of El Médano aeolian sedimentary system (total area of 2.1 km2; Fig. 1) were established based on four distinct periods of land use (Sections 4.1.1 to 4.1.4). Intense system degradation and fragmentation was predominantly observed from 1964 onwards, reducing the surface of the system to less than half (Table 3).

4.1.1. Pre-1900

Seasonal grazing was the first land use that took place in the aeolian sedimentary system. This is confirmed by the presence of skeletal remains of livestock in different deposits found in more recent times, and references to sheep grazing in the vicinity of Montaña Roja around the year 1640 (Mederos Martín and Escribano Cobo, 2016). In addition, there are indications of the exploitation of limestone in references made about the presence of three lime kilns at the beginning of the 19th century (Escolar Serrano, 1984). The development of El Médano as an urban settlement was driven by fishing, which would serve as the main economic support of the inhabitants, and the possibilities of beach anchorage and protection from the waves for the fishing vessels. The first reference to a resident population in the area dates back to 1857 (García-Casanova et al., 1996), although a few years later De Olive (1885) described the settlement as constituting just seven single-story buildings of which only one was inhabited. At the end of the 19th century, the port of Médano gained importance in the route between Santa Cruz de Tenerife and the south of the island, fostering the creation of new infrastructure in its role as an axis for economic growth. These constructions begin to occupy the aeolian sedimentary system, affecting areas of sediment input into the system, as has been found in other dune systems in the Canary Islands (Santana-Cordero et al., 2016b). In 1893, after a sample of sand from El Médano with a high iron content was displayed at the World's Columbian Exposition in Chicago, speculation began about the extraction of this mineral. British ships transported several tons of sand to study the profitability of possible extractions, and extraction requests were subsequently made for El Médano, Montaña Pelada, El Confital and La Jaquita. The extractions that were carried out in the study area took place much earlier than in similar systems in the Canary Islands, such as the Guanarteme isthmus in Gran Canaria (Santana-Cordero et al., 2014) and Jandía in Fuerteventura (Alcántara-Carrió et al., 1996). In this case, however, the extractions ceased after a few years as they were discovered to be unprofitable.

Table 3
Environmental changes in the study area (1964–2018).

Landforms/land uses/vegetation	1964		2018		Variation (km^2)	Variation (%)
	Surface (km^2)	System %	Surface (km^2)	System %		
Landforms						
Sand sheets	0.21	6.67	0.17	8.10	−0.04	1.43
Climbing dune	0.01	0.47	0.01	0.47	0	0
Nebkhas	1.03	50.95	0.69	32.86	−0.34	−18.09
Marine lagoon	0.02	0.95	0.04	1.90	0.02	0.95
Rocky outcrops	0.11	5.24	0.22	10.48	0.11	5.24
Pyroclastic deposits by rock fall	0	0	0.04	1.90	0.04	1.90
Land uses						
Urbanization	0.03	1.43	0.40	19.05	0.37	17.62
Crops	0.28	13.34	0.13	6.19	−0.15	−7.15
Aerodrome	0.13	6.19	0	0	−0.13	−6.19
Other degraded areas	0.30	14.29	0.40	19.05	0.37	4.76
Vegetation						
Groves	0.01	0.47	0	0	−0.01	−0.47
Total aeolian sedimentary system						
Total	2.10	100	1.03	49.05	−1.07	−50.95

4.1.2. 1900–1964

At the beginning of the 20th century, in addition to references to the presence of camels, El Médano consisted of 24 houses, 2 hostels, a church and a total of 70 inhabitants (López-Soler, 1906). An increasing number of references to the arrival of tourist visitors began to appear in the written press since the beginning of the 20th century. Tourists came to spend their summer in the area because of the good climate and the safety of the beaches. However, tourist development in the area was limited by poor communications and the lack of access to potable water, electricity and public sanitation.

Between 1930 and 1931, an acceleration of the urbanization process began when the local council announced they were giving away free plots of land on the condition that construction was undertaken within a maximum period of six months. A total of 24 authorizations for construction were granted in these processes. In the 1930s, the decision to construct an auxiliary runway for the landing of airplanes in Llanos de Rojas was made due to the occasional fog-related impossibility of planes landing at the airport in the north of the island. The aerodrome was opened in August 1935, but only sporadically received flights until the 1960s.

Requests began to be made to create plant barriers in the El Cabezo area, similar to the one built in Jandía in Fuerteventura (Alcántara-Carrió et al., 1996), to restrict the impact of wind-blown sand, indicating the presence of significant amounts of sand. After the end of World War II, and thanks principally to the construction of the island's southern canal in the 1940s which enabled the transfer of water from nearby municipalities, tomato crop cultivation (extensively practiced in the islands in general) made its first appearance in the area. Tomato plantations sprung up in Punta de El Cabezo, on the slopes of Montaña Roja, and throughout practically the entire northern limit of the system.

The aerodrome was reconditioned in 1947 with a runway approximately 750 m long and 70 m wide and an altered surface for its installation of 0.13 km^2. This rebuild involved the total elimination of vegetation and associated landforms, as can be seen from the aerial photography of 1964 and the field photograph (Fig. 4A). Despite the creation of the aerodrome in 1935, the expansion of tourism came late to this area of the island. However, in the same year as its rebuild, the growing importance of tourism is seen in the inauguration of El Médano Hotel which acted as a driving force behind future tourist development in the area.

With respect to the exploitation of limestone, there are only a few references in the historical documents. The stone was brought from Fuerteventura and burned in the kilns located on the coast and then taken to inland villages. According to oral sources, the firewood used in the kilns was brought from pine forests and shrubs located around 1000–1500 m above sea level (about 12 linear kilometers from El Médano). The same sources reported that little grazing took place in the system, and only on a seasonal basis since most of the herds were kept at higher altitudes and only descended to the coast when weather conditions worsened. The presence of camels and mules used for transport purposes was common, but they tended to be fed with cereal crop remains and fodder plants. In this context, it is likely that two of the historical land uses that have been found to have had the greatest impact on aeolian sedimentary systems in other islands of the Canary Islands and in Israel, namely the exploitation of vegetation to obtain fuel and for grazing purposes (Santana-Cordero et al., 2016a; Tsoar and Blumberg, 2002; Kutiel et al., 2004) did not have the same importance in El Médano due to the proximity of pine forests and other grazing land.

4.1.3. 1964–1987

In this period, the abandonment of tomato cultivation occurs at the same time as tourism expands rapidly and extensively in the south of Tenerife and the exploitation of limestone ceases, replaced by the cement trade and imported synthetic paints. In 1965, the General Urban Development Plan of the municipality reclassified a large part of the aeolian sedimentary system as land for development, requiring a Partial Plan for its urbanization which was published in 1968 but never executed. In the corresponding Plans, a strategy of massive occupation of the coast is proposed with a coastal road as the main axis and a central road in the town of El Médano. The expansion of the construction sector and the demand for aggregates for the proposed new airport in the south of the island gave rise to the beginning of massive sand extractions in 1970. These extractions, which are clearly visible in the field (Fig. 3), generated a depressed area into which water could seep at high tide resulting in the formation of a small lagoon behind the current coastal dune. Extractions were carried out in an area covering some 175,000 m^2, and the approximate total volume of extracted material amounted to 200,000 m^3 (Canary Islands Government, 2004). In consequence, the coastal dune that existed at the time and the associated vegetation were eliminated (Fig. 4B), causing a significant decline in *T. moquinii* populations. The local aerodrome was finally closed in 1975, the same year in which the Reina Sofía International Airport

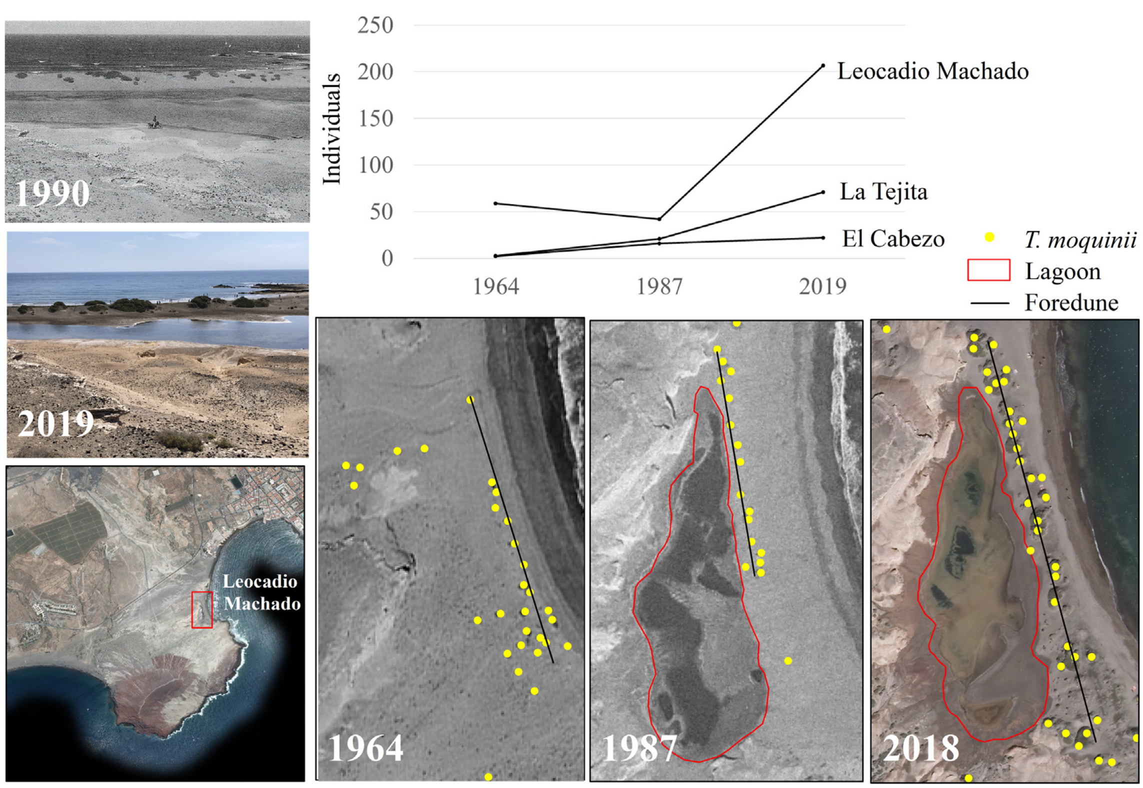

Fig. 3. Evolution of the number of *T. moquinii* specimens in el Cabezo, La Tejita and Leocadio Machado between 1964 and 2019 (Graph). Repeat photograph of the foredune of Leocadio Machado in 1990 (Author: J. García-Casanova) and 2019. Aerial photograph and orthophoto of the foredune of Leocadio Machado.
Aerial photo source: SDI Canarias (Canary Islands' Government-Grafcan S.A.).

