ULPGC
Universidad de
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Programa de Doctorado en Oceanografía y Cambio Global

Tesis Doctoral

Caracterización biogeomorfológica de la duna costera (foredune) en sistemas playa-duna áridos: naturaleza, amenazas y gestión

Biogeomorphological characterization of the foredune of arid beach-dune systems: nature, threats and management

Abel San Romualdo Collado

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Título de la Tesis: Caracterización biogeomorfológica de la duna costera (foredune) en sistemas playa-duna áridos: naturaleza, amenazas y gestión

Tesis Doctoral presentada por D. Abel San Romualdo Collado

Dirigida por el Dr. D. Luis Hernández Calvento

Codirigida por el Dr. D. Leví García Romero

Codirigida por la Dra. Dª. Irene Delgado Fernández

Las Palmas de Gran Canaria, a de de 2022

El Director,	El Codirector,	La Codirectora,	El Doctorando,
(firma)	(firma)	(firma)	(firma)

“The answer, my friend, is blowin’ in the wind”

Bob Dylan (1963)

NOTAS PRELIMINARES

*La elección de las fuentes tipográficas y los tamaños de letra utilizados en este documento se ha realizado buscando optimizar su legibilidad en dispositivos digitales (Ali et al., 2013; Hojjati & Muniandy, 2014).

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***La presente tesis doctoral opta a la Mención Internacional, por lo que algunos de sus contenidos se encuentran redactados en inglés.

Ali, A. Z. M., Wahid, R., Samsudin, K., & Idris, M. Z. (2013). Reading on the Computer Screen: Does Font Type Have Effects on Web Text Readability? *International Education Studies*, *6*(3), 26-35.

Hojjati, N., & Muniandy, B. (2014). The effects of font type and spacing of text for online readability and performance. Contemporary Educational Technology, 5(2), 161-174.

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A las islas Canarias en general y a la isla de Gran Canaria en particular, por poner su historia, su gente, su naturaleza y su espíritu al servicio de mi interés, mi inspiración, mi ocio y mi descanso.

A los amigos que vinieron en mi maleta y a los que han ido entrando. Por ser capaces de poner Segovia y Gran Canaria a distancia de abrazo. Por cuidarme y acompañarme durante de la primavera del 2020. Por estar asegurándome en el otro extremo de la cuerda. Porque ver juntos la Superbowl o cualquier otra excusa es buena para hablar un rato. Porque las penas se comparten mejor con un café (con leche sin lactosa) o unas papitas fritas. Por reencontrarnos 9 años después y 2.300 km más al sur. Por las visitas, las llamadas, los mensajes y los pensamientos. Gracias por ser y por estar.

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A María, por ser luz, compañía y refugio.

A todo aquel que se acerque a este documento con la intención de ir más allá de esta página.

¡GRACIAS!

TABLA DE CONTENIDO

PRESENTACIÓN

La presente tesis doctoral, titulada "Caracterización biogeomorfológica de la duna costera (*foredune*) en sistemas playa-duna áridos: naturaleza, amenazas y gestión", se ha realizado en el marco del *Programa de Doctorado en Oceanografía y Cambio Global* de la Escuela de Doctorado de la ULPGC, dentro de la línea de investigación "Oceanografía Biológica, Biotecnología y Medioambiente". En ella se recogen los resultados de 4 años de investigación como miembro del Grupo de Investigación *Geografía Física y Medio Ambiente* (GFyMA), adscrito al *Instituto de Oceanografía y Cambio Global* (IOCAG) de la Universidad de Las Palmas de Gran Canaria (ULPGC). La investigación realizada plantea objetivos propios de las líneas de investigación "Costas de islas volcánicas: procesos naturales e interacciones humanas" y "Sistemas sedimentarios eólicos áridos: procesos naturales e interacciones humanas" de dicho Grupo.

La investigación se ha desarrollado al amparo de un contrato de investigación con base en la ayuda BES-2017-082733 *de la Agencia Estatal de Investigación* (convocatoria de 2017) *de ayudas para contratos predoctorales para la formación de doctores contemplada en el Subprograma Estatal de Formación del Programa Estatal de Promoción del Talento y su Empleabilidad, en el marco del Plan Estatal de Investigación Científica y Técnica y de Innovación 2013-2016 (BOE nº224, de 16/09/2017)*, del Ministerio de Economía, Industria y Competitividad, y que ha contado con la cofinanciación del Fondo Social Europeo (FSE). Dicho contrato se formalizó en el ámbito del proyecto "Análisis de procesos naturales y humanos asociados a los sistemas playa-duna de Canarias" (ref. CSO2016-79673-R) del Programa Estatal de I+D+i Orientada a los Retos de la Sociedad, en el marco del Plan Estatal de Investigación Científica y Técnica y de Innovación 2013-2016, de la Secretaría de Estado de Investigación, Desarrollo e Innovación del Ministerio de Economía y Competitividad, cuyo investigador principal fue el Dr. Luis Hernández Calvento.

Luis Hernández Calvento actuó, a su vez, como tutor de la tesis doctoral y como director de la investigación, conjuntamente con el Dr. Leví García Romero, investigador postdoctoral en la ULPGC, y la Dra. Irene Delgado Fernández, Catedrática en Geomorfología de Costas en la Edge Hill University (UK) y, actualmente investigadora (acreditada a Catedrática por la ANECA) en la Universidad de Cádiz.

Los resultados de la investigación se presentan en esta tesis doctoral en formato de compendio de publicaciones sometidas a proceso de revisión por pares (*peer review*), conformando el *corpus* de la tesis 3 artículos publicados en revistas científicas internacionales con factor de impacto (JCR) y posicionadas en el primer cuartil (Q1), un artículo publicado en una revista incluida en el Emerging Sources Citation Index (ESCI) de WEB of SCIENCE (WOS), y los resultados de un quinto artículo, redactado y preparado para ser enviado a otra revista científica.

