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Effects of stone-made wind shelter structures over an arid nebkha foredune

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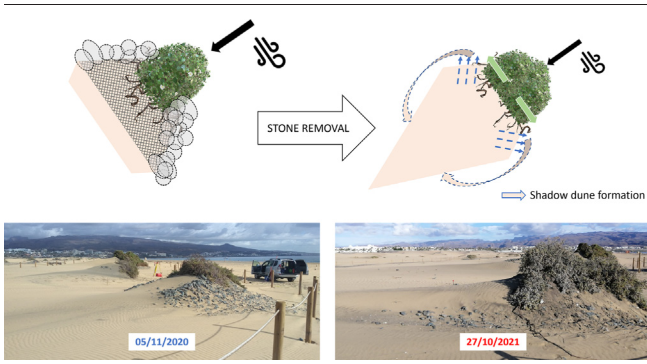
HIGHLIGHTS

- The number of human-made stone structures has rapidly increased in the Canary Islands.
- Stone structures prevent the growth of nebkhas and the formation of shadow dunes.
- Airflow and transport are modified by the presence of stone structures.
- Decadal analyses show net erosion in areas where stone structures are common.
- Passive restoration is possibly following the gradual dismantling of stone structures.

GRAPHICAL ABSTRACT



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ABSTRACT

Beach users often use a range of strategies to shelter from the wind and blown sand. This involves building structures made of stacking stones. Different from other portable wind blockers, stone-made wind shelters can remain in the landscape for a long time. The process of stone removal from their original place and stone-stacking at another location has well-known effects on rock-dwelling wildlife. Less known are the impacts of stone wind shelters on biogeomorphological processes of beach-dune systems, especially those in arid coastlines, where foredunes formed by nebkhas are naturally discontinuous. This is the case of *Playa del Inglés* beach (Gran Canaria, Spain), the main sediment input to the Maspalomas dunefield, where the presence of stone wind shelters (*goros*) made by users has increased in recent decades following an increase of visitors.

This research aims to investigate the effects of stone wind shelters on the dynamics of an arid beach-dune system at various spatiotemporal scales. The methodology includes the use of aerial photography to study the appearance and evolution of stone shelters in *Playa del Inglés* and some of their long-term effects on the foredune. Field data was also collected to investigate the effects that stone shelters have over a representative foredune nebkha in detail, by monitoring the changes (topography, airflow, and vegetation) of an individual landform as we progressively remove pebbles from a previously built stone shelter.

Results show that stone stacking has an impact on airflow and sediment transport dynamics around landforms, limiting sediment accumulation inside nebkhas and therefore arid foredune growth. Stone stacking also constrict vegetation growth and its ability to retain sediment. The impacts of these artificial structures can be reverted following their removal but that the process of dismantling stones must be carefully planned. We elaborate some recommendations here to do it avoid damaging foredune vegetation.

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1. Introduction

Rock-stacking is a centuries old practice in human history. While people have been stacking stones for both spiritual reasons and practical reasons (e.g., marking paths, locating burial sites, etc.), the practice has recently spread widely because of social media (Rocha et al., 2020). Like other apparently harmless practices, it is the large number of people doing the same action that causes the damage and adds to a global tourism footprint (Gross, 2018). The removal and displacement of stones for their stacking can disturb microhabitats and rock-dwelling organisms, promote soil erosion, and lead to vegetation damage (Rocha et al., 2020). However, the bio-geomorphological effects of the stone-stacking structures themselves have received little attention, especially on sedimentary coastlines where they can interfere with surface mobility.

The 1960s marked the beginning of mass tourism in the Canary Islands, with consequences for the environment in general and for the evolution of beach-dune systems in particular, including numerous impacts in Maspalomas and *Playa del Inglés* beach (García-Romero et al., 2019a; Hernández-Calvento et al., 2014; Hernández-Cordero et al., 2017; Smith et al., 2017; Viera-Pérez et al., 2019). Among other alterations to the natural bio-geomorphology, urbanisation and mass tourism led to the appearance of erosive landforms and the decline in foredune vegetation (García-Romero et al., 2021; Hernández-Cordero et al., 2018; Peña-Alonso et al., 2019). Landscape changes also resulted from incorrect beach management and uses such as the presence of kiosks in environmentally sensible locations, mass use of sunbeds and parasols, and an increase in the construction of *goros* (Sanromualdo-Collado et al., 2021). *Goro* is the local name for stone-made structures built by users to protect them from strong winds. They are often found on the back-beach, away from the high tides. These circular and semi-circular structures are constructed with large pebbles from paleo-barriers, mostly phonolites. They are sometimes built over the foredune and annexed to *Traganum moquinii* plant specimens to take advantage of the windbreak effect of the plants (Fig. 1). Stone-made structures are so common in the Canary Islands and other locations around the world (Rocha et al., 2020) that their presence can been used as an indicator of human pressure (Peña-Alonso et al., 2018).

Nebkha is the main dune mode of naturally discontinuous arid foredunes (García-Romero et al., 2019c; Goudie, 2022; Hesp et al., 2021a). As coastal vegetated dunes, these ecosystems play a fundamental role in the regulation of sediment transport inland (Hernández-Cordero et al., 2015) and coastal protection against storms (Feagin et al., 2019). Arid coastal nebkhas are bio-geomorphological units that result from the interdependence between plant characteristics, sediment transport dynamics, and geomorphology (Sanromualdo-Collado et al., 2022). The porous obstacle created by the plant produces a gradual retention of sediment that favours the formation of nebkhas and shadow dunes (Al-Awadhi, 2014; Dupont et al., 2014; Hesp and Smyth, 2017; Mayaud et al., 2017; Zhao et al., 2020; Zhao and Gao, 2021). Under a profuse sediment supply, between two adjacent nebkhas, coalescence of their shadow dunes can occur (Yang et al., 2019), giving rise to a tongue dune (Cabrera-Vega et al., 2013; Domínguez-Brito et al., 2020; Viera-Pérez, 2015). In transgressive dune fields, like Maspalomas, these tongue dunes end up freeing themselves from the vegetation of the foredune and feeding the interior of the system in the form of free dunes, such as barchans and barchanoid ridges (Cabrera-Vega et al., 2013; Hernández-Cordero et al., 2012).

Wind flow and aeolian sediment transport around nebkhas and shadow dune formation have been measured both in the field (Domínguez-Brito et al., 2020; Gillies et al., 2014; Viera-Pérez, 2015; Zhao and Gao, 2021) and in wind tunnels (Yang et al., 2019; Zhao et al., 2020), as well as modelled using computational methods (Hesp and Smyth, 2017; Zhao et al., 2019). The presence of roughness elements on the beach and foredune can affect airflow, sediment transport, and sand deposition patterns (Eamer and Walker, 2010; Grilliot et al., 2019a, 2019b, 2018; Nordstrom et al., 2011).

The impact that buildings have on wind flow and sediment deposition patterns around them (Fackrell, 1984; Hunt, 1971; Peterka et al., 1985; Poppema et al., 2021; Pourteimouri et al., 2021) and at the beach or beach-dune interface (Hernández-Calvento et al., 2014; Jackson and Nordstrom, 2011; Nordstrom and McCluskey, 1984; Sanromualdo-Collado et al., 2021; Wijnberg et al., 2021) has been well studied, but there is a lack of knowledge about the impact of smaller structures such as user-made stone wind shelters. Recent work suggests that the decrease of nebkha vegetation is directly linked with an increasing number of stone shelters (Sanromualdo-Collado et al., 2021). However, little is known about the effects of these structures on nebkha formation and evolution, with no studies (to the knowledge of the authors) conducted on changes to dune growth patterns as a result of users building them. This knowledge gap can lead to a lack of policies regulating the presence of these stone-made structures on beaches and foredunes.

This article analyses the impact that user-made stone wind shelters (*stone structures* or *goros*, hereinafter) have on arid foredunes. The research hypothesis is that artificial stone structures prevent natural plant development and modify airflow and sediment transport dynamics, with implications for nebkhas and shadow dune evolution. The objectives of this study are to investigate the decadal evolution of an area affected by the presence of *goros*, to identify bio-geomorphological processes affected by them, and to discuss management recommendations based on field observations.

2. Study area

Playa del Inglés (27°44′26.4″N, 15°34′11.2″W) is a sandy beach to the east of Maspalomas dunefield (Gran Canaria Island, Spain) (Fig. 1). The beach stretches 2.5 km in the north-south direction, and it is the main source of sediment of the dunefield. The effective prevailing winds from NE, ENE and E (Máyer Suárez et al., 2012) push the sediment through the transgressive dunefield, where dunes reached over 20 m height before the onset of mass tourism (Hernández-Calvento, 2006). The sediment is then delivered to the *Maspalomas* beach at the southern end of the system, and from there to the sea. Much of the output sediment at southern *Maspalomas* beach is recirculated back into input areas in *Playa del Inglés* by marine currents, but some of the sediment is lost deep into marine zones leading to an overall sedimentary deficit in the system (Hernández-Calvento, 2006; Hernández-Calvento et al., 2014).