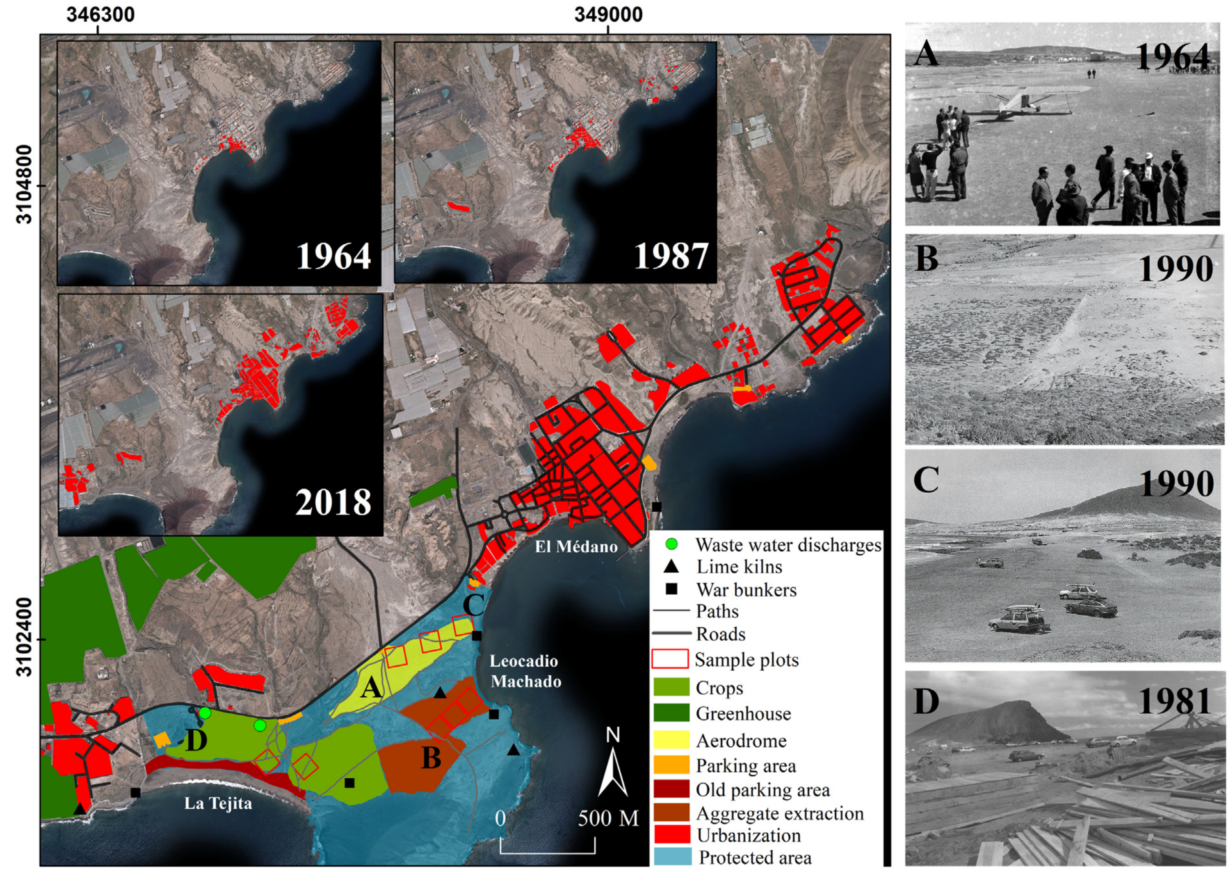

Fig. 4. Left: Main historical land uses in the study area and built surface in 1964, 1987 and 2018. Orthophoto source: SDI Canarias (Canary Islands Government-Grafcan S.A.). Right: A: Aerodrome (Author: Alemany Nuez, P., 1964); B: Aggregate extraction (Author: García-Casanova, J., 1990); C: Car parking areas at Leocadio Machado beach (Author: García-Casanova, J., 1990); D: Car parking area and materials for building at La Tejita beach (ATAN, 1989).

was inaugurated in the south of the island. The urban development work proposed years earlier finally began in 1985 and led to the disappearance of various plant communities, including the groves of *Tamarix canariensis* (Table 3) shrubs which were situated next to the pier covering an area of 0.01 km^2 and forming part of the El Cabezo aeolian landforms (ATAN, 1989).

4.1.4. From 1987 to the present day

In 1987, Montaña Roja and the sandy corridor between Leocadio Machado beach and La Tejita were declared a Nature Reserve of National Interest (Law 12/1987, of June 19, on the Declaration of Natural Spaces of the Canary Islands). The same area was reclassified in 1994 as a Special Nature Reserve (Law 12/1994, of December 19, on Natural Areas of the Canary Islands). However, the associated planning instrument for the protection of the area (Master Plan) was not definitively approved until October 2004. While most of the activities that used to be carried out have now ceased, some of their impacts remain, including for example, the dumped debris and sewage, the effects of the continuous transit of vehicles that accessed the beach (Fig. 4C and D) or the conditioning of the esplanade of the beach of La Jaquita for soccer practice. The elimination of road traffic inside the aeolian system was one of the most important protection results. In 2001, when the Tenerife Government began its Trail Rehabilitation Program, the tracks were closed to road traffic and a car parking area was created north of La Tejita beach. Finally, in 2013 a wall was built around the Montaña Pelada sector with the aim of stopping the flow of sand towards the interior of the urbanization. Despite the environmental protection that was afforded by the legislation described above, the brake on human impacts was insufficient to maintain or restore the natural dynamics of the system, unlike what happened in other wind sedimentary systems which did in fact benefit from the same legislation (Santana-Cordero et al., 2016a). The result of the evolution of human uses has been a reduction (between 1964 and 2018) in the areas occupied by nebkhas to 0.69 km^2 and an increase in flooded surfaces (0.04 km^2). In addition, a significant amount of land has been occupied by urbanization (0.4 km^2) or degraded surfaces (0.4 km^2) for the creation of car parking lots, debris dumping or plots whose construction was abandoned (Table 3). There has also been a recovery in the populations of *T. moquinii* since 1987 and an increase in the length of the foredune on Leocadio Machado beach from 102.8 m in 1987 to 257 m in 2018 (Fig. 3). Likewise, new deposits of pyroclasts have been observed that have become detached from the volcanic cones present in the limits of the wind system.

The reconstruction of the historical land uses shows that the impact that traditional activities had on the ecosystem was very limited, unlike other similar ecosystems such as the coastal dunes of Israel (Tsoar and Blumberg, 2002; Kutiel et al., 2004; Levin and Ben-Dor, 2004) or other such systems in the Canary Islands (Marrero-Rodríguez et al., 2020; Santana-Cordero et al., 2016a). This seems to be due to the existence of abundant pine forest resources in the vicinity and the late occupation of this system and its surroundings. In El Médano, only a small sector was used for agriculture and seasonal grazing when climatic conditions were unfavorable at higher altitudes. It is the more recent land uses, which have mostly taken place since 1947 with the construction of the old airfield (urbanization, development of transport roads, aggregate extraction, recreational uses, among others), that are in all probability responsible for the widespread degradation in the system (Fig. 5), as has been demonstrated in places such as Fire Island in New York and other sites in the Canary Islands (Nordstrom and McCluskey, 1985; Nordstrom, 1994; Nordstrom, 2004; Cabrera-Vega et al., 2013; Hernández-Calvento et al., 2014; García-Romero et al., 2016).