El texto se estructura en ocho capítulos:

- El primer capítulo recoge una introducción en la que establece el estado del conocimiento en lo referente a la caracterización de la duna costera de sistemas playa-duna localizados en regiones áridas, poniendo de manifiesto la necesidad de ampliar la frontera en lo relativo a su naturaleza, sus principales amenazas y la gestión desarrollada en ellas.
- El segundo capítulo expone la hipótesis de partida de la investigación, así como los objetivos generales y específicos derivados de ésta.
- El tercer capítulo presenta las características principales del área de estudio en el que se ha llevado a cabo la investigación.
- En el cuarto capítulo se presenta el proceso metodológico seguido para alcanzar los objetivos propuestos y contrastar las hipótesis.
- El quinto capítulo recoge los resultados de la investigación, publicados en los siguientes artículos, los cuales están ordenados por orden lógico, de acuerdo con el argumento de la investigación (no por orden cronológico de publicación):
    1. Environmental variables affecting an arid coastal nebkha. **Sanromualdo-Collado, A.**, Gallego-Fernández, J.B., Hesp, P.A., Martínez, M.L., O'Keeffe, N., Ferrer-Valero, N., Hernández-

Calvento, L. (2022). *Science of the Total Environment*, 815, 152868. https://doi.org/10.1016/j.scitotenv.2021.152868

2. Spatiotemporal analysis of the impact of artificial beach structures on biogeomorphological processes in an arid beach-dune system. **Sanromualdo-Collado, A.**, García-Romero, L., Peña-Alonso, C., Hernández-Cordero, A.I., Ferrer-Valero, N., Hernández-Calvento, L. (2021). *Journal of Environmental Manage*ment, 282, 111953. https://doi.org/10.1016/j.jenvman.2021.111953
3. Effects of stone-made wind shelter structures over an arid nebkha foredune. **Sanromualdo-Collado, A.,** García-Romero, L., Viera-Pérez, M., Delgado-Fernández, I., Hernández-Calvento, L. (*preparado para ser enviado*).
4. Foredune responses to the impact of aggregate extraction in an arid aeolian sedimentary system. **Sanromualdo-Collado, A**., Marrero-Rodríguez, N., García-Romero, L., Delgado-Fernández, I., Viera-Pérez, M., Domínguez-Brito, A. C., Cabrera-Gámez, J. (2022). *Earth Surfaces Processes and Landforms*, 47 (11), 2709–2725. https://doi.org/10.1002/esp.5419
5. Coastal Dune Restoration in El Inglés Beach (Gran Canaria, Spain): a Trial Study. **Sanromualdo-Collado, A.**, Hernández-Cordero, A.I., Viera-Pérez, M., Gallego-Fernández, J.B., Hernández-Calvento, L. (2021). *Revista de Estudios Andaluces,* 41, 187–204. https://doi.org/10.12795/rea.2021.i41.10

- En el sexto capítulo se presenta una discusión general de los resultados y se recogen las conclusiones generales de la investigación.
- En el séptimo capítulo se proponen perspectivas futuras de investigación sobre la base del trabajo presentado en esta tesis doctoral.
- El octavo y último capítulo recoge las distintas actividades de formación, docentes y de divulgación realizadas durante este periodo, y se muestra el alcance y la transferencia de los resultados de la investigación a la sociedad.

RESUMEN

La complejidad de los sistemas playa-duna deriva tanto de su condición de frontera física entre el medio terrestre y marino como de su funcionalidad ambiental, social y económica. La duna costera (*foredune*), primera línea de dunas costeras, cobra especial relevancia como elemento fundamental encargado de conectar y regular la interacción entre las playas y los sistemas dunares asociados.

Las especificidades de las condiciones climáticas áridas no solo condicionan la naturaleza de las *foredunes* localizadas en estos ambientes, sino que también repercuten en los efectos biogeomorfológicos derivados de los usos asociados a la actividad social y económica. En este sentido, las *foredunes* de los sistemas playa-duna de las islas Canarias son un excelente ejemplo de la complejidad de estos sistemas. A la movilidad del sedimento y los procesos naturales, derivados de las altas temperaturas y la escasa precipitación, se une una actividad humana prácticamente constante a lo largo del año que es susceptible de afectar y alterar dichos procesos, lo que, a su vez, pone de manifiesto la importancia de la gestión ambiental realizada en estos espacios. La actividad humana sobre los sistemas playa-duna de las islas Canarias en general, y de su *foredune* en particular, se ha incrementado desde la década de 1960, ligada al desarrollo urbano-turístico alrededor de los sistemas sedimentarios eólicos de las islas motivado por el cambio de modelo socioeconómico de la región. A pesar de la existencia de estudios previos que han caracterizado algunos de los impactos que la actividad urbano-turística ocasiona sobre las dunas costeras y las playas de las islas Canarias, el conocimiento sobre el comportamiento de las *foredunes* áridas en condiciones naturales y su evolución en presencia de interferencias humanas es todavía escaso.

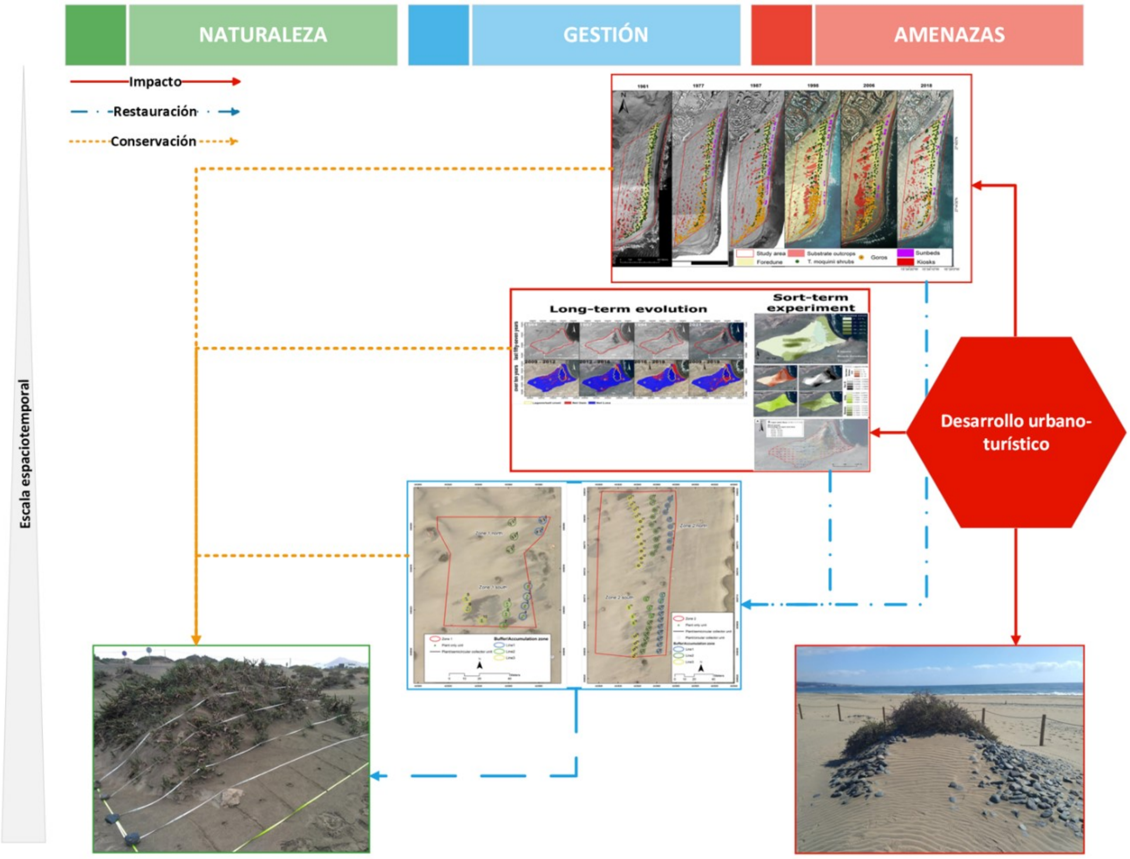
Considerando estos precedentes, esta investigación pretende atender los vacíos de conocimiento detectados sobre la caracterización detallada de los procesos biogeomorfológicos de las *foredunes* localizadas en sistemas playa-duna áridos formadas especialmente por nebkhas, incluyendo los procesos naturales y su interacción con los usos humanos.