The arid climate is the key factor that determines sediment dynamics and geo-ecological aspects of aeolian systems in the Canary Islands (Hernández-Cordero et al., 2019). With a slight variation over the year, the average temperature in Maspalomas is 21 °C, and the mean annual precipitation is close to 81 mm (Hernández-Cordero et al., 2019). These conditions favour halophytic shrub species in the foredune (Hernández-Cordero et al., 2015) and dune development by nebkhas (Hesp et al., 2021a). The shrub species that forms the foredune in *Playa del Inglés* is *Traganum moquinii*¸ which stretches from the foreshore to up to 200 m into the dunefield and acts as a dune-builder. *T. moquinii* shrubs contribute to the initial accumulation of sediment followed by the formation of nebkhas and shadow dunes, which then evolve into barchan dunes and barchanoid ridges (Hernández-Cordero et al., 2012; Viera-Pérez, 2015). In turn, this sand deposition stimulates plant growth with some *T. moquinii* shrubs reaching up to 5 m in *Playa del Inglés*, where nebkhas can also reach 5 m in height (García-Romero et al., 2021).

Starting in the 1960s, *Playa del Inglés* has been subject to increasing mass tourism and human pressure over the foredune and its vegetation (García-Romero et al., 2021; Hernández-Cordero et al., 2017; Sanromualdo-Collado et al., 2021; Viera-Pérez et al., 2019). The beach-dune system is an area of intensive tourist use throughout the year (Hernández-Calvento, 2006). Kiosks, parasols and sunbeds tend to occupy the northern half of the beach, and *goros* tend to be more common in the southern half (Sanromualdo-Collado et al., 2021), hence the focus on the area marked by a red polygon in Fig. 1 in this study.

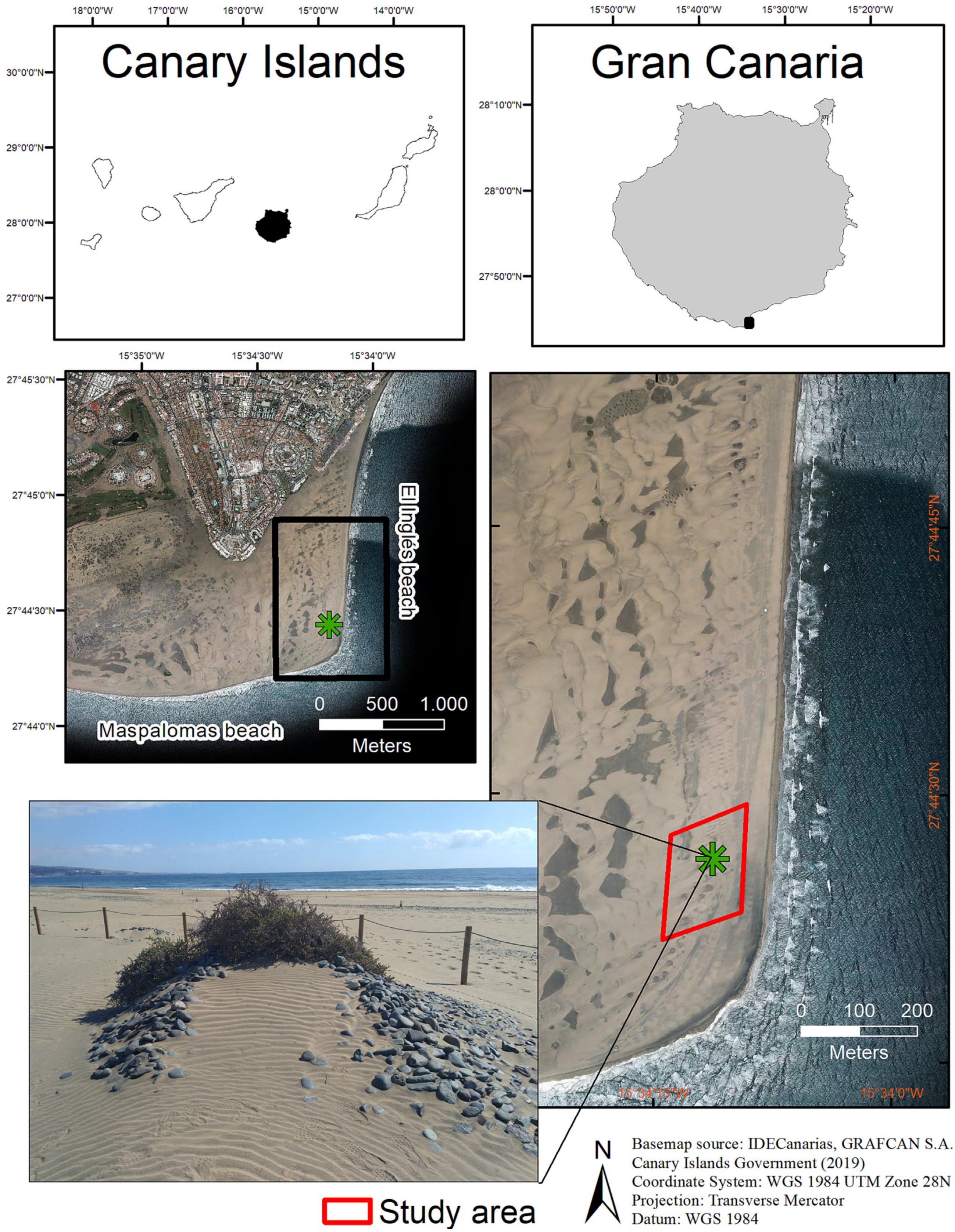

Fig. 1. Location of the study area in Playa del Inglés beach and detail of the studied stone wind shelter structure (goro) built over a nebkha (green asterisk) before the study period.

Table 1
Characteristics of the cartographic sources used.

Type (source)	Year	Spatial resolution (m)
Historical aerial photographs (1, 2)	1961 (1:5000)	0.25
Orthophotos (2, 3, 4)	1987, 1996, 2003, 2006, 2011, 2018, 2019, 2020	0.15–0.25
DEMs (4, 6)	05/1987, 11/2003	4
DEMs (2, 3, 5, 7)	10/2006, 03/2011, 11/2018, 05/2019	1

(1) SDI Gran Canaria; (2) SDI Canarias-Grafcan S.A.; (3) Grupo de Geografía Física y Medio Ambiente (IOCAG, ULPGC); (4) Instituto Geográfico Nacional (IGN); (5) MASDUNAS project (Cabildo de Gran Canaria); (6) Photogrammetric restitution; (7) LiDAR flight (2006, 2011, 2018, 2019).

3. Methods

3.1. Landscape (decadal) scale

Analyses were conducted at various spatiotemporal scales. The largest scale covered the period from 1987 to 2019 and consisted of analysing the topographic evolution of a 23,800 m^2 plot rich in *goros* located on the foredune of *Playa del Inglés* (Fig. 1). Point-type vectors representing *goros* were available from previous work by Sanromualdo-Collado et al. (2021). Digital Elevation Models (DEMs) of years 1987, 1996, 2003, 2006, 2011, 2018, 2019 and 2020 were obtained from a range of sources (Table 1).

DEMs of differences (DoDs) between initial and final states were calculated to locate areas of accretion (positive values) and areas of erosion (negative values) (Carvalho et al., 2020; Delgado-Fernández et al., 2018; Hesp et al., 2021b). The DEMs and DoDs were processed and analysed using the Geomorphic Change Detection (GCD) software, including the calculation of raw and threshold errors (Wheaton et al., 2010b, 2010a). DoD errors (%) from DEMs between 1987 and 2019 were: accumulation (15.45, 9.99, 11.07, 4.21) and erosion (18.22, 8.71, 5.78, 7.12), for periods 1987–2003, 2006–2011, 2011–2018 and 2018–2019, respectively.