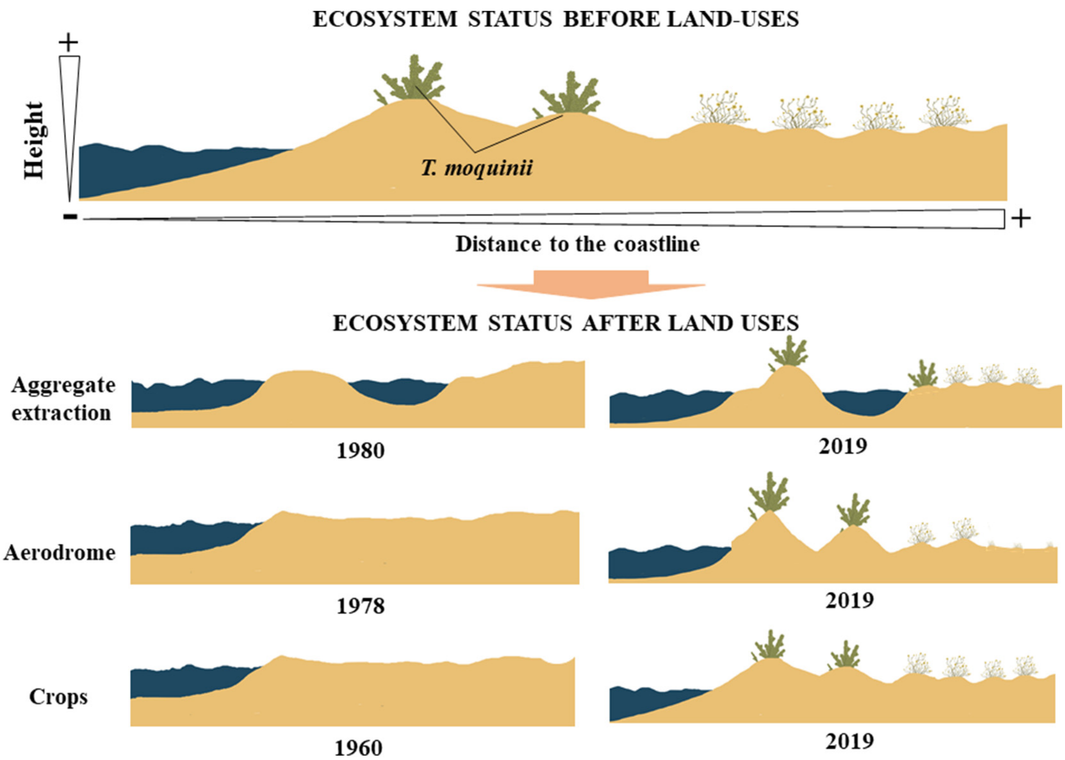

Fig. 5. Ecosystem status before and after the historical land uses analyzed in this paper.

4.2. Statistical analysis of the biogeomorphological processes/gradients in the sample plots

Statistically significant differences were found between the three identified historical land uses in the variables studied: morphological variables - *height* ($p < 0.01$; K-W test X^2 62.3), *longitudinal axis* ($p < 0.01$; K-W test X^2 22.3) and *transverse axis* ($p < 0.001$; K-W test X^2 16.6); vegetation variables - *cover* ($p < 0.05$; K-W test X^2 145.1), *T. moquinii* distribution ($p < 0.01$; K-W test X^2 13.7) and *species richness* ($p < 0.01$; K-W test X^2 13.6); and plant status variables - *dry plants* ($p < 0.0001$; K-W test X^2 13.5) and Dry front ($p < 0$; K-W test X^2 30.1). No statistically significant differences were found between the different historical land uses for the variable *exhumed roots* (Table 4).

With respect to *height*, *longitudinal axis* and *transverse axis*, the dunes situated in the *crop cultivation* area are higher than those situated in the *aggregate extraction* and *aerodrome* areas, while no significant differences were found in the morphological variables between the latter two land uses. Crop cultivation ceased in the 1960s, and the period of time that has passed since then may have enabled the recovery of the corresponding plots. This recovery may also be due to the greater sand supply of the dunes, a fundamental factor in dune size (Davidson-Arnott and Law, 1990), and not to exposure as detected by van Puijenbroek et al. (2017), because in this case the aerodrome and aggregate extraction areas are more exposed. Perhaps in the case of El Médano, exposure is not significant because there are no seasonal changes throughout the year (unlike temperate regions), and the main reason for recovery is sand supply because its origin is a mixture of inland sources (local ravines, with rainfall) and marine sources (practically all year).

The *crop cultivation* area has the highest *cover* and also the lowest *species richness*. This may be because the crops, being fertilized, can give rise to the growth of opportunistic plants (ruderal and generalist species) which replace other native or indigenous species, reducing the richness of species (Nordstrom, 2003; Levin et al., 2007). There is a lower presence of *T. moquinii* specimens in the *aggregate extraction* area than in the *aerodrome* or *crop cultivation* areas (Dunnett's test Extr.-Cult. Mean dif = −0.112, $p = 0.036$; Dunnett's test Extr.-Aero. Mean dif = −0.160, $p = 0.001$), with no statistically significant differences between the latter two areas. The results also show a statistically significant higher number of plants with *dry plants* in the *aggregate extraction* area than in the *crop cultivation* or *aerodrome* areas, again with no statistically significant differences between the latter two areas. Likewise, the *aggregate extraction* area has the highest number of plants with *dry front*, and the *aerodrome* area more than the *crop cultivation* area. In this case, the exposure of the dunes is an important factor for vegetation development (Moreno-Casasola, 1986; Hesp, 2002).

With respect to *distance to the coast*, a gradient was found in terms of nebkha dimensions. The dimensions decrease as *distance to the coast* increases, as seen in the morphological parameters *height* (Spearman's rho = −0.806, $p < 0.01$) (Fig. 4), *longitudinal axis* (Spearman's rho = −0.765, $p < 0.01$) and *transverse axis* (Spearman's rho = −0.765, $p < 0.01$). This may be due to plant height diminishing as the distance to the coast increases. The plants which attain a greater height (as *Traganum moquinii*) tend to occur with less frequency further inland and increase in the first few meters of the foredune, as also reported for other arid dune systems (Hernández-Cordero et al., 2015b). That is to say, on the one hand the vegetation modifies the deposition of the sand (Hesp, 1983; Arens, 1996; Keijsers et al., 2014) and, on the other, the highest dunes in the first few meters of the foredune can affect the wind flow pattern, thus affecting sand deposition (Walker and Nickling, 2002). This causes exposed nebkhas to present a higher overall growth compared to protected (i.e. inland) nebkhas (van Puijenbroek et al., 2017).

4.2.1. Aerodrome

Important differences were found in dune morphology between the different plots of the *aerodrome* area, with a gradient in the morphological variables of the nebkhas which is dependent on *distance to the coast* as for example the height ($R^2 = 0.6524$). The height of the closest dunes to the beach (sample plot A1) was generally above 1 m, whereas those

Table 4
Kruskal-Wallis test results. Significant at 0.05 (bilateral).

Contrast statistics (a,b)										
	Height	Axis_Long	Axis_Trans	Cover	*T. moquinii*	Species richness	Exhumed roots	Dry plants	Dry front	Coast distance
X^2	62.3	22.4	16.6	145.1	13.7	13.6	4.6	13.5	30.1	48.6
p	0	0	0	0	0.001	0.001	0.102	0.001	0	0
a	Kruskal-Wallis test									
b	Grouping variable: area									

in the third plot (A3) did not exceed 0.5 m (Fig. 6). The same pattern is repeated for dune *longitudinal axis* and *transverse axis*, which in both cases present a negative correlation with *distance to the coast* (Spearman's rho = −0.765; $p < 0.01$, in both cases) (Table 5). Given this correlation between dune morphology (*height*, *longitudinal axis* and *transverse axis*) and *distance to the coast*, it can justifiably be argued that there exists a gradient of recovery and that the foredune affected by this historical land use is now stabilized, allowing plant species to establish themselves (Hesp, 2002). The dunes closest to the coast are the first to undergo recovery, whereas the speed of recovery is slower for the dunes further away from the coast as they take longer to begin to capture sediment in significant amounts. In addition, the pattern of lower nebkha height as the distance to the coast increases is related to the decrease in the number of larger-sized plant species, such as *T. moquinii*.

Distance to the coast also shows a strong correlation with *cover*, the presence of *T. moquinii* and *species richness* in the *aerodrome* area (Table 5). *Cover* (Spearman's rho = −0.574, $p < 0.01$) shows the same trend as that observed in the case of the morphological variables (*height*, *longitudinal axis* and *transverse axis*), generally exceeding 65% in the first two plots, but failing to exceed 40% in the third. This same trend is also seen with the presence of *T. moquinii* (Spearman's rho = −0.557, $p < 0.01$), which decreases as *distance to the coast* increases. Changes in *species richness* are also complex, with a higher number of species observed in the first and second plots (11 and 10, respectively) than in the third (7). Species richness in the first two plots may be related to the fact that the shrub plants (*T. moquinii*, *L. arborescens*, among others) fix the sand and thereby change the environmental conditions (Brown and Porembski, 1997; Blank et al., 1998; El-Bana et al., 2002b), generating patches of water availability that allow herbaceous plants to establish themselves (e.g. L. *sessilifolius*). A further factor that needs to be taken into account is the higher sediment input in plots closer to the coast. There is also an important variation of species between plots (Fig. 7), with *T. moquinii* and L. *arborescens* dominating the plot closest to the coastline along with a high number of plants associated to them, such as *P. nivea*, *S. vermiculata* and *C. maritima*. In the second plot, *T. moquinii* and *L. arborescens* are less abundant, and *P. nivea*, *S. vermiculata* and *S. sericea* become the dominant species. Finally, in the third plot, along with *S. vermiculata* and *P. nivea*, there is a larger number of *F. capitata* and L. *pectinatum* individuals. This pattern is similar to that described for Maspalomas by Hernández-Cordero et al. (2015b), in that the gradient with the distance to the coastline and the topography are factors that influence the establishment of individual plant communities depending on their ecological requirements.