Para ello se desarrolló una metodología en dos escalas espaciotemporales. La primera escala analizó la evolución biogeomorfológica de las *foredunes* a largo plazo (decadal) mediante el uso de fuentes históricas e imágenes aéreas, entre otras técnicas. La segunda escala se centró en experimentos a corto plazo y en el análisis de las variables y procesos comprendidos en la dinámica de las *foredunes* áridas.

Los resultados ponen de manifiesto que las especificidades climáticas, ambientales y sociales de los sistemas playa-duna áridos condicionan el comportamiento y la evolución biogeomorfológica de los sistemas playa-duna áridos en general, y sus *foredunes*, en particular. La caracterización detallada de las interacciones naturales entre variables y procesos ambientales, así como de los impactos producidos por la actividad humana y sus efectos asociados, facilita la propuesta de medidas de gestión basadas en información científica actualizada. En caso de ser necesario, esta investigación propone acciones de restauración adaptadas a dichas especificidades que permiten la conciliación del uso humano con la conservación de estos espacios de importancia singular.

Palabras clave: *nebkha*; islas Canarias; *Traganum moquinii*; impactos humanos; restauración ambiental; dinámica eólica árida.

RESUMEN GRÁFICO



PRESENTATION

This Ph. D. thesis, titled "Biogeomorphological characterization of the foredune of arid beach-dune systems: nature, threats and management", carried out within the framework of the Oceanography and Global Change PhD Program, ULPGC Doctoral School, specifically within the "Biological oceanography, Biotechnology and Environment" research line. It summarises 4 years of investigations as a member of the *Geografía Física y Medio Ambiente (GFyMA)* research group, at the *Instituto de Oceanografía y Cambio Global (IOCAG)*, University of Las Palmas de Gran Canaria (ULPGC). This study addresses several *GFyMA* objectives within the following research lines: "Coasts of volcanic islands: natural processes and human interactions" and "Arid aeolian sedimentary systems: natural processes and human interactions".

The work has been conducted under a research contract (BES-2017-182733) following the *Resolución de la Presidencia de la Agencia Estatal de Investigación por que se aprueba la convocatoria, correspondiente al año 2017 de las ayudas para contratos predoctorales para la formación de doctores contemplada en el Subprograma Estatal de Formación del Programa Estatal de Promoción del Talento y su Empleabilidad, en el marco del Plan Estatal de Investigación Científica y Técnica y de Innovación 2013-2016 (extracto publicado en BOE nº224, de 16/09/2017),* supported by the Spanish Ministry of Economy, Industry and Competitiviness and co-financed by the European Social Fund (ESF). This contract was formalized within the framework of the project "Analysis of natural and human processes associated with beach-dune systems of the Canary Islands" (ref. CSO2016-79673-R) of the National Program of R&D Oriented to Challenges of the Society, of the *Secretaría de Estado de Investigación, Desarrollo e Innovación del Ministerio de Economía y Competitividad*, whose principal investigator was Dr. Luis Hernández Calvento.

Luis Hernández Calvento was academic tutor and co-director of PhD thesis, in collaboration with Dr. Leví García Romero, postdoctoral researcher at ULPGC, and Dr. Irene Delgado Fernández, Professor of Coastal Geomorphology by Edge Hill University (UK) and ANECA (Spain), and currently a researcher at University of Cádiz.

Results of this doctoral thesis are presented as a compendium of 5 publications: three peer-reviewed papers published in international scientific journals with impact factor (JCR) and positioned in quartile 1 (Q1), one peer-reviewed article published in a journal included in the Emerging Sources Citation Index (ESCI) of the WEB of SCIENCE, and one finished manuscript ready to be sent to a peer-reviewed international journal.

This document is structured in eight chapters:

- Chapter 1 consists of an introduction that establishes the state of knowledge on the characterisation of foredunes in beach-dune systems located in arid regions, and the need to investigate their nature, main threats, and management.
- Chapter 2 sets out the hypotheses of the research, as well as general and specific objectives.
- Chapter 3 characterises the areas of study in this thesis.
- Chapter 4 summarises the methods and techniques used to address objectives and test hypotheses.
- Chapter 5 presents the research results in the form of scientific articles logically ordered by argument (instead of publication date):
    1. Environmental variables affecting an arid coastal nebkha. **Sanromualdo-Collado, A.**, Gallego-Fernández, J.B., Hesp, P.A., Martínez, M.L., O'Keeffe, N., Ferrer-Valero, N., Hernández-Calvento, L. (2022). *Science of the Total Environment*, 815, 152868. https://doi.org/10.1016/j.scitotenv.2021.152868
    2. Spatiotemporal analysis of the impact of artificial beach structures on biogeomorphological processes in an arid beach-dune system. **Sanromualdo-Collado, A.**, García-Romero, L., Peña-Alonso, C., Hernández-Cordero, A.I., Ferrer-Valero, N., Hernández-Calvento, L. (2021). *Journal of Environmental Management*, 282, 111953. https://doi.org/10.1016/j.jenvman.2021.111953

3. Effects of stone-made wind shelter structures over an arid nebkha foredune. **Sanromualdo-Collado, A.,** García-Romero, L., Viera-Pérez, M., Delgado-Fernández, I., Hernández-Calvento, L. (*ready for submission*).
4. Foredune responses to the impact of aggregate extraction in an arid aeolian sedimentary system. **Sanromualdo-Collado, A**., Marrero-Rodríguez, N., García-Romero, L., Delgado-Fernández, I., Viera-Pérez, M., Domínguez-Brito, A. C., Cabrera-Gámez, J. (2022). *Earth Surfaces Processes and Landforms*, 47 (11), 2709–2725. https://doi.org/10.1002/esp.5419
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- Chapter 6 discusses results in detail and elaborates the main conclusions of this research.
- Chapter 7 proposes future research and new perspectives arising from this PhD work.
- Chapter 8 lists some of the various training, teaching and dissemination activities carried out during the research period and shows the scope and transfer of the research results to the society.