3.2. Landform (monthly) scale: field experiment

For more detailed spatiotemporal scale analyses, we followed a selected nebkha inside the study area during a 6-month period (November 2020 to May 2021; Fig. 1). The objective at this scale was to monitor the evolution of the nebkha as we removed the *goro* previously built on it, and to investigate the effect that the stone structure had on wind dynamics around the landform. A 20 × 10 m plot was established around the nebkha and LiDAR-derived DEMs of the plot between November 2018 and May 2019 were used as control (Section 3.2.1). An initial topographic survey using a Leica TS06 Total Station was carried out on 5 November 2020, followed by a field experiment that included: (i) the measurement of wind data prior to the removal of the *goro* (Section 3.2.3); (ii) the dismantling of the *goro* itself, with most stones manually removed and returned to the nearest paleo-barrier. We avoided digging stones, to avoid damaging the plant, because the shrub foliage was partially supported by the stones and their rapid removal could have resulted in some broken brunches and left the plant's structure suddenly exposed to incoming winds. Instead, we chose to carefully remove only the stones that were in sight (and then allow the wind to deposit fresh sand during the following weeks). Stones within a random area of 1 × 1 m were weighed to estimate the mass of material removed. The surface covered by stones was also estimated through photointerpretation of orthophotos (Section 3.2.2); (iii) the final step consisted of measuring wind characteristics after the intervention. Subsequent changes in nebkha characteristics were observed every 3 weeks using on-site photogrammetry (Section 3.2.2). Following the topographical survey, at the end of every 3 weeks field campaign, all the stones newly exposed by the winds were carefully removed to continue with the progressive dismantling of the *goro* without damaging the plant (Fig. 2). An additional topographic survey with the TS06 Total Station was conducted on 17 May 2021, to quantify net volumetric and morphological changes over the 6-month study period and compare these with LiDAR data for the time same period during the previous year.

Finally, regional wind characteristics from October 2018 to June 2019 and from October 2020 to June 2021 were obtained from the Gran Canaria Airport (LPA) met station by the Agencia Estatal de Meteorología (AEMET), located 25 km northeast of the study area (Smith et al., 2017). Daily averages for wind speed and wind direction recorded were used to compare conditions during the experiment period with the same period of the previous years (Fig. 3).

3.2.1. LiDAR

LiDAR data for the 6-month period ranging from November 2018 to May 2019 were obtained monthly as part of the MASDUNAS program run by the Gran Canaria Island Council and were used to derive 0.3 m pixel resolution DEMs. DoD errors (%) from LiDAR data (file.las) between 2018 and 2019 were: Accumulation (7.86) erosion (5.63). DoD errors (%) from topographic survey between 2020 and 2021 were: Accumulation (4.32) erosion (3.98).

Fig. 2. Example of the state of the goro before (left) and after (right) stone removal. Stones newly uncovered and exposed by wind between campaigns can be appreciated.

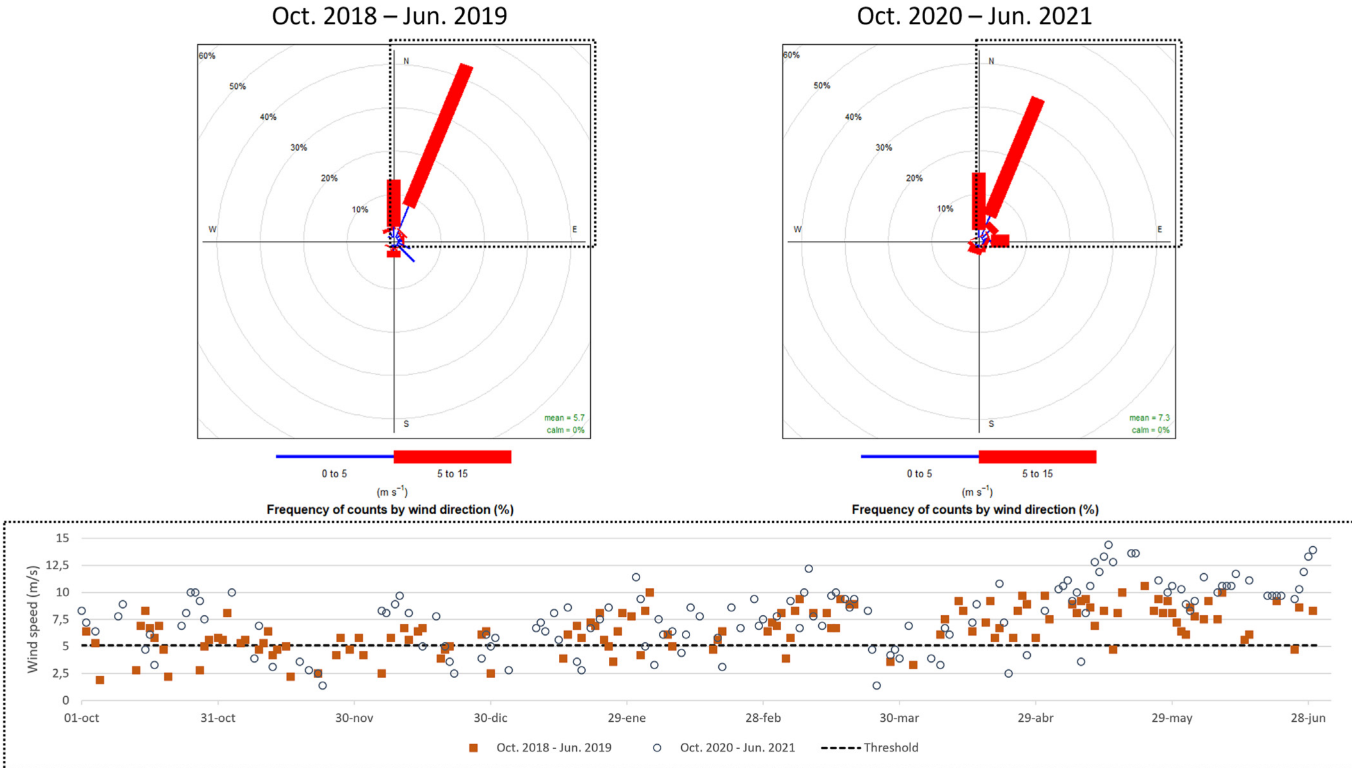

Fig. 3. Wind variability in Gran Canaria Airport (LPA). The graphics at the bottom shows only wind events from the first quadrant.

3.2.2. Photogrammetry

A total of 8 field surveys were carried out from November 2020 to May 2021 (Table 2). Morphological data were collected using structure-from-motion (SfM) photogrammetry (Fonstad et al., 2013; Smith et al., 2015; Van Puijenbroek et al., 2017). Multiple photographs were taken around the nebkha and shadow dune with a 64 Megapixels camera on a telescopic pole of approximately 3 m long. The position of control points for photo georeferentiation was measured by a GNSS system TOPCON Hiper V, connected in real time to the Agüimes (Gran Canaria) base station (Canary Islands Network of Permanent Stations, Government of the Canary Islands). Topographic data were georeferenced to a UTM (28 N) coordinate system and a WGS84 Datum (REGCAN 2001).

DEMsS were obtained from the field photographs following the successful application of SfM to beaches and dunes (Grottoli et al., 2020; Poppema et al., 2021; Van Puijenbroek et al., 2017). Agisoft Metashape SfM photogrammetry software was used to overlap the images and generate a 3D point cloud from where the DEMs (spatial resolution: 0.1 m) and orthophotos (spatial resolution: 0.005 m) were derived. Agisoft Metashape settings for photo alignment were high, whereas for the dense cloud generation was low due to the high resolution of the photographs. At the initial and final stages, the point clouds obtained by SfM were compared Point-to-Point with those obtained by total station from topographical campaigns (Smith et al., 2015), resulting in a RMSE <0.003 m.

Three profiles were drawn to obtain the topographical evolution of the nebkha: the first along the main axis, the second transversal to the first and along the top of the nebkha, and another transversal third transect behind the plant, in the shadow dune area.

Table 2
Photo properties and outputs of the structure-from-motion process.

Date	Megapixels (MP)	Photos (number)	Total aligned photos (number (%))	Tie points	Final cloud points (lowest quality)
05/11/2020	64	50	37 (74 %)	17,649	2,155,783
27/11/2020	64	124	62 (50 %)	69,018	2,191,670
12/12/2020	64	104	82 (79 %)	63,281	2,086,729
31/12/2020	64	116	68 (59 %)	74,426	2,278,783
26/01/2021	64	103	70 (68 %)	64,781	2,602,306
24/02/2021	64	98	66 (67 %)	29,999	2,468,572
17/03/2021	64	114	59 (52 %)	12,278	1,484,287
17/05/2021	64	166	166 (100 %)	91,112	2,632,033

3.2.3. Wind data

Airflow data were collected on 5 November 2020. A grid of 18 sample points was designed around the nebkha and *goro*, including 6 points along a 25 m central line (from C1 located 10 m in front of the canopy to C6 located 10 m behind), 6 'north' points (N1-N6), and 6 'south' points (S1-S6). An additional sample point was located 22 m in front of the nebkha (control) (Fig. 4, A).