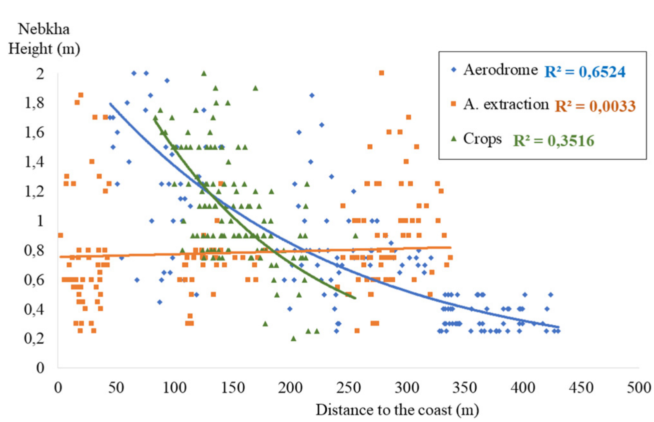

Fig. 6. Relationship between distance to the coast (m) and nebkha height (m) in the aerodrome, aggregate extraction and crop cultivation areas.

Table 5
Multiple comparisons (Dunnett's test) results. *Significant at 0.05 (bilateral). A = Aerodrome. E = Aggregate extraction. C = Crops.

Variables	Historical land uses		Dunnett's test	Sig.
Height	A	C	−0.29378(*)	0
	E	C	−0.29411(*)	0
	E	A	−0.00033	1
Axis_Long	A	C	−0.63137	0.461
	E	C	0.70049	0.4
	E	A	1.33186(*)	0.033
Axis_Trans	A	C	−0.34924	0.494
	E	C	−0.08364	0.958
	E	A	0.2656	0.632
Cover	A	C	−35.12686(*)	0
	E	C	−26.78374(*)	0
	E	A	8.34312(*)	0.002
T. moquinii	A	C	0.048	0.475
	E	C	−0.112(*)	0.036
	E	A	−0.160(*)	0.001
Species richness	A	C	0.414(*)	0.006
	E	C	0.411(*)	0.007
	E	A	−0.004	0.999
Dry plants	A	C	−0.004	0.994
	E	C	0.146(*)	0.006
	E	A	0.150(*)	0.002
Dry front	A	C	0.093(*)	0.028
	E	C	0.215(*)	0
	E	A	0.123(*)	0.001
Distance to the coast	A	C	89.69411(*)	0
	E	C	10.63572	0.575
	E	A	−79.05839(*)	0

4.2.2. Aggregate extraction

With respect to the *aggregate extraction* area, the most important consequences have been in the extractions made below sea level, the subsequent disruption to the original slope, and the elimination of the surface sand sheet, as occurs in other ecosystems with similar characteristics (Fernández-Montoni et al., 2014; Price et al., 2005; Garriga-Sintes et al., 2017). As a result of the extractions, an underground filtering of sea water generates a lagoon at high tide. However, in this case, the trend shown by the morphological and vegetation variables is for them to increase with *distance to the coast* (Table 6), with the exception of the *T. moquinii* variable (Spearman's rho = −0.395; $p < 0.01$). This trend is the opposite to that observed in both the *crop cultivation* and *aerodrome* plots. In addition, the variables show low or very low levels of correlation (with the exception of *species richness*: Spearman's rho = 0.606, $p < 0.01$). Such patterns are not common and are difficult to explain in systems with natural sedimentary dynamics. In this particular case, as can be seen in Fig. 4 (Aggregate extraction, R^2: 0.0033), the effect of aggregate extraction has been such that there is presently very little indication of a morphological gradient as was observed in the area affected by the aerodrome. Distance to the coast cannot therefore

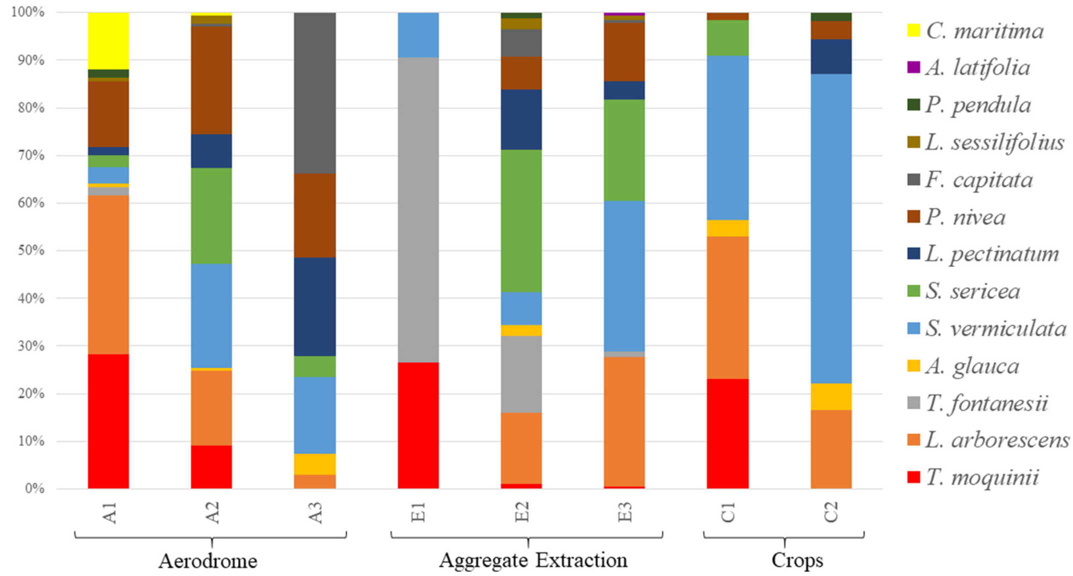

Fig. 7. Plant species in the nebkhas of each plot.

be considered a determining factor as it was in the *aerodrome* area (*height*: Spearman's rho = 0.195, $p < 0.05$; *length*: Spearman's rho = 0.363, $p < 0.01$; *width*: Spearman's rho = 0.237, $p < 0.01$) (Table 6). As a consequence of the topographic modifications generated by the extractions, changes have occurred in the capacity of the vegetation to recolonize the modified surface and, therefore, in the volume of retained sand, as shown by Durán and Moore (2013). In this respect, *T. moquinii*, a crucial element in coastal dune formation (Hernández-Cordero et al., 2015a, 2015b) is only present in significant numbers in the first plot (E1), whereas further inland it is practically non-existent (Fig. 7).

There are also important variations with respect to *species richness* when compared with the *crop cultivation* and *aerodrome* areas. In this case, there has been an alteration of the natural characteristics, disrupting the influence of natural gradients (Nordstrom, 2008). In consequence, the presence is found in the first plot of only *T. moquinii*, *T. fontanesii* and *S. vermiculata* (Fig. 7), whereas in the other plots a total of 11 plant species are found. These three species form halophilic plant communities which can tolerate moderate waterlogging of the substrate. In addition, as reported by Hernández-Cordero et al. (2017), *T. fontanesii* evinces erosion processes as seen by the high presence of exhumed roots in the foredune. However, the extractions that were made below sea level have resulted in the creation of a lagoon which has a continuous water content and fills up at high tide through filtration from the beach. As no plants in the area are able to tolerate these conditions, no colonization is taking place and, consequently, no sediment accumulation, as was also detected in Ley et al. (2007). The sand is being fixed by the vegetation in the plots further inland where the extraction activities only eliminated the surface sand sheet. Thus, species richness has been altered as a result of changes in the influence of natural factors, including wind-borne sediment input, sea water flooding, topographic characteristics, and the influence of the water table, among others (e.g. Moreno-Casasola, 1986; Ehrenfeld, 1990; Dech and Maun, 2005; Lortie and Cushman, 2007). The recovery process in the *aggregate extraction* area differs depending on the plot in question and the type of extraction that was performed. As in other ecosystems (Price et al., 2005), the zones where the extractions were topographically more significant have had a lower capacity for recovery than where only surface extraction of materials took place.

With respect to volumetric changes (Fig. 8), it can be seen that accumulation processes are only taking place in the foredune where vegetation is present (especially *T. moquinii*). The rest of the area shows generalized erosion processes taking place between 2009 and 2015, especially in the lagoon sector where the DEM profiles reveal a reduction in height. However, an increase in vegetation can also be observed in the coastal dune and inland sectors.

Table 6
Spearman's correlation between distance to the coast and nebkha morphological variables, vegetation variables and plant status variables in the aerodrome, aggregate extraction and crop cultivation areas. **Correlation significant at 0.01 (bilateral). *Correlation significant at 0.05 (bilateral).