ABSTRACT

The complexity of beach-dune systems is due not only to their condition as border environments between terrestrial and marine processes, but also to their environmental, social and economic functions. Foredunes, the first line of coastal dunes, play a particularly important role as they connect and regulate the interaction between dynamic beaches seawards, and associated dune fields landwards.

Aridity not only determines the nature of foredunes in arid environments, but it also influences the biogeomorphological effects of human activities carried out on them. Foredunes of beach-dune systems in the Canary Islands are an excellent example of the complexity of these systems. In addition to mobility rates and natural processes characteristic from dunes affected by high temperature and scarce precipitation, all-year round human activities affect these processes, which points to the importance of management carried out in these areas. Human activity on beach-dune systems in the Canary Islands in general, an on their foredunes in particular, has increased since the 1960s, when changes to socio-economic models in the region led to increases in urbanization and the development of a touristic industry that depended on beach-dune systems, but strongly affected these environments. While previous studies have characterised some of the impacts that urbanization and tourism have on coastal dunes and beaches in the Canary Islands, knowledge about the behaviour of natural arid foredunes, and their evolution in the presence of human interferences was still scarce.

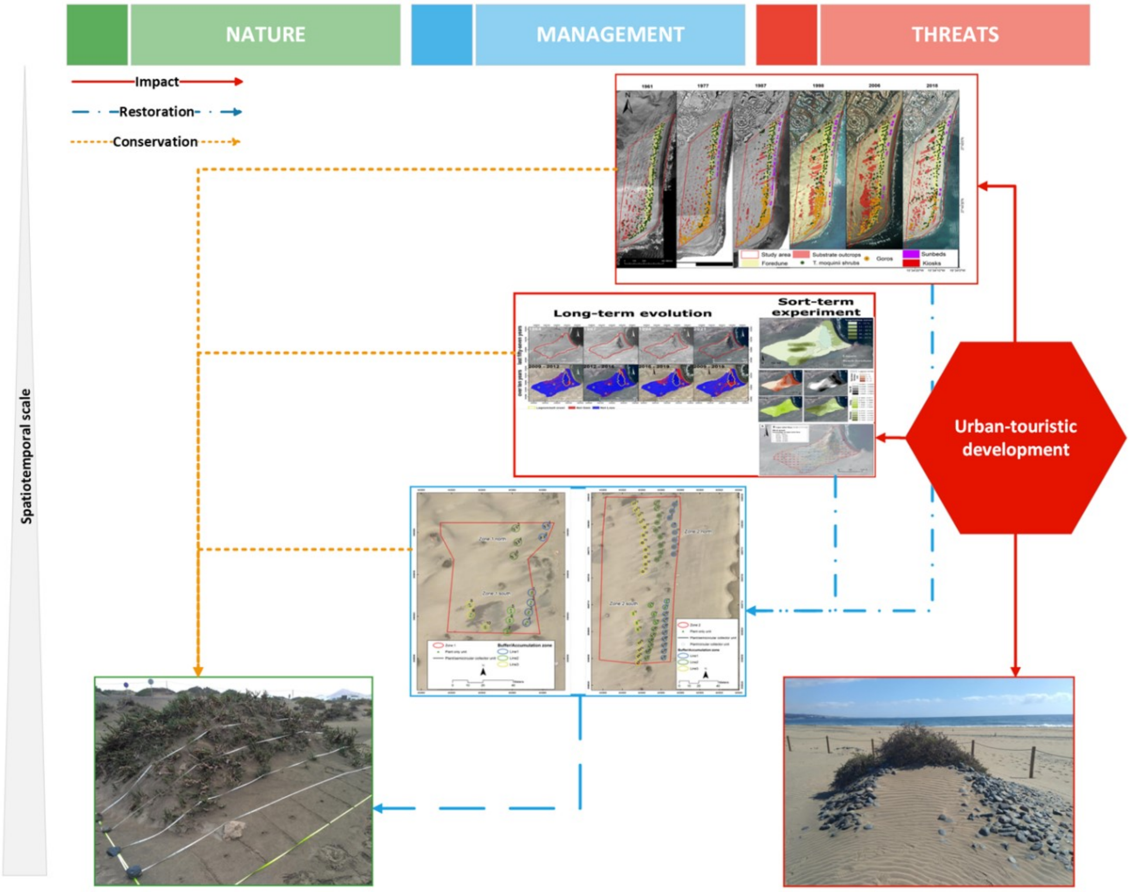
This PhD research aimed at filling important knowledge gaps regarding the biogeomorphological characterisation of arid foredunes formed by nebkhas, including the natural processes and their interaction with human uses.

To this end, the methodology was developed to target two spatiotemporal scales. The first scale analysed the biogeomorphological evolution of foredunes in the long-term (decadal) by using historical sources and aerial imagery among other techniques. The second scale focused on short-term experiments and the analysis of variables and processes involved in arid foredune dynamics.

Results show that climatic, environmental and social variables drive the biogeomorphological behaviour and evolution of arid beach-dune systems in general, and of arid foredunes in particular. The detailed characterisation of natural interactions between environmental drivers and responses, as well as the impacts produced by human activities, facilitate up-to-date scientific information to management. Where appropriate, this PhD work proposes restoration actions that allow the conciliation of human uses with the conservation of these uniquely important areas.

Keywords: nebkha; Canary Islands; *Traganum moquinii*; human impacts, environmental restoration; arid aeolian dynamics.