Airflow was measured by 10 wind stations consisting of an anemometer-vane-data logger system (Fig. 4, C) with wireless communication (Domínguez-Brito et al., 2020; García-Romero et al., 2019b). Wind speeds and directions were initially sampled every 2 s at 0.1 m height above the surface (where most sediment transport occurs). One wind station remained fixed in the 'control' position throughout the experiment. The other 9 were first deployed to collect wind data along the 'front' side of the nebkha (Run 1) and then moved to collect wind data along the 'lee-side' of the nebkha (Run 2). While this meant that Run 1 and 2 were not synchronous in time, this design allowed us to collect wind data at a finer spatial resolution and over the entire grid.

Airflow was recorded for 15 min at each position, and averaged every 30 s, with the aim of having representative averages that could be compared spatially within each run. Then these 30 s averages were normalised by their corresponding time averaged wind data at the control station, to minimize the effect of moving wind sensors and allow for inter-run comparisons over the entire sampling grid (e.g., Delgado-Fernández et al., 2013; García-Romero et al., 2019a, 2019b).

A second round of measurements was conducted after the removal of the *goro* that day. The same approach was followed, with winds sampled over 15 min periods first on the 'front' side of the nebkha (Run 4) and

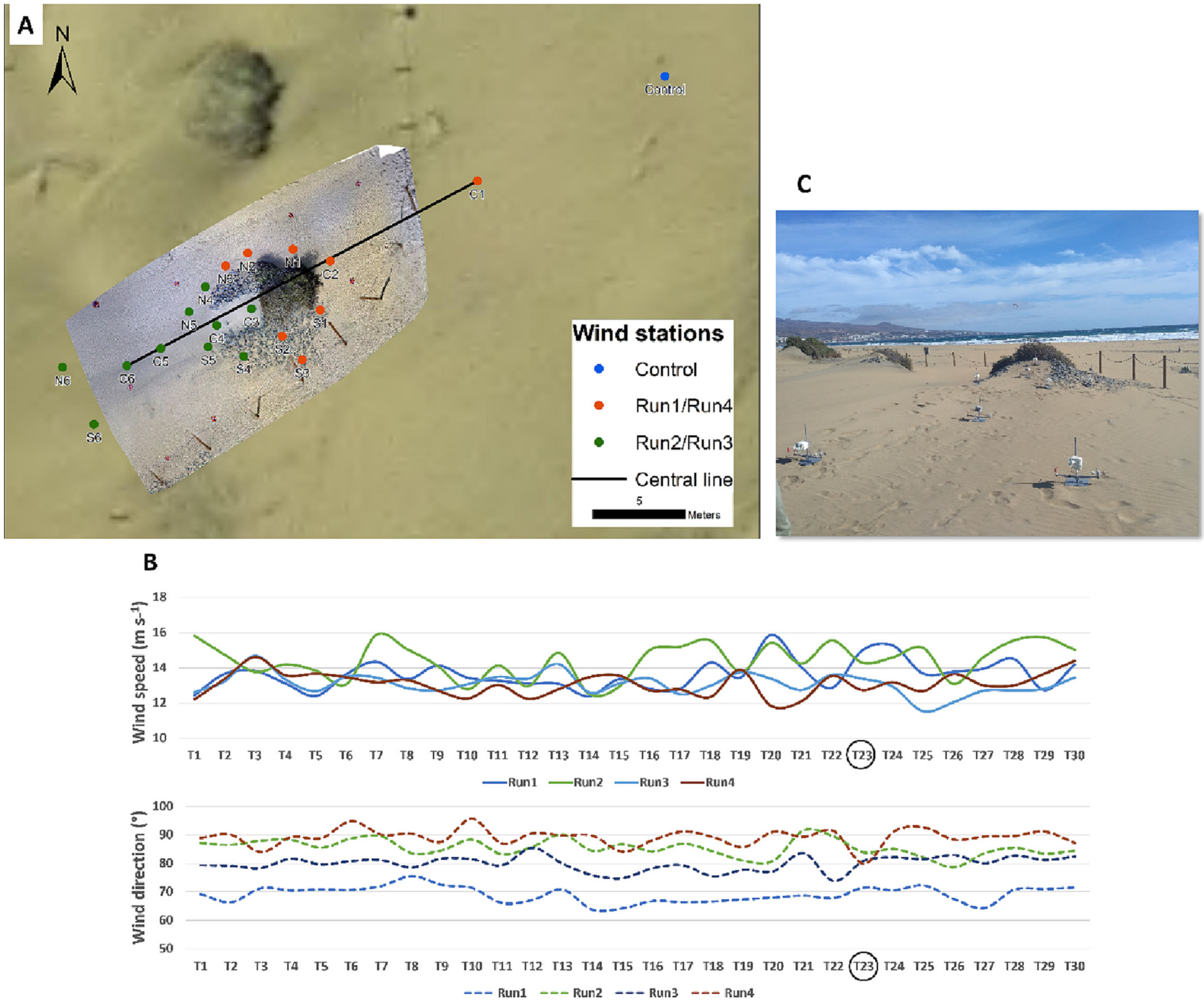

Fig. 4. A) Deployment array of sampling points around the study area. B) Temporal series of wind speeds and directions in the control station for Run 1 (STARTING TIME: 09:48) and Run 2 (STARTING TIME: 10:33), prior to the removal of the goro, and for Run 3 (STARTING TIME: 11:20) and Run 4 (STARTING TIME: 11:49) following the removal of the goro. C) Anemometers deployed around the nebkha during the field experiment.

then on the 'lee-side' of the nebkha (Run 3). Like the other runs, data was averaged every 30 s and then normalised by the corresponding averages from the fixed control station. Start and end times for all runs are provided in Fig. 4 as well as wind conditions measured by the control station throughout the day.

Wind characteristics for all runs corresponding to timeslot T23 in the control station were selected to elaborate maps of wind spatial patterns (Fig. 4, B). Despite some differences, the range of incident wind directions at the fixed location was narrowest for T23 (15° or less between all runs) and showed the lowest standard deviation (78.984 ± 5.324°). This allowed comparison of maps of airflow spatial patterns before and after the removal of the *goro* by ensuring that changes in input wind direction were minimum when data was collected.

4. Results and interpretation

4.1. Landscape (decadal) scale

The 1961 historical image of the study site shows no *goros* in the study area (Fig. 5), and the largest number of nebkhas and associated shadow dunes. The presence of shadow dunes growing downwind from isolated nebkhas is common in foredunes of arid regions, especially those formed by *T. moquinii* species (García-Romero et al., 2021; Sanromualdo-Collado et al., 2022; Viera-Pérez, 2015). Landscape analyses by Sanromualdo-Collado et al. (2021), show that artificial stone structures began to appear between 1961 and 1977 in the central and southern areas of the beach as touristic resorts developed, reaching >200 in 1987 on the foredune of *Playa del Inglés*. Up to 40 *goros* were identified in 1996 within the study area, with numbers decreasing to approximately 20 by 2006 (Fig. 5, top). This likely reflects the application of a new Master Plan for the Natural Park published in 1999, which introduced actions to remove *goros* and restore areas of the beach-dune system affected by them.

Aerial photography from 2003 (Fig. 5) shows a relatively constant presence of stone structures within the study zone, with small oscillations in the number of *goros* and their location. This was despite an express mandate to prohibit them by the Master Plan of 1999, and likely reflected two processes: i) some *goros* could have been buried by sand and not removed, only to resurface months later; ii) other *goros* were being built and maintained by users.