	Distance to the coast					
	Aerodrome $N = 174$		Aggregate extraction $N = 164$		Crops $N = 123$	
	Spearman's Corr.	Sig.	Spearman's Corr.	Sig.	Spearman's Corr.	Sig.
Morphology						
Height	−0.806(**)	0	0.195(*)	0.012	−0.208(*)	0.021
Axis_Long	−0.765(**)	0	0.363(**)	0	−0.117	0.197
Axis_Trans	−0.765(**)	0	0.237(**)	0.002	−0.178(*)	0.049
Vegetation						
Cover	−0.574(**)	0	0.136	0.082	−0.198(*)	0.028
T. moquinii	−0.557(**)	0	−0.395(**)	0	−0.096	0.293
Species richness	−0.376(**)	0	0.606(**)	0	0.145	0.11
Plant status						
Dry plants	−0.172(*)	0.023	−0.152	0.053	−0.055	0.543
Exhumed roots	−0.190(*)	0.012	−0.154(*)	0.049	0.071	0.433
Dry front	−0.353(**)	0	0.322(**)	0	−0.17	0.06

4.2.3. Crops

In the *crop cultivation* area, no statistically significant differences were found between various variables (*length*, *species richness*, *T. moquinii*, *dry plants*, *dry front* or *exhumed roots*) and *distance to the coast* (Table 6). This pattern is reinforced by the absence of any significant correlation at the $p < 0.01$ level. Statistically significant correlations at the $p < 0.05$ level were obtained in just 3 variables, though these were low or very low (*height*: Spearman's rho = −0.208, $p < 0.05$; *width*: Spearman's rho = −0.178, $p < 0.05$; *cover*: Spearman's rho = −0.198 $p < 0.05$). Thus, *distance to the coast* is not a determining factor in the

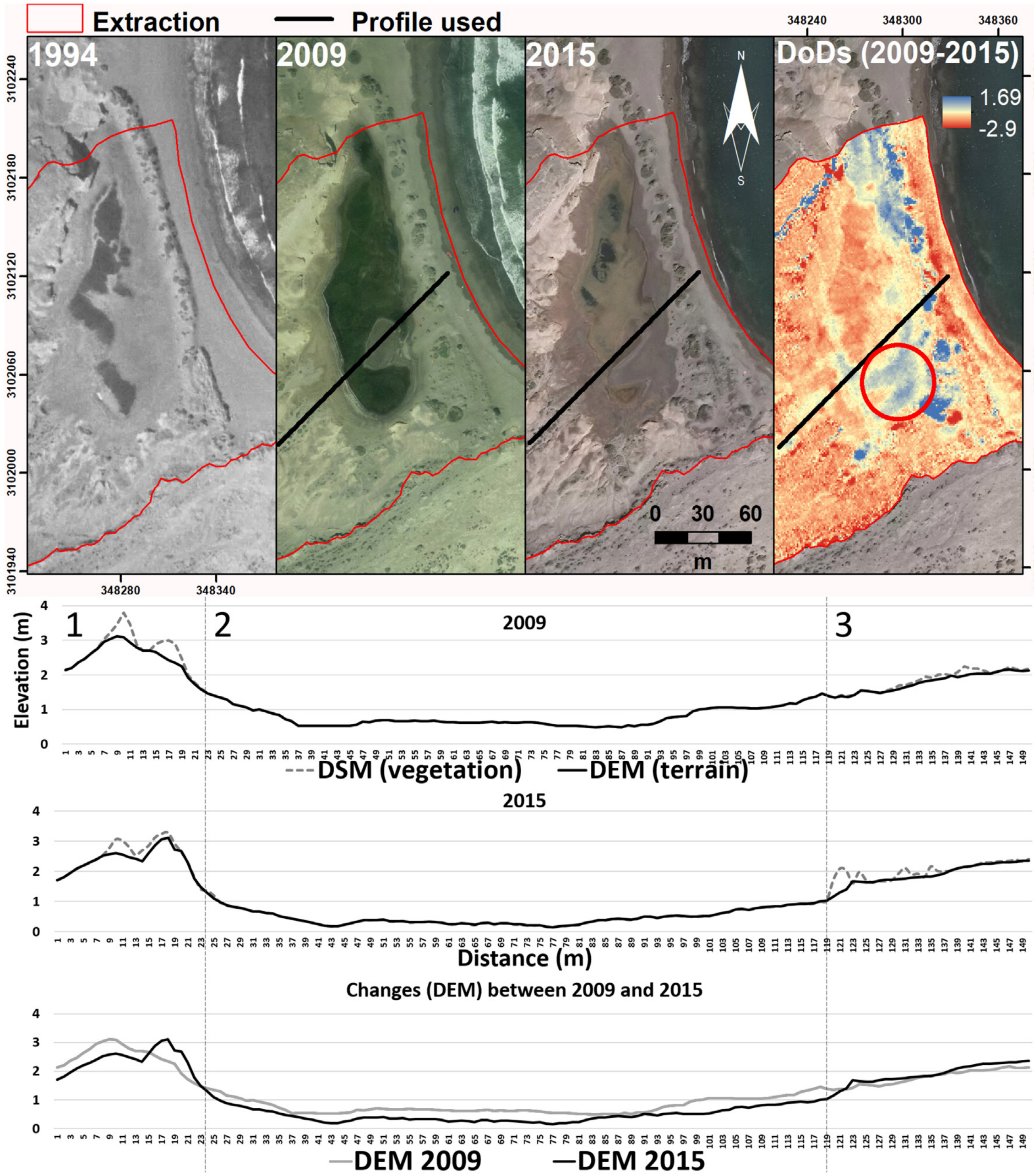

Fig. 8. Above left and center: Biogeomorphological evolution of the aggregate extraction area between 1994 and 2015, especially in the foredune. Above right: DoDs (2009–2015): Erosion and accumulation near the foredune and lagoon. Below: 2009 and 2015 DEM profiles (terrain and vegetation) extracted using LiDAR measurements. 1: Area closest to the coastline. 2: Lagoon area. 3: Area further southwest.

crop area variables. The morphological variables of nebkha *height* and *width* presented the highest correlations. The correlation with *height* was greater than in the *aggregate extraction* area and, as in the case of the *aerodrome* area, the correlations were negative. Again, the pattern, though not statistically significant (Fig. 4, Crops; R^2: 0.3516), is common in the formation and development of the foredune and dune systems (Hesp, 2002). With respect to the plant species, *T. moquinii* is found in the foredune (Plot C1) along with L. *arborescens* and *S. vermiculata* as well as specimens of some other plants in fewer numbers. The most dominant plant by far in the nebkhas of the second plot is *S. vermiculata*.

Special mention should also be made of the abundant presence of *Mesembryanthemum crystallinum* specimens in nebkhas in areas of low sediment accumulation. Although this plant species does not appear in Fig. 6, *M. crystallinum* has been identified as being indicative of the presence of heavy metals (Ghnaya et al., 2007) and tends to be found in areas of agricultural practices and other anthropic activities (Del Arco et al., 2010), which explains why it appears only in the crops area.

4.3. Relationships between current biogeomorphological processes and historical land uses

The current biogeomorphological processes that are taking place are the result of changes induced in the landscape by historical land uses (Fig. 5). In this sense, the distance from the coastline and the conservation of the characteristic topography of the system seem to be two key elements in the biogeomorphological recovery process (Fig. 9). These two factors have been influenced and altered by historical land uses. Areas where waterlogging was practically zero now remain flooded the entire year, changes in sediment accumulation areas have been

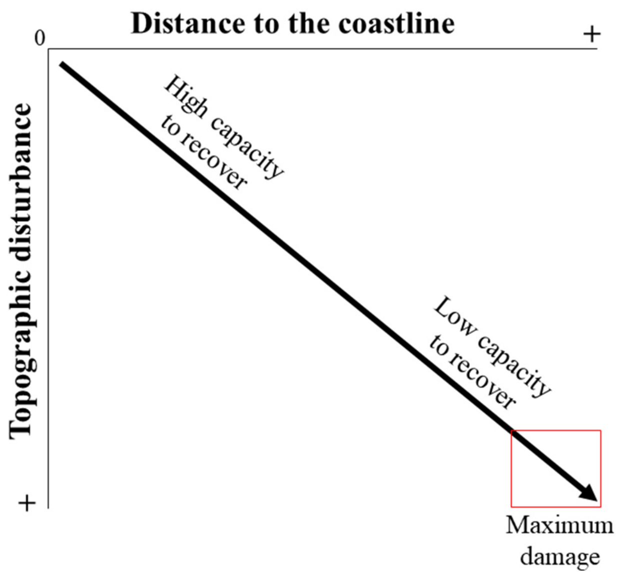

Fig. 9. Conceptual diagram showing the relationship between the capacity of the system to recover related to the distance to the coastline and the topographic disturbance.

induced, and the initial topography of the basement on which the aeolian landforms are located has been altered.

The anthropic modifications of climatic and topographic factors uncovered in the present study are in addition to other alterations that have been found in similar systems such as Maspalomas (Canary Islands, Spain), where urbanization resulted in wind flow modification (García-Romero et al., 2019a) and changes to the coastline (Hernández-Cordero et al., 2018). The historical land uses determined in the present study have impacted on the characteristics of the current aeolian landforms (nebkhas) and the distribution of plant species, as described in the previous section. Climatic, ecological and topographic factors are essential elements in the proper functioning and natural recovery capacity of the system and, therefore, any alteration to these factors must be taken into account when carrying out restoration and management tasks. In reference to plant communities, it is important to emphasize that species richness increases as the level of stress associated with a high degree of environmental alteration decreases. In this respect, A3 is the most degraded plot of the *aerodrome* area and the one with the least number of species. In the case of the *crop cultivation* area, the plots have a lower level of stress due to the low degradation of the topography and the pyroclastic cover added by farmers that helps plant colonization by retaining moisture.

While the human uses of the system have been an important factor in its biogeomorphological evolution, other factors are also involved which will need to be considered in future studies. Among these factors are the possible reduction in the contribution of sediments from the erosion of land deposits (Alcántara-Carrió et al., 2010; Alonso et al., 2011) and in marine contributions whose decrease has been determined in other systems of the archipelago (Cabrera Vega, 2010; Hernández-Calvento et al., 2014), climate change (Petit and Prudent, 2010), and the presence of invasive alien species in the study area such as *Oryctolagus cuniculus*.