GRAPHICAL ABSTRACT



INTRODUCCIÓN

El contenido de esta investigación se vertebra sobre tres ejes temáticos fundamentales referidos a la caracterización biogeomorfológica de la duna costera en los sistemas playa-duna localizados en regiones áridas (Figura 1): i) la naturaleza, entendida como el conjunto de elementos y procesos que interactúan en condiciones naturales para conformar el espacio; ii) las amenazas, centradas, en el caso concreto de esta investigación, en aquellos efectos derivados de la actividad humana que son susceptibles de producir consecuencias negativas sobre el entorno; y iii) la gestión llevada a cabo en estos espacios, responsable última de los usos permitidos y de las acciones desarrolladas.

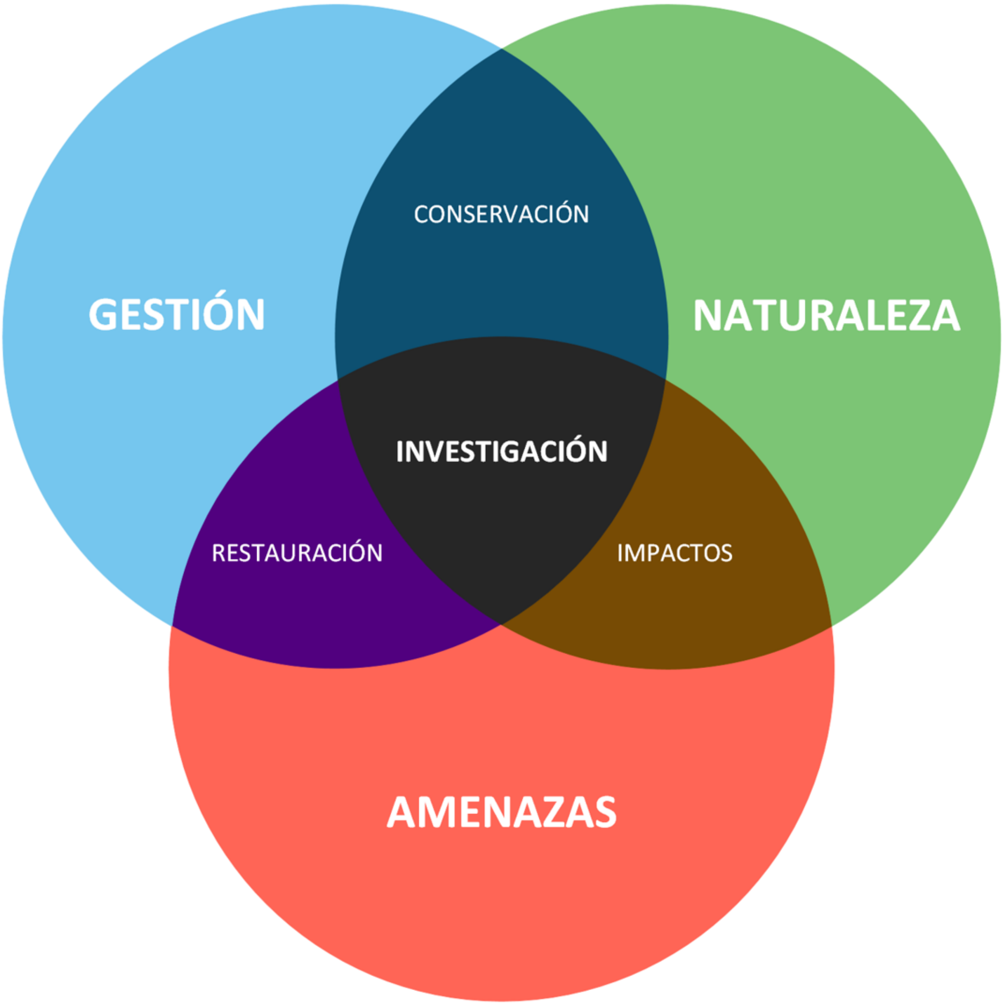


Figura 1: Integración de los ejes temáticos en el contexto de la investigación.

Sobre estos tres ejes temáticos se sitúa el concepto de *caracterización biogeomorfológica*, motivo principal de la investigación desarrollada. El concepto de *biogeomorfología* (Corenblit et al., 2011) hace referencia a la unión recíproca entre los procesos de la superficie terrestre y sus accidentes geográficos, y los procesos ecológicos y evolutivos; de forma que cuando la vegetación (*fitogeomorfología*) coloniza una parte de la superficie terrestre, produce cambios complejos en los procesos naturales, generando geoformas que están íntimamente relacionadas con la evolución de la vida (Davies and Gibling, 2010; Murray et al., 2008). Así, la *caracterización biogeomorfológica* sobre la que se centra esta investigación atiende al análisis de los cambios inducidos por la vegetación al interferir sobre los procesos físicos naturales para dar lugar a geoformas características (Hesp, 1981). Este enfoque no es sencillo, en tanto que requiere un consenso entre distintos campos de la Ciencia. Así, desde la Geomorfología, se debe aceptar la necesidad de incorporar a la investigación conocimiento sobre la vegetación y los ecosistemas, mientras que los estudios realizados desde la Ecología deben considerar necesariamente evaluaciones geomorfológicas y relacionadas con los procesos hidrológicos cuando traten de entender los patrones de la vegetación y los ecosistemas (Wainwright, 2009). Además, en el contexto de cambio global derivado del Antropoceno reciente, es imprescindible incorporar al análisis biogeomorfológico los efectos que el ser humano, como especie, está produciendo sobre los procesos naturales (Crutzen, 2006; Zalasiewicz et al., 2008).

Esta íntima relación entre la actividad humana, la vegetación y los cambios que estas provocan en los procesos físicos de la superficie terrestre y sus geoformas fundamenta el enfoque abordado en esta tesis para la caracterización biogeomorfológica de la duna costera de sistemas playa-duna áridos atendiendo a la naturaleza, las amenazas y la gestión.