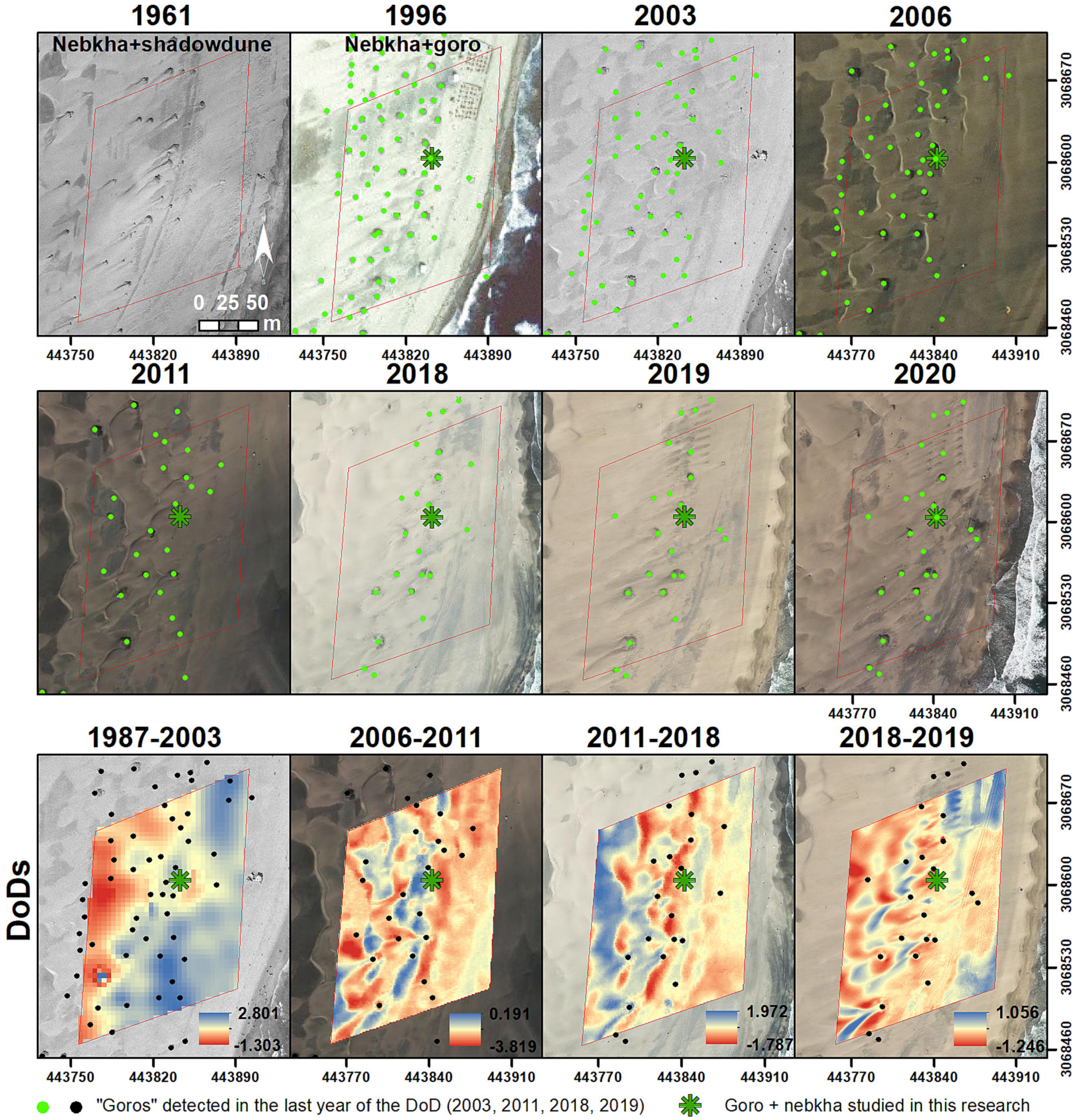

Fig. 5. Long term evolution of the study area in Playa del Inglés beach. Top: Visual evolution of the study area and goros detected from 1961 to 2020. Bottom: Topographic evolution over 32 years (1987–2019) obtained through DoDs. DoDs dates for comparison have been selected according to the limitations derived from DEMs spatial resolution (see Table 1) (Orthophotos source: SDI Canarias – Canary Islands Government-Grafcan S.A.)

DoDs over the last 32 years (Fig. 5, bottom) show, in general, an increase in erosion in the study plot. Except for the period 1987–2003, where positive elevation changes were observed in the seaward section, the remaining DoDs show sand loses from the study area. Erosion occurred around the *goros*, normally built on nebkhas. Shadow dunes like those observed in 1961 did not develop in the presence of stone structures. Instead, erosional patterns were visible behind many of the *goros*, suggesting the presence of deflation surfaces such as those observed behind artificial structures studied by Díaz Guelmez and Hernández-Calvento (2004) and Sanromualdo-Collado et al. (2021). The growth in the number and size of deflation surfaces, the impact and potential loses of *T. moquinii* specimens because of the installation of *goros*, and large levels of pedestrian traffic, are all causes for foredune fragmentation (García-Romero et al., 2021; Hernández-Calvento, 2006; Hernández-Cordero et al., 2012; Sanromualdo-Collado et al., 2021).

4.2. Landform (monthly) scale: field experiment

4.2.1. Morphological evolution

4.2.1.1. Pre-goro removal (Oct 2018–June 2019). The *goro* studied in detail was already visible in 1987 (Fig. 5) and hence had been affecting the evolution of the associated nebkha for 3 decades or more. LiDAR data from Oct 2018 and June 2019 (before the removal of the *goro*) (Fig. 6, top) showed two well differentiated zones: a windward zone surrounding the nebkha characterized by small amounts of sediment accumulation (max. +0.168 m), and a landwards erosive zone (max. −0.475 m) behind the nebkha. It is precisely in this landward area where one would expect sand deposition and the formation of a shadow dune (Hesp, 1981; Hesp and Smyth, 2017; Yang et al., 2019). Instead, the maximum elevations were found towards the back of the nebkha (intersecting with transect C). The

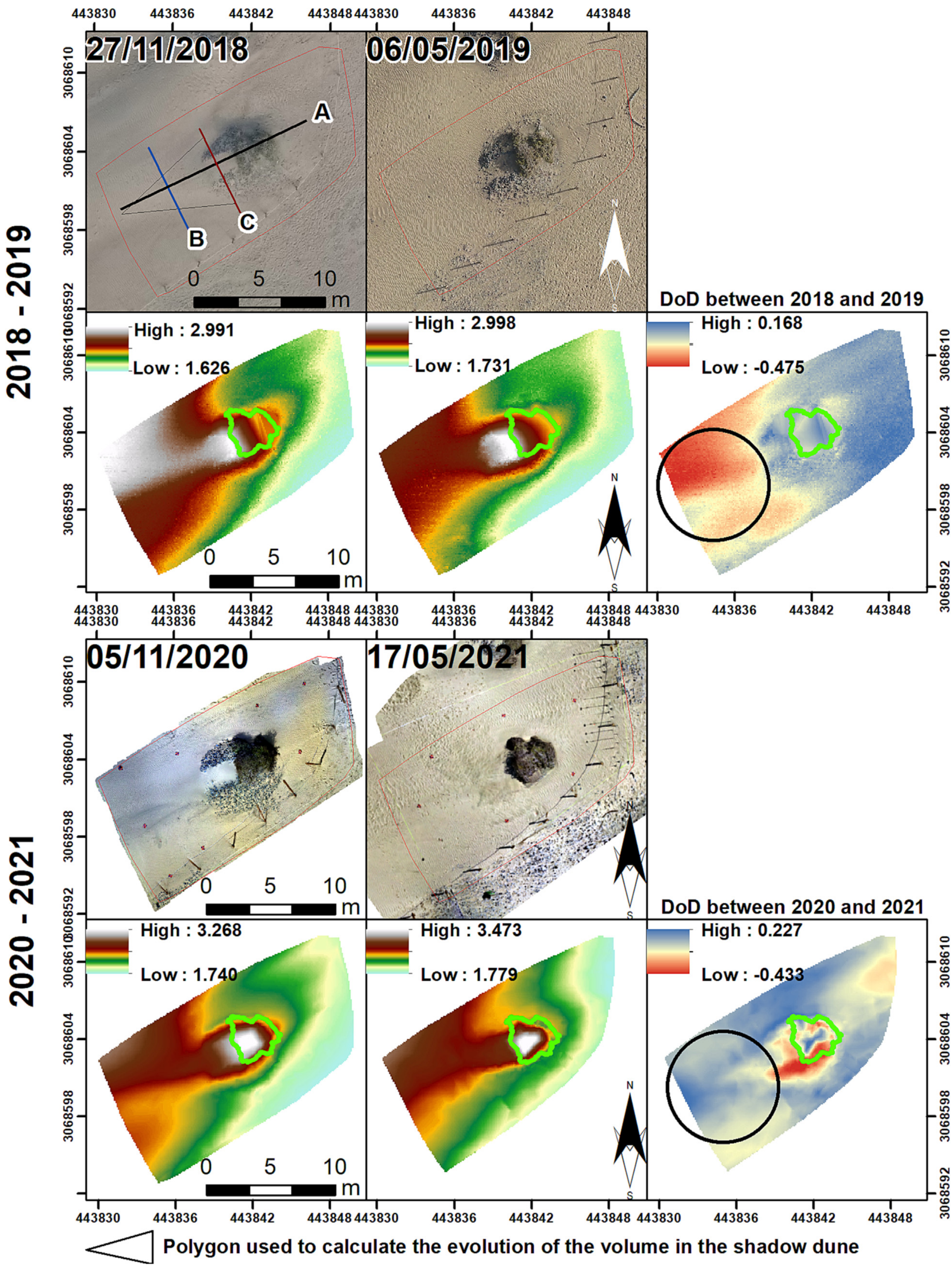

Fig. 6. Initial (left column) and final (second column) states of the nebkha during the study periods. Right column shows DoDs between initial and final states, where plant contour is highlighted. Black circle marks the potential zone for shadow dune formation. Top-left image shows the three orthogonal profiles drawn for topographic monitoring (A, B, and C) and the triangular polygon used to calculate the volume of the potential shadow dune.

presence of the *goro* and the stacking of stones likely helped retaining sediment at this location and prevented natural sand avalanching which feeds the shadow dune.