Nonetheless, the present work shows that historical land uses have had more varied consequences than the elimination of vegetation cover and the consequent remobilization of sediments which have been found in other arid aeolian sedimentary systems of the Canary Islands (Marrero-Rodríguez et al., 2020; Santana-Cordero et al., 2016a). Specifically, in relation to each land use, other consequences were identified: sand compaction to facilitate the takeoff of aircraft in the case of the aerodrome; the breaking of the slope, remobilization of sand sheets, excavation below sea level and the reduction of sediment available in the system, in the case of aggregate extraction; finally, in the case of the crop cultivation area, there has been a massive use of phytosanitary products and fertilizers and the area is covered with pyroclasts which retain moisture. All of these factors have conditioned the evolution of the landforms and vegetation after the cessation of the corresponding uses.

The methodology applied in the present work can be of interest not only for areas with similar historical land uses, characteristics and processes as in El Médano, but also for semi-temperate regions (Mediterranean, for example) where there is a growing possibility of aridification due to climate change and other historical land uses that have featured in aeolian sedimentary systems.

5. Conclusions

The environmental changes that have taken place in the aeolian sedimentary system of El Médano (Canary Islands, Spain), as well as the current biogeomorphological processes, have been shown in the present study to be strongly influenced, along with other factors, by historical land uses. The system presents different responses to the three uses studied (*aerodrome*, *aggregate extraction* and *crop cultivation*), but it seems that the distance to the coastline and the conservation of the characteristic topography of the system are the two most important factors in the biogeomorphological recovery process. The second of these two factors have been influenced and altered by historical land uses creating flooded areas due to alterations to the initial topography of the system basement (E1 and E2). This can be seen in the plots where the topography was not altered (A1, A2, A3, C1 and C2), as the status of the system is closer to the ideal status as described in the scientific literature and to full environmental recovery. Low level impacts such as crops might not necessary lead to the loss of too much sediment from the system and recover relatively fast when the anthropogenic stress is removed. However, when there is a level of impact that involve removing sediment from the system, the clearest example of this being sand extractions, these result in negative sediment budgets due to intense 'topographic damage'. The results indicate that these areas didn't recover in 40 years, and that the higher the distance to the coast is, the less they have recovered. It can therefore be concluded that the historical land uses analyzed in the present study have had more varied consequences than those determined to date for arid aeolian sedimentary systems of the Canary Islands, namely the elimination of vegetation cover and the consequent removal of sediments. When the land uses cease, the system does not return to its natural conditions but adapts and reorganizes depending on the new conditioning factors (topography, availability of sediments, vegetation's ability to recolonize degraded areas, among others). This research also helps us to understand that sometimes different environmental patterns in the same system may not be natural but rather the result of human activity and historical land uses. Such knowledge can be especially useful to help make correct and more appropriate decisions for the management of such areas.

Declaration of competing interest

The authors declare that there is not conflict of interest.

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References

Alcántara-Carrió, J., Alonso, I., Hernández, L., Pérez-Chacón, E., Romero, L.E., 1996. Landscape evolution and human alterations of the aeolian sediment dynamics in the Jandía Isthmus (Fuerteventura, Spain). Partnership in Coastal Zone Management. Samara Publ. Ltd., Cardigan, pp. 283–290.

Alcántara-Carrió, J., Fernández-Bastero, S., Alonso, I., 2010. Source area determination of aeolian sediments at Jandia Isthmus (Fuerteventura, Canary Islands). J. Mar. Syst. 80 (3–4), 219–234.

Alonso, I., Sánchez-Pérez, I., Rodríguez, S., Pejenaute, I., Hernández, A., Menéndez, I., ... Pérez-Chacón, E., 2007. Aeolian dynamics changes due to the obstacle generated by Traganum moquinii. Proceeding of International Conference on Management and Restoration of Coastal Dunes ICCD 2007, pp. 11–18.

Alonso, I., Hernández, L., Alcántara-Carrio, J., Cabrera, L., Yánez, A., 2011. Los grandes campos de dunas de Canarias. In: Sanjaume, E., Gracia, J. (Eds.), Las Dunas de España. Sociedad Española de Geomorfología, pp. 467–496.

Arens, S.M., 1996. Patterns of sand transport on vegetated foredunes. Geomorphology 17, 339–350. https://doi.org/10.1016/0169-555X(96)00016-5.

Arens, S.M., Slings, Q.L., Geelen, L.H., Van der Hagen, H.G., 2013. Restoration of dune mobility in the Netherlands. Restoration of Coastal Dunes. Springer, Berlin, Heidelberg, pp. 107–124.

ATAN, 1989. Plan de restauración paisajística de El Cabezo, Santa Cruz de Tenerife. ATAN (66 pp.).

Barbier, E.B., Hacker, S.D., Kennedy, C., Koch, E.W., Stier, A.C., Silliman, B.R., 2011. The value of estuarine and coastal ecosystem services. Ecol. Monogr. 81 (2), 169–193. https://doi.org/10.1890/10-1510.1.

Blank, R.R., Young, J.A., Trent, J.D., Palmquist, D.E., 1998. Natural history of a saline mound ecosystem. Great Basin Naturalist 58, 217–230.

Brown, G., Porembski, S., 1997. The maintenance of species diversity by miniature dunes in a sand depleted *Haloxylon salicornicum* community in Kuwait. J. Arid Environ. 37, 461–473. https://doi.org/10.1006/jare.1997.0286.

Bürgi, M., Gimmi, U., 2007. Three objectives of historical ecology: the case of litter collecting in Central European forest. Landsc. Ecol. 22, 77–87. https://doi.org/10.1007/s10980-007-9128-0.

Cabrera Vega, L.L., 2010. Sedimentología, estratigrafía, dinámica sedimentaria y evolución de El Jable (Lanzarote). Propuesta de gestión. Universidad de Las Palmas de Gran, Canaria (Doctoral dissertation). (252 pp.).

Cabrera-Vega, L.L., Cruz-Avero, N., Hernández-Calvento, L., Hernández-Cordero, A., Fernández-Cabrera, E., 2013. Morphological changes in dunes as an indicator of anthropogenic interferences in arid dune fields. J. Coast. Res. 65, 1271–1276. https://doi.org/10.2112/SI65-215.1.

Criado, C., Yanes, A., Hernández, L., Alonso, I., 2011. Origen y formación de los depósitos eólicos en Canarias. In: Saumell, E. Sanjaume, Prieto, F.J. Gracia (Eds.), Las Dunas en España. Sociedad Española de Geomorfología, Cádiz, pp. 447–465.

Curr, R.H.F., Koh, A., Edwards, E., Williams, A.T., Davies, P., 2000. Assessing anthropogenic impact on Mediterranean sand dunes from aerial digital photography. J. Coast. Conserv. 6, 15–22.

Davidson-Arnott, R.G.D., Law, M.N., 1990. Seasonal patterns and controls on sediment supply to coastal foredunes, Long Point Lake Erie. Coastal Dunes: Forms and Process. Wiley, London, UK, pp. 177–200.

De Olive, P.M., 1885. Diccionario estadístico-administrativo de las Islas Canarias. Estab. tip. de J. Jepús.

Dech, J.P., Maun, M.A., 2005. Zonation of vegetation along a burial gradient on the leeward slopes of Lake Huron sand dunes. Can. J. Bot. 83 (2), 227–236. https://doi.org/10.1139/b04-163.

Del Arco, M.J., González-González, R., Garzón-Machado, V., Pizarro-Hernández, B., 2010. Actual and potential natural vegetation on the Canary Islands and its conservation status. Biodivers. Conserv. 19 (11), 3089–3140. https://doi.org/10.1007/s10531-010-9881-2.

Delgado-Fernández, I., O'Keeffe, N., Davidson-Arnott, R.G.D., 2019. Natural and human controls on dune vegetation cover and disturbance. Sci. Total Environ. 672, 643–656. https://doi.org/10.1016/j.scitotenv.2019.03.494.

Delgado-Fernandez, I., Davidson-Arnott, R., Hesp, P., 2019. Is 're-mobilizaiton' nature restoration or nature destruction? A commentary. J. Coast. Conserv. 23, 1093–1103.

Dolnik, C., Peyrat, J., Volodina, A., Sokolov, A., 2011. Neophytic Coripsermum pallasii(stev.) (chenopodiaceae) invading migrating dunes of the southern coast of the Baltic Sea. Pol. J. Ecol. 59 (1), 95–103.

Durán, O., Moore, L.J., 2013. Vegetation controls on the maximum size of coastal dunes. Proc. Natl. Acad. Sci. 110 (43), 17217–17222. https://doi.org/10.1073/pnas.1307580110.

Ehrenfeld, J.G., 1990. Dynamics and processes of barrier-island vegetation. Rev. Aquat. Sci. 2 (3–4), 437–480.

El-Bana, M.I., Khedr, A., Van Hecke, P., Bogaert, J., 2002a. Vegetation composition of a threatened hypersaline lake (Lake Bardawil), North Sinai. Plant Ecol. 163, 63–75. https://doi.org/10.1023/A:1020351704409.

El-Bana, M.I., Nijs, I., Kockelbergh, F., 2002b. Microenvironmental and vegetational heterogeneity induced by phytogenic nebkhas in an arid coastal ecosystem. Plant Soil 247, 283–293. https://doi.org/10.1023/A:1021548711206.

El-Bana, M.I., Nijs, I., Khedr, A.H.A., 2003. The importance of phytogenic mounds (Nebkhas) for restoration of arid degraded rangelands in Northern Sinai. Restor. Ecol. 11 (3), 317–324. https://doi.org/10.1046/j.1526-100X.2003.00222.x.

Escolar Serrano, F., 1984. Estadística de Las Islas Canarias, 1793–1806. Las Palmas de Gran Canaria. Ed. Caja Insular de Ahorros.