PROCESOS NATURALES EN LA DUNA COSTERA DE SISTEMAS PLAYA-DUNA ÁRIDOS

Los sistemas playa-duna son ecosistemas localizados en la interfase entre los ambientes marinos y continentales. La gran relevancia a nivel socioecológico que poseen estos sistemas deriva de su papel como fuente de servicios y recursos para el bienestar de la población, entre los que se incluyen el control de la erosión costera, su valor educativo, recreativo y científico, su uso como espacios de esparcimiento y relajación, o la provisión de servicios culturales y hábitats para la diversidad de determinadas especies de flora y fauna (Arévalo-Valenzuela et al., 2021; Barbier et al., 2011; Dang et al., 2021; Everard et al., 2010; Lithgow et al., 2013; Marrero-Rodríguez et al., 2021b; Martínez et al., 2013; Mendoza-González et al., 2021; Miththapala, 2008; Richardson and Nicholls, 2021). Esta relevancia explica, por un lado, el aumento en las últimas décadas del uso de estos espacios por parte de la población como destino recreativo y de descanso y, por otro lado, el aumento del interés científico en la caracterización y la monitorización de la evolución de estos espacios (Bauer et al., 2015; Bon de Sousa et al., 2022; Cabrera-Vega et al., 2013b; Delgado-Fernández et al., 2013; Di Paola et al., 2020; Fontán-Bouzas et al., 2019; García-Romero et al., 2021; Hernández-Calvento, 2006; Moulton et al., 2021; Nicolae Lerma et al., 2022; Pérez-Chacón et al., 2010; Walker et al., 2017).

El papel de la foredune en sistemas playa-duna

Dentro de los sistemas playa-duna, la duna costera (*foredune*) se puede entender como una estructura biogeomorfológica formada por la dinámica sedimentaria eólica desde la playa (Figura 2), especialmente desde el intermareal (*foreshore*), y que resulta en la deposición de sedimento por acción de la vegetación en la parte alta (*backshore)* de las playas (Davidson-Arnott et al., 2019). Por tanto, se trata de una parte muy dinámica de los sistemas playa-duna, debido a que está bajo la influencia de la acción marina y eólica (Cohn et al., 2018; Donker et al., 2018; Hesp, 2012; Sherman and Bauer, 1993). A su vez, es una estructura fundamental para el funcionamiento de los sistemas playa-duna en tanto que, entre otras funciones, proporciona protección a la costa arenosa frente a temporales marinos (Feagin et al., 2019; Ley et al., 2007; Maximiliano-Cordova et al., 2021, 2019), regula la erosión costera de estos ambientes (Carter and Stone, 1989; Davidson et al., 2020; Feagin et al., 2005), proporciona hábitats para especies características (Hernández-Cordero et al., 2015a; Martínez et al., 2020) y mantiene el balance sedimentario entre la playa y las dunas (Bauer et al., 2015; Everard et al., 2010; García-Romero et al., 2021; Hernández-Cordero et al., 2015b; Silva et al., 2019; Viera-Pérez, 2015).

La formación, la dinámica y la morfología de la *foredune* están condicionadas por el equilibrio entre factores ambientales, como el transporte eólico, los procesos hidrodinámicos de la costa, la disposición de sedimento y las características morfológicas y sedimentológicas de la playa (Aagaard et al., 2004; Bauer et al., 2009, 2015; Bauer and Davidson-Arnott, 2002; Costas et al., 2020a; Davidson-Arnott et al., 2005, 2018; Delgado-Fernandez, 2011; Delgado-Fernández et al., 2013; Hesp, 2002, 2012; Hesp et al., 2021b; Pellón et al., 2020; Rader et al., 2018; Silva et al., 2019; Walker et al., 2021). En este sentido, la estimación de las tasas de transporte de sedimento por la actividad eólica en estos ambientes sigue siendo una cuestión compleja y recurrente de investigación, que es abordada desde distintos campos y que centra gran parte de los esfuerzos de investigación actuales en ampliar el conocimiento de la física del transporte sedimentario y del flujo de viento mediante la recogida de datos experimentales (Aagaard et al., 2004; Baas et al., 2020; Barchyn et al., 2014; Bauer et al., 2015; Davidson-Arnott et al., 2012; Davidson et al., 2022; Domínguez-Brito et al., 2020; Eichmanns and Schüttrumpf, 2020; Farrell et al., 2012; Gillies et al., 2014; Grilliot et al., 2019a; Hernández-Cordero et al., 2015b; Hesp et al., 2005; Hugenholtz and Barchyn, 2011; Jackson and Nordstrom, 2013; Kuriyama et al., 2005; Lancaster et al., 2002; Lynch et al., 2008; Mayaud et al., 2016; Nguyen et al., 2021; Nordstrom et al., 2011, 2007; Poppema et al., 2022; Rotnicka and Dłu˙ Zewski, 2022; Shumack et al., 2022; Terwisscha van Scheltinga et al., 2021; Yang et al., 2019; Zhao et al., 2021) y el desarrollo de modelos específicos (Baas and Nield, 2007; Bauer and Davidson-Arnott, 2002; Burkow and Griebel, 2016; Charbonneau et al., 2022; Cohn et al., 2019; Delgado-Fernandez, 2011; Delgado-Fernández, 2010; González et al., 2007; Hesp and Smyth, 2016b, 2016a; Huang et al., 2020; Keijsers et al., 2016; Latif Bhutto et al., 2022; Le Ribault et al., 2021; Li et al., 2022; Mayaud et al., 2017b; McKenna Neuman and Bédard, 2015; Namikas, 2003; Nield and Baas, 2008a; Parteli et al., 2014; Pourteimouri et al., 2021; Roelvink and Costas, 2019; Smyth and Hesp, 2015; Suter-Burri et al., 2013; Sutton and McKenna Neuman, 2008; van Rijn, 2022; van Rijn and Strypsteen, 2020; Wakes et al., 2010; Walker and Nickling, 2002; Xiao et al., 2021; Zhang et al., 2015). Sin embargo, las comparaciones entre ambos ponen de manifiesto la necesidad de invertir más esfuerzos para mejorar la capacidad predictiva de dichos modelos (Bauer and Sherman, 1999; Davidson-Arnott et al., 2018; Fu, 2019; Sherman, 2020, 1995).

Figura 2: Ejemplo de duna costera. Flecha de El Rompido, Lepe (Huelva). Fuente: Juan B. Gallego.

Entre los factores relacionados con la vegetación, uno de los principales que intervienen en la formación, la dinámica y la morfología de la *foredune* es la tipología de las plantas (arbórea, arbustiva o herbácea) y su desarrollo en el espacio y en el tiempo, en términos de densidad, cobertura o distribución de las especies (Biel et al., 2019; da Silva et al., 2008; Hesp, 2002, 1991, 1984; Keijsers et al., 2015; Lancaster and Baas, 1998; Martínez et al., 2001; Moreno-Casasola, 1986; Shumack et al., 2022; Van Puijenbroek et al., 2017). A su vez, el tipo de vegetación presente en los sistemas playa-duna, que determina el modo de desarrollo de la *foredune,* está condicionado, a escala global, por las características climáticas (García-Romero et al., 2019c; Hesp, 2002; Hesp et al., 2021a; Hesp and Walker, 2021; Nield and Baas, 2008b).