4.2.1.2. Goro removal and post-goro evolution (Nov 2020–May 2021). The dismantling of the *goro* started on 5 November 2020 with approximately half of the stones, 1000 kg, removed that day. An additional 1200 kg of stones were gradually removed over the next few months, with a total of 2200 kg of stones extracted from the area at the end of the study period (May 2021, Fig. 7, bottom diagram). The stones covered a surface of 18 m^2 in Nov 2020, which was reduced and fragmented in smaller patches as stones were gradually exposed and removed throughout the study period, especially to the south of the nebkha (Fig. 7, top diagram).

The dismantling of the *goro* led to morphological changes of the nebkha and its surroundings (Fig. 6, bottom). In general, sand accumulated around the nebkha (max. 0.227 m), both windward and leeward (except for erosion at the flanks, see next paragraph). An increase of >20 cm in maximum nebkha height was observed in the period following the *goro* removal (Nov 2020 to May 2021). This was in contrast with no changes in maximum nebkha heights observed during the previous year (Oct 2018–June 2019). This increase in nebkha height was also characterized by a displacement of the maximum elevation towards an inner zone of the plant canopy, as the nebkha gradually recovered following the removal of the constraints imposed by the stone structure (Lang et al., 2013; Sanromualdo-Collado et al., 2022) and as fresh sand accumulated in regions that were more sheltered from wind erosion (Dupont et al., 2014).

The removal of stones led to a decrease of surface elevation (max. −0.443 m) of the southern flank of the nebkha (Fig. 6, bottom right), the area where most stones were removed from (compare photograph in Nov 2020 with that in May 2021 in Fig. 6). The extraction of stones left a gap in this area and triggered sand avalanching at the flanks (previously prevented by the presence of the structure). Despite avalanching, sand did not completely fill this gap during the study period, because steep slopes, airflow acceleration along the nebkha flanks (Hesp and Smyth, 2017; Zhao et al., 2019), and the lack of vegetation, favored sand transport from here and other areas upwind towards the nebkha lee-side (Hesp, 1981; Sanromualdo-Collado et al., 2022).

The removal of the *goro* led to sand accumulation downwind (in contrast with erosion of the same area during the period when the goro was still present; compare DoDs in Fig. 6). The increase of available sand did not lead to the formation of a shadow dune within the 6-month monitoring period, suggesting that not enough time may have passed for the landform to develop in these environmental conditions. We argue that it is expected that a shadow dune will eventually grow leeward of the nebkha, with a triangular morphology and symmetrical flanks shaped by reversing lee-side vortices (Hesp and Smyth, 2017; Zhao et al., 2019). While locations with large variability in wind direction tend to favour the formation of rounded nebkhas with short tails (Li et al., 2021; Zhang et al., 2020), Maspalomas is subject to prevailing winds from the first quadrant (Máyer Suárez et al.,

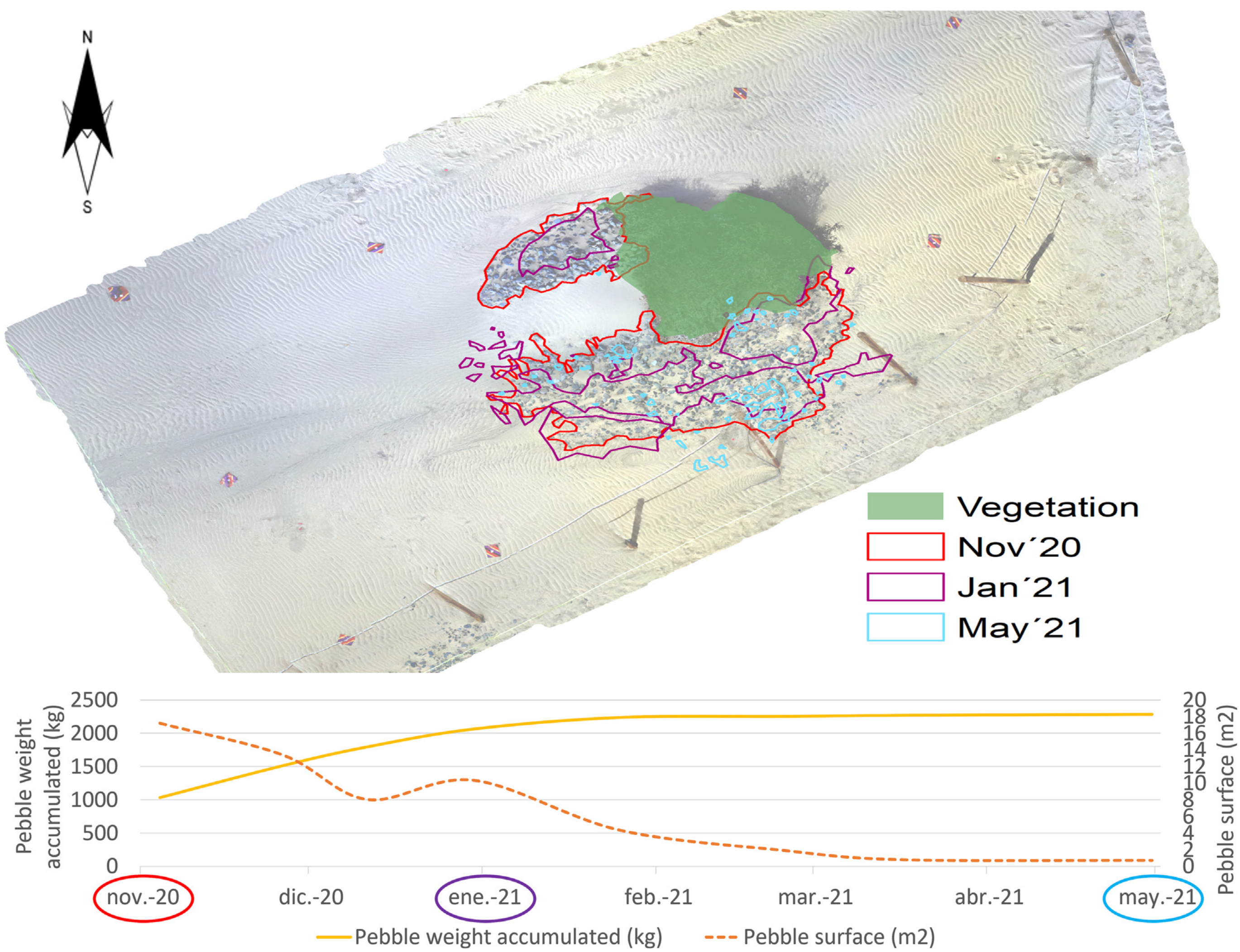

Fig. 7. Spatial evolution of surface covered by pebbles in initial (Nov'20), intermediate (Jan'21), and final (May'21) states of the experiment. The base map is an example of the ortho-mosaics obtained using Structure from Motion (FM) photogrammetry.

2012) which favour the formation of shadow dunes with long tails as can be seen in *Playa del Inglés* (García-Romero et al., 2021) and in the 1961 orthophoto of the study area (Fig. 5, top).

In addition to being the area from where the largest number of stones was removed, the southern flank of the nebkha was also slightly oriented to the east and more exposed to incident wind directions, which could have increased shear stresses in this zone (Luo et al., 2012; Zhao et al., 2020; Zhao and Gao, 2021).

The evolution of the longitudinal profile (Fig. 8, A) showed a general trend of sand accumulation across the landform as the *goro* was removed, additional to the increase in maximum nebkha height described above. We argue that the presence of the *goro* not only interfered with airflow and sediment transport patterns (next section) but also limited plant growth by adding extra weight and preventing the plant to develop in a natural way. The removal of stones gradually restored wind-sediment-plant interactions (Davidson-Arnott et al., 2012; Dupont et al., 2014; Leenders et al., 2007; Sanromualdo-Collado et al., 2022) and allowed the nebkha to intercept more sediment transported in saltation and suspension (Li and Ravi, 2018; Yang et al., 2018).

The two transversal profiles (Fig. 8, B and C) showed changes that were consistent with trends observed in the DoDs (Fig. 6). The presence of the *goro* on 5 Nov 2020 created artificially steep and high flanks (C) and prevented avalanches (Mehta and Barker, 1994; Parteli et al., 2014). As the stone structure was removed, the landform 'relaxed' and started to adopt a more asymmetrical shape adapted to local airflow and transport dynamics. Sand avalanches provided sediment downwind, the flanks became less steep, and sand deposition generally favored the NW section of the landform (Fig. 8, B and C).

The volume of sand accumulated leeside of the nebkha increased during the 6-month monitoring, and hence the potential for shadow dune formation (Fig. 8, D). There was an initial peak following the first survey when close to half of all stones were removed. Sand accumulation continued to rise in this zone from January 2021, when winds from the NE become more constant (Fig. 3).