Everard, M., Jones, L., Watts, B., 2010. Have we neglected the societal importance of sand dunes? An ecosystem services perspective. Aquat. Conserv. Mar. Freshwat. Ecosyst. 20 (4), 476–487. https://doi.org/10.1002/aqc.1114.

Faggi, A., Dadon, J., 2011. Temporal and spatial changes in plant dune diversity in urban resorts. J. Coast. Conserv. 15, 585–594. https://doi.org/10.1007/s11852-011-0148-1.

Fernández-Montoni, M.V., Fernández-Honaine, M., Del Río, J.L., 2014. An assessment of spontaneous vegetation recovery in aggregate quarries in coastal sand dunes in Buenos Aires province, Argentina. J. Environ. Manag. 54 (2), 180–193. https://doi.org/10.1007/s11852-011-0148-1.

Fogerty, J.E., 2005. Oral history: a guide to its creation and use. In: Egan, D., Howell, E.A. (Eds.), The Historical Ecology Handbook. Island Press, Washington DC, pp. 101–120.

Fritschle, J.A., 2009. Pre-EuroAmerican settlement forests in redwood national park, California, USA: a reconstruction using line summaries in historic land surveys. Landsc. Ecol. 24 (6), 833–847. https://doi.org/10.1007/s10980-009-9361-9.

García-Casanova, J., Rodríguez-Delgado, O., Wilpret-De La Torre, W., 1996. Montaña Roja. Naturaleza e historia de una Reserva Natural y su entorno (El Médano- Granadilla de Abona). Centro de la Cultura Popular Canaria, Tenerife (404 pp.).

García-Romero, L., Henández-Cordero, A., Fernandéz-Cabrera, E., Peña, C., Hernández-Calvento, L., Pérez-Chacón, E., 2016. Urban-touristic impacts on the aeolian sedimentary systems of the Canary Islands: conflict between development and conservation. Island Studies Journal 11 (1), 91–112. http://www.islandstudies.ca/sites/islandstudies.ca/files/ISJ-11-1-E-Garcia-Romero-et-al.pdf.

García-Romero, L., Delgado-Fernández, I., Hesp, P.A., Hernández-Calvento, L., Viera-Pérez, M., Hernández-Cordero, A.I., Cabrera-Gámez, J., Domínguez-Brito, A.C., 2019a. Airflow dynamics, vegetation and aeolian erosive processes in a shadow zone leeward of a resort in an arid transgressive dune system. Aeolian Res. 38, 48–59. https://doi.org/10.1016/j.aeolia.2019.03.006.

García-Romero, L., Delgado-Fernandez, I., Hesp, P.A., Hernández-Calvento, L., Hernández-Cordero, A.I., Viera-Pérez, M., 2019b. Biogeomorphological processes in an arid transgressive dunefield as indicators of human impact by urbanization. Sci. Total Environ. 650, 73–86. https://doi.org/10.1016/j.scitotenv.2018.08.429.

Garnasjordet, P.A., Aslaksen, I., Giampietro, M., Funtowicz, S., Ericson, T., 2012. Sustainable development indicators: from statistics to policy. Environ. Policy Gov. 22 (5), 322–336. https://doi.org/10.1002/eet.1597.

Garriga-Sintes, C., Martín-Prieto, J.Á., Roig-Munar, F.X., Rodríguez-Perea, A., 2017. Reactivación del sistema playa-duna de Tirant (N de Menorca) asociada a la falta de gestión y extracción de áridos. Geotemas (Madrid) 17, 167–170.

Ghnaya, T., Slama, I., Messedi, D., Grignon, C., Ghorbel, M.H., Abdelly, C., 2007. Effects of Cd2+ on K+, Ca2+ and N uptake in two halophytes Sesuvium portulacastrum and Mesembryanthemum crystallinum: consequences on growth. Chemosphere 67 (1), 72–79. https://doi.org/10.1016/j.chemosphere.2006.09.064.

Gimmi, U., Bugmann, H., 2013. Preface: Integrating Historical Ecology and Ecological Modeling. , pp. 785–787 https://doi.org/10.1007/s10980-013-9884-y.

Gobierno de Canarias, 2004. Plan Director de la Reserva Natural Especial de Montaña Roja.

Grossinger, R.M., Striplen, C.J., Askevold, R.A., Brewster, E., Beller, E.E., 2007. Historical landscape ecology of an urbanized California valley: wetlands and woodlands in the Santa Clara Valley. Landsc. Ecol. 22 (1 Supplement), 103–120. https://doi.org/10.1007/s10980-007-9122-6.

Hernández-Calvento, L., Jackson, D.W.T., Medina, R., Hernández-Cordero, A.I., Cruz, N., Requejo, S., 2014. Downwind effects on an arid dunefield from an evolving urbanized area. Aeolian Res. 15, 301–309. https://doi.org/10.1016/j.aeolia.2014.06.007.

Hernández-Cordero, A.I., Pérez-Chacón, E., Hernández-Calvento, L., 2006. Vegetation colonisation processes related to a reduction in sediment supply to the coastal dune field of Maspalomas (Gran Canaria, Canary Islands, Spain). J. Coast. Res. 69–76.

Hernández-Cordero, A.I., Pérez-Chacón, E., Hernández-Calvento, L., 2012. La investigación como soporte de la gestión: el ejemplo de la duna costera (foredune) de Maspalomas (Gran Canaria, Islas Canarias). In: Rodríguez-Perea, A., Pons, G.X., Roig-Munar, F.X., Martín-Prieto, J.Á., Mir-Gual, M., Cabrera, J.A. (Eds.), La gestión integrada de playas y dunas: experiencias en Latinoamérica y Europa. Mon. Soc. Hist. Nat. Balears, 19, pp. 289–306.

Hernández-Cordero, A.I., Hernández-Calvento, L., Pérez-Chacón Espino, E., 2015a. Relationship between vegetation dynamics with dune mobility in an arid transgressive coastal system, Maspalomas, Canary Islands. Geomorphology 238, 160–176. https://doi.org/10.1016/j.geomorph.2015.03.012.

Hernández-Cordero, A.I., Pérez-Chacón, E., Hernández-Calvento, L., 2015b. Vegetation, distance to the coast, and aeolian geomorphic processes and landforms in a transgressive arid coastal dune system. Phys. Geogr. 36 (1), 60–83. https://doi.org/10.1080/02723646.2014.979097.

Hernández-Cordero, A.I., Hernández-Calvento, L., Pérez-Chacón Espino, E., 2017. Vegetation changes as an indicator of impact from tourist development in an arid transgressive coastal dune field. Land Use Policy 64, 479–491. https://doi.org/10.1016/j.landusepol.2017.03.026.

Hernández-Cordero, A.I., Hernández-Calvento, L., Hesp, P.A., Pérez-Chacón, E., 2018. Geomorphological changes in an arid transgressive coastal dune field due to natural