En las regiones costeras áridas del planeta (Köppen, 1900; Kottek et al., 2006) la vegetación de la *foredune* presenta una apariencia distinta a aquella localizada en regiones templadas (Figura 2) y tropicales, donde la cobertura y densidad de la vegetación son mayores, dando lugar a una *foredune* continua o semicontinua paralela a la línea de costa (Hesp, 2002; Hesp et al., 2021a; Hesp and Walker, 2013; Keijsers et al., 2015; Nield and Baas, 2008b). Sin embargo, la escasez de precipitaciones y las temperaturas elevadas y relativamente constantes de las regiones áridas, que inducen una alta evaporación, condicionan que la vegetación desarrollada sea escasa y generalmente de tipo arbustivo y con baja densidad (Buis et al., 2010; Hernández-Cordero et al., 2015c; Luo and Zhao, 2019). La interacción entre la dinámica sedimentaria eólica y la vegetación arbustiva dispersa da lugar a una morfología de la *foredune* en regiones áridas (Figura 3) estructurada fundamentalmente por *nebkhas* aisladas que se reparten paralelas a la línea de costa (García-Romero et al., 2021; Hernández-Calvento, 2006; Hernández-Cordero et al., 2019, 2012; Hesp et al., 2021a; Hesp and Walker, 2013; Nield and Baas, 2008a; Viera-Pérez, 2015). En presencia de sedimento suficiente, a sotavento de las *nebkhas se* generan acumulaciones conocidas como dunas de sombra (*shadow dunes*), de forma triangular y con una cresta afilada debida a los vórtices generados en los flancos de la *nebkha* (Cooke et al., 1993; Hesp, 1981; Hesp and Smyth, 2017; Zhao et al., 2019a; Zhao and Gao, 2021).

Las nebkhas como estructuradoras de la foredune en regiones áridas

Las *nebkhas* o dunas en montículo (también nombradas en la literatura internacional como: *coppice dunes, hummock dunes, sand mounds* o *phytogenic dunes)* son dunas fijas formadas por la acumulación de sedimento alrededor o en el interior de plantas discretas (Cooke et al., 1993; Goudie, 2022; Hesp and McLachlan, 2000). Las *nebkhas* se distribuyen de forma global por las regiones áridas y semiáridas del planeta (Goudie, 2022; Li et al., 2020), por lo que han sido objeto de amplio interés científico en lo referente a su tamaño y su morfología (Al-Awadhi and Al-Dousari, 2013;

Amini et al., 2012; Du et al., 2010; El-Bana et al., 2002; Khalaf et al., 2014; Khalaf and Al-Awadhi, 2012; Lang et al., 2013; Li and Ravi, 2018; Li et al., 2021; Luo et al., 2021; Luo and Zhao, 2019; Nickling and Wolfe, 1994; Zhang et al., 2020; Zhou et al., 2015), a su distribución (Bradley et al., 2019; Buis et al., 2010; El-Bana et al., 2002; Luo et al., 2016; Nield and Baas, 2008a; Quets et al., 2013; Yousefi Lalimi et al., 2017; Zhou et al., 2015), a la interacción entre la dinámica sedimentaria eólica y la vegetación formadora de la *nebkha* y de la *shadow dune* (Al-Awadhi, 2014; Baas and Nield, 2007; Charbonneau et al., 2021; Cheng et al., 2018; Cooke et al., 1993; Dupont et al., 2014; Gillies et al., 2014; Hesp, 1981; Hesp et al., 2021b; Hesp and Smyth, 2017; Latif Bhutto et al., 2022; Li and Ravi, 2018; Liu et al., 2018; Luo et al., 2012; Mayaud et al., 2017a; Mayaud and Webb, 2017; Okin, 2013; Quets et al., 2013; Shumack et al., 2022; Walker et al., 2021; Yang et al., 2019; Zhao et al., 2020, 2019a; Zhao and Gao, 2021), a las características del material sedimentario que las conforman (Al-Awadhi and Al-Dousari, 2013; Al-Dousari et al., 2008; Arens, 1996; Ebrahimi Meymand et al., 2020; Khalaf and Al-Awadhi, 2012; Kidron and Zohar, 2016; Kono and Okuro, 2021; Lee et al., 2019; Li and Ravi, 2018; Ravi et al., 2007; Xiaohong et al., 2019) y a su función ecológica y ambiental (Buis et al., 2010; El-Bana et al., 2007, 2003, 2002; El-Bana and Al-Mathnani, 2009; Ravi et al., 2010; Schlesinger et al., 1996; Wang et al., 2010, 2006; Webb et al., 2021; Zhang et al., 2020; Zhao et al., 2019b).

De manera más específica, la literatura científica sobre la naturaleza de las *nebkhas* localizadas en sistemas de dunas costeros, en general, y en su *foredune*, en particular, ha puesto el foco en la caracterización morfológica y sedimentaria de las geoformas eólicas (Hernández-Cordero et al., 2012; Khalaf et al., 2014; Khalaf and Al-Awadhi, 2012), en el efecto de la interacción entre la vegetación y los procesos sedimentarios eólicos para la formación de la *foredune* (Cabrera-Vega et al., 2013b; Charbonneau et al., 2021; Van Puijenbroek et al., 2017; Viera-Pérez, 2015) y en la función de las *nebkhas* dentro del ecosistema dunar costero (Badreldin et al., 2015; El-Bana et al., 2007, 2003, 2002; Hernández-Cordero et al., 2015c).

La foredune en los sistemas playa-duna de Canarias

En este campo, las islas Canarias son un área recurrente para el estudio de los sistemas playa-duna áridos y de sus *foredunes* estructuradas mediante *nebkhas* (Hernández-Cordero et al., 2019), en tanto que albergan sistemas sedimentarios eólicos de especial valor debido a la escasez de sistemas similares en otras islas oceánicas (Hernández-Calvento et al., 2017). A esta exclusividad se une el hecho de que la aridez característica de las costas canarias acelera la dinámica de los procesos naturales con respecto a los sistemas sedimentarios eólicos de regiones templadas, debido al menor papel que ejerce la vegetación y a las limitaciones impuestas por la escasez de precipitaciones (Cabrera-Vega et al., 2013b; Hernández-Cordero et al., 2018; Hesp, 2013). Este alto dinamismo de los procesos sedimentarios eólicos, a su vez, facilita la observación de los efectos y alteraciones que se puedan producir al interferir en los procesos (García-Romero et al., 2019b; Hernández-Calvento et al., 2014; Hernández-Cordero et al., 2018).