4.2.2. Wind dynamics

Results from the wind dynamics experiments suggest that stone structures modify airflow patterns around the nebkha (Fig. 9) with implications for shadow dune formation. The presence of the *goro* increased the angle of the flanks creating stepper walls. This accelerated the airflow along the north side of the plant (zone 1, in Fig. 9). When stones were removed, the airflow at this area decelerated, and maximum wind speeds 'moved' towards the edge of the nebkha (Leenders et al., 2007; Mayaud et al., 2016). An opposite pattern was observed in the south side of the nebkha (zone 2), where the presence of the *goro* generally slowed down the airflow, and its dismantling opened this zone up to stronger airflows. Leeside of the plant, in zone 3, the airflow was strongest after the removal of stones, and hence more capable of transporting sand towards the shadow dune area (Hesp, 1981; Hesp and Smyth, 2017; Zhao et al., 2019; Zhao and Gao, 2021). The wake (lee) area (zone 3) was sheltered from the wind by the presence of the stone structure at the beginning of data collection. When obstacles are higher than the average saltation height (as was the case of this *goro*), these produce stagnation zones that significantly reduce the amount of sand particles transported landwards (Zhao et al., 2019; Zhao and Gao, 2021). This could have limited the formation of a shadow dune at the site in the presence of the *goro*. Once the stones were removed, wind speed in the wake area (zone 3) increased, as well as the potential for sand transport in the shadow dune area (zone 4). Restored airflow dynamics in these zones contributed to sediment transport leeward and the gradual elongation of the shadow dune (Zhao and Gao, 2021).

Porosity also played an important role in overall airflow circulation. Nebkhas vegetation allows airflow and sand to move through the shrub and continue its path towards the lee (Cheng et al., 2018; Latif Bhutto et al., 2022). However, the presence of stone structures transform nebkhas in nonporous obstacles, deflecting the airflow and sand transport horizontally and vertically (Dong et al., 2008; Gillies et al., 2014; Mayaud et al., 2016; Mayaud and Webb, 2017; Zhao et al., 2019). This can lead to scouring around the obstacle, as is the case with tree trunks, woody debris, buildings, and other solid roughness elements (Dupont et al., 2014; Grilliot et al., 2018; Leenders et al., 2007; Mayaud et al., 2016; McKenna Neuman and Bédard, 2015; Poppema et al., 2022; Sutton and McKenna Neuman, 2008; Zhao and Gao, 2021).

5. Discussion

Field results suggest that the presence of stone structures modify the evolution of nebkha foredunes. Stone-stacking led to artificially steep flanks and lower porosity levels, which modified airflow and transport patterns, and prevented the formation of a shadow dune (Fig. 6). Short-term results over the selected nebkha were in line with decadal landscape analyses using aerial photography. While there is a need to investigate the effect of other types of human impacts (e.g., trampling), DoD analyses both at a landscape (Fig. 5) and landform (Fig. 6) scale indicate the development of erosional features in the presence of *goros* in the study area. Limited shadow dune formation in impacted nebkha at *Playa del Inglés* over the last decades means less sand retained within frontal dunes, preventing the formation of 'tongue dunes', and increasing foredune fragmentation and vulnerability (Viera-Pérez, 2015). In other words, we argue that *goros* could be limiting overall foredune growth by changing airflow and transport dynamics around nebkha and impacting the vegetation's ability to grow and trap sand. Future research should be conducted on the effects of different types of *goros* (e.g., morphology, height) on arid foredune evolution, including an analyses of interactions between airflow, surface roughness, and shrub vegetation (Fu, 2019; Smyth, 2016).

Highly dynamic beach-dune systems such as Maspalomas can recover quickly following the removal of human-made disturbances (Jackson et al., 2013). Our results indicate that the removal of stone structures from nebkha dunes can reset the transport system and lead to more natural morphologies (Fig. 6), as well as trigger sediment accumulation on the lee side (Fig. 8). No shadow dune was observed at the end of the 6-month monitoring period but evidence for the formation of a shadow dune was clear a year later (Fig. 10). The morphology of this new shadow dune resembled those found in non-impacted nebkhas dune fields of the Canary Islands (Sanromualdo-Collado et al., 2022).

The speed of recovery and the success of nebkha restoration at *Playa del Inglés* and other sites will also depend on various other factors. First, users keep rebuilding *goros*, prompting the need for educational and environmental campaigns in the area. Second, our field intervention suggests that the process of dismantling a *goro* is gradual, because large accumulations of stones tend to become exposed as the previous ones are removed. Third, recovery rates will depend on wind conditions, sediment supply, and the health condition of dune vegetation.

5.1. Management recommendations

Several simple management recommendations can be made from our short-term experiment and visual observations during the *goro* removal experience:

(1) We advise removing stones gradually, over a period of time adjusted to the plant "needs" (*T. moquinii*, in our case). Observations during the site visits suggested that the visible part of the *goro* (the one we initially identified in Nov. 2020) was only 'the tip of the iceberg'. This is, there was a more complex structure buried underneath and built over the years/decades. The accumulation of stones had altered the growth and morphology of the *T. moquinii* specimen. The buried stratums of the *goro* acted as a flowerpot that limited the natural growth of adventitious roots, which are essential for plant growth and nebkha development in arid environments (Luo and Zhao, 2019). Additionally, the weight and presence of stones forced branches to grow in a cylindrical pattern and in a limited space (bonsai effect). It was quickly obvious that if the entire *goro* structure were to be removed in a single site visit this would lead to the collapse of the *T. moquinii* specimen in a

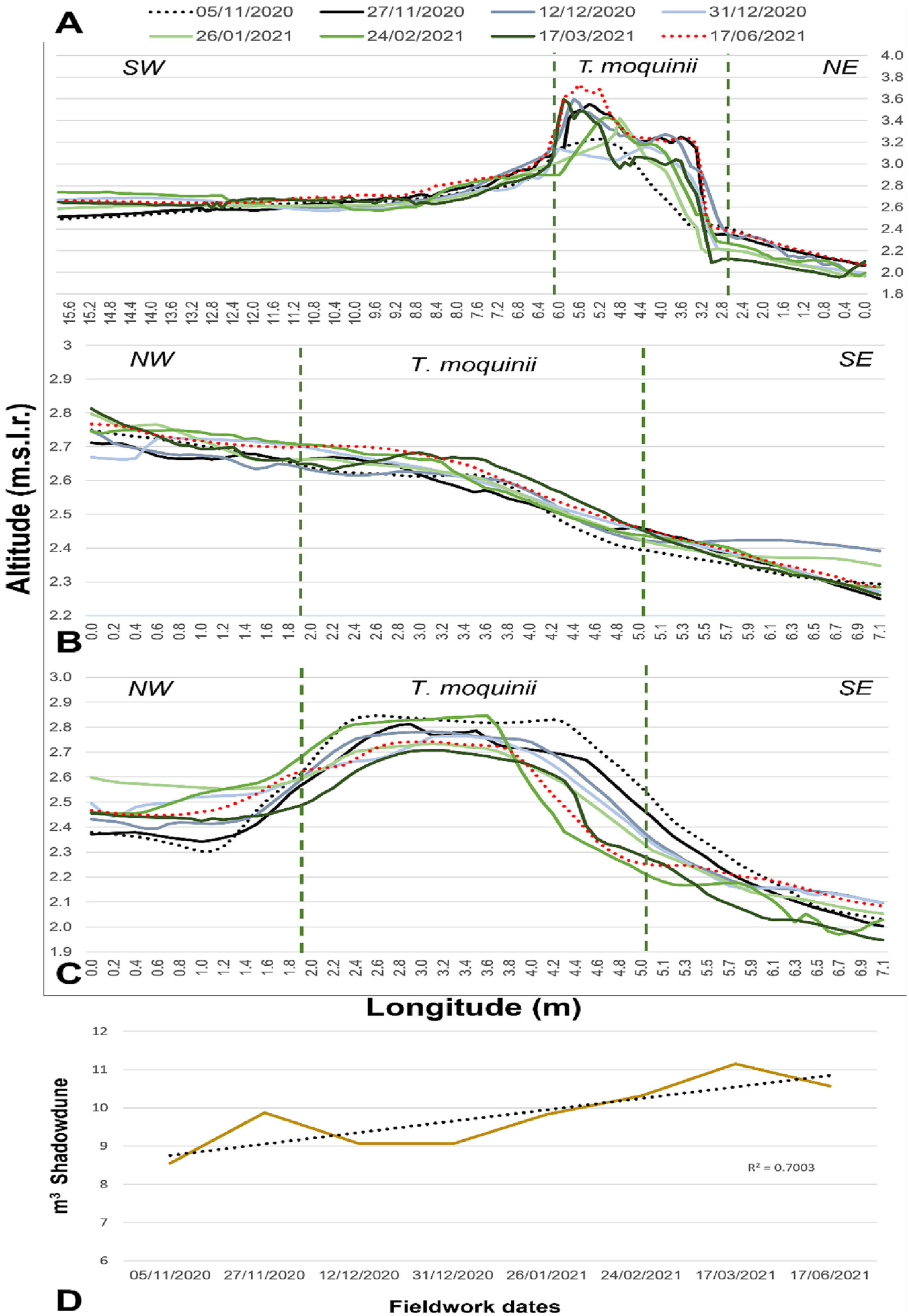

Fig. 8. Landform profiles evolution. A) Longitudinal profile. B and C) Transversal profiles. D) Volume evolution in the potential shadow dune (triangular polygon leeside of the nebkha). Note that dotted lines represent the initial (blue) and final (red) profiles.