processes and human impacts. Earth Surf. Process. Landf. 43 (10), 2167–2180. https://doi.org/10.1002/esp.4382.
Hernández-Cordero, A.I., Peña-Alonso, C., Hernández-Calvento, L., Ferrer-Valero, N., Santana-Cordero, A.M., García-Romero, L., Pérez-Chacón, Espino E., 2019. Aeolian sedimentary systems of the Canary Islands. In: Morales, J.A. (Ed.), The Spanish Coastal Systems. Springer, Cham, pp. 699–725.
Hesp, P.A., 1983. Morphodynamics of incipient foredunes in NSW, Australia. In: Brookfield, M.E., Ahlbrandt, T.S. (Eds.), Eolian Sediments and Processes. Elsevier, Amsterdam, pp. 325–342.
Hesp, P., 2002. Foredunes and blowouts: initiation, geomorphology and dynamics. Geomorphology 48 (1–3), 245–268. https://doi.org/10.1016/S0169-555X(02)00184-8.
Houser, C., Hamilton, S., 2009. Sensitivity of post-hurricane beach and dune recovery to event frequency. Earth Surf. Process. Landf. 34 (5), 613–628. https://doi.org/10.1002/esp.1730.
IGME, 1972. Geological Map 1:25.000. Sheet 1118 - (3-63) Granadilla de Abona. Servicio de publicaciones del ministerio de industria y energía.
Jackson, M.L., Nordstrom, K.L., 2011. Aeolian sediment transport and landforms in managed coastal systems: a review. Aeolian Res. 3 (2), 181–196. https://doi.org/10.1016/j.aeolia.2011.03.011.
Keijsers, J.G.S., Poortinga, A., Riksen, M.J.P.M., Maroulis, J., 2014. Spatio-temporal variability in accretion and erosion of coastal foredunes in the Netherlands: regional climate and local topography. PLoS One 9, e91115. https://doi.org/10.1371/journal.pone.0091115.
King, J., Nickling, W.G., Gillies, J.A., 2006. Aeolian shear stress ratio measurements within mesquite-dominated landscapes of the Chihuahuan Desert, New Mexico, USA. Geomorphology 82 (3–4), 229–244. https://doi.org/10.1016/j.geomorph.2006.05.004.
Kombiadou, K., Costas, S., Carrasco, A.R., Plomaritis, T.A., Ferreira, Ó., Matias, A., 2019. Bridging the gap between resilience and geomorphology of complex coastal systems. Earth Sci. Rev. 102934.
Kutiel, P., Zhevelev, H., Harrison, R., 1999. The effect of recreational impacts on soiland vegetation of stabilised coastal sand dunes in the Sharon Park, Israel. Ocean Coast. Manag. 42, 1041–1060. https://doi.org/10.1016/S0964-5691(99)00060-5.
Kutiel, P., Cohena, O., Shoshany, M., Shubb, M., 2004. Vegetation establishment on the southern Israeli coastal sand dunes between the years 1965 and 1999. Landsc. Urban Plan. 67, 141–156. https://doi.org/10.1016/S0169-2046(03)00035-5.
Levin, N., Ben-Dor, E., 2004. Monitoring sand dune stabilization along coastal dunes of Ashdod-Nizanim, Israel, 1945–1999. J. Arid Environ. 58, 335–355. https://doi.org/10.1016/j.jaridenv.2003.08.007.
Levin, N., Kidron, G.J., Ben-Dor, E., 2007. Surface properties of stabilizing coastal dunes: combining spectral and field analyses. Sedimentology 54, 771–788. https://doi.org/10.1111/j.1365-3091.2007.00859.x.
Ley, C., Gallego, J.B., Vidal, C., 2007. Manual de restauración de las dunas costeras. Dirección General de Costas, Ministerio de Medio Ambiente, Madrid (248 pp.).
López-Soler, J., 1906. Viaje a la Isla de Tenerife. Su descripción general y geografía (160 pp.).
Lortie, C.J., Cushman, J.H., 2007. Effects of a directional abiotic gradient on plant community dynamics and invasion in a coastal dune system. J. Ecol. 95 (3), 468–481. https://doi.org/10.1111/j.1365-2745.2007.01231.x.
Marrero-Rodríguez, N., García-Romero, L., Pérez-Chacón, E., 2019. Identificando los cambios el paisaje por usos históricos en un sistema playa-duna mediante fotografía repetida a largo plazo: el caso de El Médano (Tenerife, islas Canarias). Actas del X Jornadas de Geomorfología Litoral. Castelldefels. 153–156.
Marrero-Rodríguez, N., García-Romero, L., Sánchez-García, M.J., Hernández-Calvento, L., Espino, E.P.C., 2020. An historical ecological assessment of land-use evolution and observed landscape change in an arid aeolian sedimentary system. Sci. Total Environ., 137087 https://doi.org/10.1016/j.scitotenv.2020.137087.
Mederos Martín, A., Escribano Cobo, G., 2016. Prospección arqueológica alrededor del Puerto de Abona y Atalayas de las montañas de Magua, del Puerto y de la Centinela (Arico, Tenerife, Islas Canarias). Anuario de Estudios Atlánticos (37 pp.).
Miththapala, S., 2008. Seagrasses and Sand Dunes. vol. 3. IUCN.
Moreno-Casasola, P., 1986. Sand movement as a factor in the distribution of plant communities in a coastal dune system. Vegetatio 65 (2), 67–76. https://doi.org/10.1007/BF00044876.
Morton, R.A., Paine, J.G., Gibeaut, J.C., 1994. Stages and durations of poststorm beach recovery, southeastern Texas coast. J. Coast. Res. 10, 884908.
Nordstrom, K.F., 1994. Beaches and dunes of human-anthropized coasts. Prog. Phys. Geogr. 18 (4), 497–516. https://doi.org/10.1177/030913339401800402.
Nordstrom, K.F., 2003. Beaches and Dunes of Developed Coasts. Cambridge University Press.
Nordstrom, K.F., 2004. Beaches and Dunes of Developed Coasts. Cambridge University Press.
Nordstrom, K., 2008. Beach and Dune Restoration. Cambridge University Press.
Nordstrom, K.F., McCluskey, J.M., 1985. The effects of houses and sand fences on the eolian sediment budget at Fire Island, New York. J. Coast. Res. 1 (1), 39–46.
Paskoff, R., 1993. Côtes en danger. Practiques de la Géographie, Masson, París (247 pp.).
Paskoff, R., 2001. Dune management on the Atlantic coast of France: a case study. In: Houston, J.A., Edmondson, S.E., Rooney, P.J. (Eds.), Coastal Dune Management. Shared Experience of European Conservation Practice. Proceedings of the European Symposium Coastal Dunes of the Atlantic Biogeographical Region, Southport, NW England, September 1998. Liverpool University Press, pp. 34–40.
Peña-Alonso, C., Gallego-Fernández, J.B., Hernández-Calvento, L., Hernández-Cordero, A.I., Ariza, E., 2018. Assessing the geomorphological vulnerability of arid beach-dune systems. Sci. Total Environ. 635, 512–525. https://doi.org/10.1016/j.scitotenv.2018.04.095.
Pérez-Chacón, E., Hernández-Calvento, L., Hernández-Cordero, A., Máyer-Suárez, P., Pejenaute-Alemán, I., Romero-Martín, L., Sánchez-Pérez, I., Alonso-Bilbao, I., Mangas-Viñuela, J., Menéndez-González, I., Rodríguez-Valido, S., 2007. Estudio de la relación existente entre la dinámica dunar y la vegetación en la Reserva Natural Especial de las Dunas de Maspalomas. Informe Técnico (inédito) para el Cabildo de Gran Canaria (111 pp.).
Petit, J., Prudent, G., 2010. Climate Change and Biodiversity in the European Union Overseas Entities. IUCN, Gland, Switzerland and Brussels, Belgium (178 pp.).
Price, O., Milne, D., Tynan, C., 2005. Poor recovery of woody vegetation on sand and gravel mines in the Darwin region of the Northern Territory. Ecol. Manag. Restor. 6 (2), 118–123. https://doi.org/10.1111/j.1442-8903.2005.00228.x.
Provoost, S., Jones, M.L.M., Edmondson, S.E., 2011. Changes in landscape and vegetation of coastal dunes in northwest Europe: a review. J. Coast. Conserv. 15 (1), 207–226.
van Puijenbroek, M.E., Nolet, C., Groot, A.V.D., Suomalainen, J.M., Riksen, M.J., Berendse, F., Limpens, J., 2017. Exploring the contributions of vegetation and dune size to early dune development using unmanned aerial vehicle (UAV) imaging. Biogeosciences 14 (23), 5533–5549.
Pye, K., Blott, S.J., 2012. A geomorphological survey of Welsh dune systems to determine best methods of dune rejuvenation. CCW Science Report No. 1002.
Robinson, A.H., Sale, R.D., Morrison, J.L., Muehrcke, P.C., 1987. Elementos de Cartografía. Omega. Barcelona. ES. 1987 (543 pp.).
Santana-Cordero, A., Monteiro-Quintana, M.L., Hernández-Calvento, L., 2014. Reconstructing the environmental conditions of extinct coastal dune systems using historical sources: the case of the Guanarteme dune field (Canary Islands, Spain). J. Coast. Conserv. 18 (4), 323–337.
Santana-Cordero, A., Monteiro-Quintana, M.L., Hernández-Calvento, L., Pérez-Chacón, E., García-Romero, L., 2016a. Long-term human impacts on the coast of La Graciosa, Canary Islands. Land Degrad. Dev. 27 (3), 479–489. https://doi.org/10.1002/ldr.2369.
Santana-Cordero, A., Monteiro-Quintana, M.L., Hernández-Calvento, L., 2016b. Reconstruction of the land uses that led to the termination of an arid coastal dune system: the case of the Guanarteme dune system (Canary Islands, Spain), 1834–2012. Land Use Policy 55, 73–85. https://doi.org/10.1016/j.landusepol.2016.02.021.
Smith, A.B., Jackson, D.W.T., Cooper, J.A.G., Hernández-Calvento, L., 2017. Quantifying the role of urbanization on airflow perturbations and dunefield evolution. Earth's Future 5, 520–539. https://doi.org/10.1002/2016EF000524.
Tsoar, H., Blumberg, D.G., 2002. Formation of parabolic dunes from barchan and transverse dunes along Israel's Mediterranean coast. Earth Surf. Process. Landf. 27, 1147–1161. https://doi.org/10.1002/esp.417.
Viera-Pérez, M., 2015. Estudio detallado de la duna costera de Maspalomas (Gran Canaria, Islas Canarias): interacción "Taganum moquinii"-dinámica sedimentaria eólica en un entorno intervenido. Recomendaciones de cara a su gestión. (Unpublished doctoral dissertation). Universidad de Las Palmas de Gran Canaria, Las Palmas de Gran Canaria (570 pp.).
Villagra, P.E., Defosse, G.E., del Valle, H.F., Tabeni, S., Rostagno, M., Cesca, E., Abraham, E., 2009. Land use and disturbance effects on the dynamics of natural ecosystems of the Monte Desert: implications for their management. J. Arid Environ. 73, 202–211. https://doi.org/10.1016/j.jaridenv.2008.08.002.
Walker, I.J., Nickling, W.G., 2002. Dynamics of secondary airflow and sediment transport over and in the lee of transverse dunes. Prog. Phys. Geogr. 26, 47–75. https://doi.org/10.1191/0309133302pp325ra.
Wheaton, J.M., Brasington, J., Darby, S.E., Merz, J.E., Pasternack, G.B., Sear, D.A., Vericat, D., 2010a. Linking geomorphic changes to salmonid habitat at a scale relevant to fish. River Res. Appl. 26, 469–486. https://doi.org/10.1002/rra.1305.
Wheaton, J.M., Brasington, J., Darby, S.E., Sear, D.A., 2010b. Accounting for uncertainty in DEMs from repeat topographic surveys: improved sediment budgets. Earth Surf. Process. Landf. 35, 136–156. https://doi.org/10.1002/esp.1886.
Xu, Z., Hu, R., Wang, K., Mason, J.A., Wu, S.Y., Lu, H., 2018. Recent greening (1981–2013) in the Mu Us dune field, north-central China, and its potential causes. Land Degrad. Dev. 29, 1509–1520. https://doi.org/10.1002/ldr.2910.