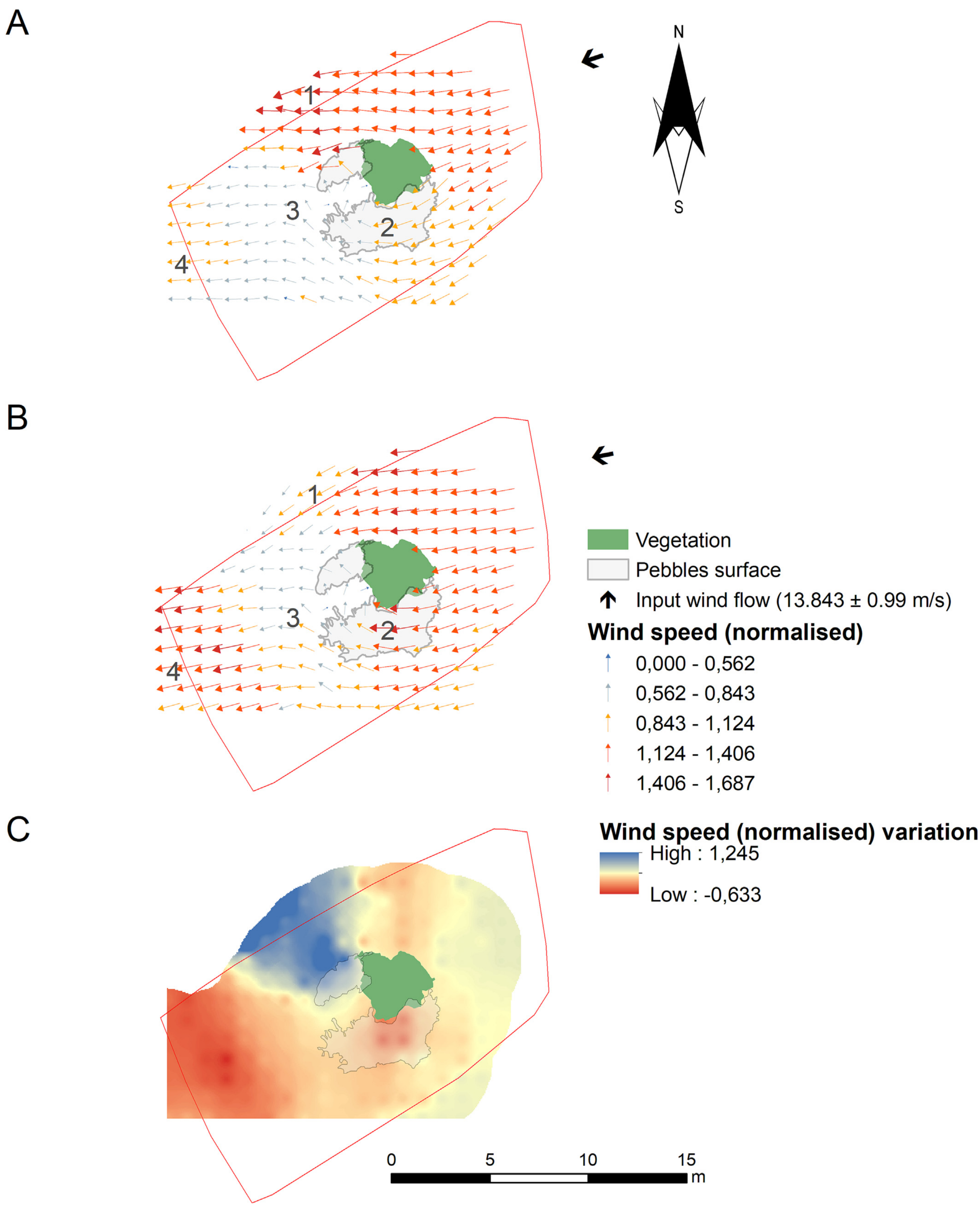

Fig. 9. Streamline distribution around the nebkha before pebble removal (A) and after pebble removal (B). Differences in wind speed after pebble removal (C). Input wind flow speed = 13.843 ± 0.99 m/s; Input wind flow direction = 78.984 ± 5.324°.

Fig. 10. Front and side views of the of the studied nebkha, goro and shadow dune in the initial state on 27/11/2020 (top) and almost one year after the start of the experiment on 27/10/2021 (bottom).

short period of time due to its own weight and gravity. Instead, a gradual dismantling of the *goro* over weeks would prevent the breakdown of branches and roots, as wind-blown sand naturally filled in the gaps left by the removal of stones. Our experience is that this process allowed the vegetation to gradually settle on fresh sand deposits. The roots also got progressively buried, which reactivated and rejuvenated *T. moquinii* specimens (Viera-Pérez, 2015).

(2) Stone-staking has consequences for source areas, such as impacting rock microhabitats and biodiversity (Rocha et al., 2020). At *Playa del Ingles*, most stones used to build *goros* and other structures come from coastal paleo-barriers. Additional to negative effects on rock-dwelling organisms, removing and transporting stones to other locations means destroying the paleo-barriers, and therefore a unique geological record. In line with Rocha et al. (2020), we recommend that authorities implement educational programmes about the importance of rock-associated habitats as they dismantle artificial stone structures and return pebbles to their original source areas.

Future research in arid dune systems such as those in the Canary Islands and other coastal areas is needed to further investigate the impact of stone structures in flora and fauna, as well as consequences for foredune mobility in the context of coastline change. This will also allow comparison of rates of dune recovery as well as investigation of other potential restoration interventions.

6. Conclusions

The construction of windbreaks by stacking stones over the foredune is a common practice on beach-dune systems, especially in those subject to large amounts of visitors. This research investigated the effects that stone structures built on arid environments have on the biogeomorphological processes and evolution of nebkha dunes. The study was conducted at *Playa del Inglés*, in the Canary Islands, where user-made stone windbreakers (locally called *goros*) have exponentially increased over the last decades since they first started to appear in the 1960s–1970s.

Our findings show that *goros* prevent the natural functioning of nebkhas. The *goro* acted as a 'flowerpot', modifying the porosity of the nebkha and limiting the capacity of *T. moquinii* to develop roots and branches. The stones made the flanks slopes steeper and prevented sand avalanches, limiting sediment transport to the nebkha leeside, and decreasing the volume of sediment available for shadow dune formation. The presence of the *goro* modified airflow patterns around the landform, speeding up the airflow on the windward side and creating a relatively large area of low (stagnated) wind speeds in the leeside. Following the removal of roughly 50 % of all stones, airflow circulation was restored in the wake area of the nebkha, and sediment transport was reactivated.

Stone structures in Gran Canaria had been dismantled before (Section 4.1) but without any monitoring of their evolution or data to assess restoration success. Our experience in dismantling a *goro* suggests that a) it is possible to restore nebkha foredunes negatively affected by the presence of stone structures; b) the stones should be removed gradually, allowing new sand to fill in the gaps and minimising the damage to vegetation; c) restoration is straightforward and inexpensive, and when combined with appropriate identification of stones original source areas, it can also lead to additional benefits such as the partial restoration of paleo-barriers.

Results presented in this study provide a biogeomorphological understanding of the effects that stone structures have on arid coastal dunes. We provide simple recommendations to management which, together with controls on visitors' pressure, will favour conditions for passive restoration of nebkha and the formation of shadow dunes associated to them.

CRediT authorship contribution statement

Abel Sanromualdo-Collado: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Writing – original draft, Writing – review & editing. **Leví García-Romero:** Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Visualization, Writing – original draft, Writing – review & editing. **Manuel Viera-Pérez:** Conceptualization, Data curation, Investigation, Methodology, Resources. **Irene Delgado-Fernández:** Formal analysis, Supervision, Writing – review &

editing. **Luis Hernández-Calvento:** Conceptualization, Resources, Project administration, Funding acquisition.

Data availability

Data will be made available on request.

Declaration of competing interest

No conflict of interest exists.

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