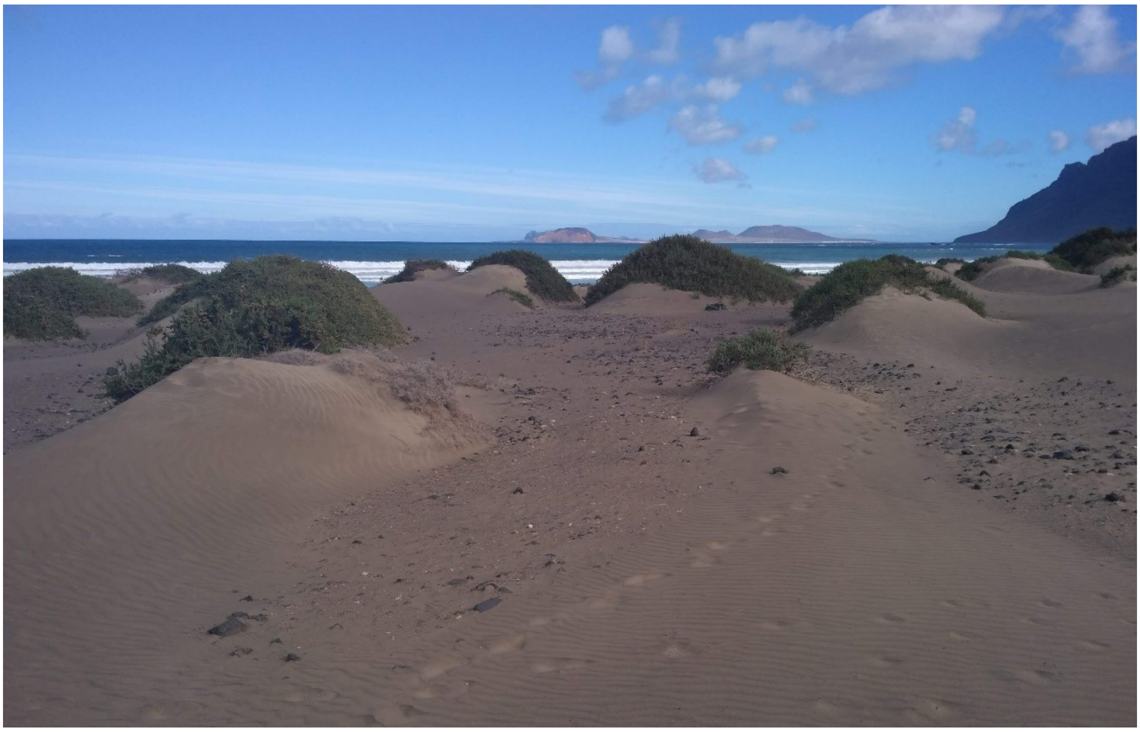


Figura 3: Ejemplo de duna costera árida. Caleta de Famara (Lanzarote).

La *foredune* de los sistemas playa-duna de las islas Canarias comprende las *nebkhas* como su unidad biogemorfológica fundamental (Domínguez-Brito et al., 2020; García-Romero et al., 2021; Hernández-Cordero et al., 2019, 2012; Hesp et al., 2021b, 2021a; Marrero-Rodríguez et al., 2020a; Pérez-Chacón et al., 2010; Viera-Pérez, 2015). Las características climáticas áridas condicionan el desarrollo de la vegetación y de la *foredune* a partir de *nebkhas* generadas alrededor de vegetación arbustiva (García-Romero et al., 2019c; Hesp et al., 2021a), mientras que la disponibilidad de sedimento para el transporte eólico condiciona, a su vez, el tamaño y número de *nebkhas* (Hesp et al., 2021b) y la tipología del sistema de dunas transgresivo desarrollado (Pickart and Hesp, 2019).

De acuerdo con la clasificación de Hesp y Walker (2013), en las islas Canarias se encuentran dos tipologías de sistemas de dunas transgresivos: i) campos de dunas transgresivos (*transgressive dunefields*), cuando la disponibilidad de sedimento es abundante; y ii) mantos de dunas transgresivos (*transgressive dune sheets*), cuando la disponibilidad de sedimento es escasa (Hernández-Cordero et al., 2019). El bajo volumen de sedimento disponible en los mantos de dunas transgresivos limita la formación de geoformas complejas, como dunas libres, y facilita la colonización por distintas comunidades de plantas arbustivas y herbáceas en función de la distancia a la costa, la movilidad y el volumen del sedimento disponible y del tipo de sustrato (Pérez-Chacón et al., 2010). La movilidad y el volumen de sedimento disponible condicionan las principales geoformas eólicas desarrolladas y la vegetación dominante, pudiendo dar lugar a mantos eólicos (*sand sheets*) o campos de nebkhas (*nebkha fields*), que pueden encontrarse activos o estabilizados (Hernández-Cordero et al., 2015a; Pérez-Chacón et al., 2010). Por otra parte, los campos de dunas transgresivos, con un abundante volumen de sedimento y una alta movilidad, presentan una amplia variedad y complejidad de geoformas eólicas que incluyen dunas fijadas por la vegetación (e. g. *nebkhas* y dunas de sombra), dunas libres (e. g. dunas barjanas y cordones barjanoides), geoformas erosivas (e. g. superficies de deflación y *blowouts*) o dunas dependientes del relieve (e. g. dunas rampantes y dunas de caída) (García-Romero et al., 2019a; Hernández-Calvento, 2006; Hernández-Cordero et al., 2015b; Hesp et al., 2011; Hesp and Walker, 2013; Pickart and Hesp, 2019).

En ambos casos, la *foredune* se desarrolla a partir de *nebkhas* de tamaño y altura variable en la zona alta de la playa (*backshore*), donde el sedimento transportado por la dinámica eólica forma las primeras dunas por interacción con la vegetación pionera. A diferencia de las regiones templadas, donde las *nebkhas* embrionarias están formadas generalmente por herbáceas perennes rizomatosas (e. g. *Ammophila spp.*) que crecen y se fusionan para formar cordones continuos o barreras paralelas a la línea de costa (Hesp, 2002; Hesp and Walker, 2013; Keijsers et al., 2015), en la *foredune* de los sistemas playa-duna áridos las plantas que estructuran las *nebkhas* de la *foredune* son especies leñosas de porte arbustivo (principalmente de la especie *Traganum moquinii*), sin posibilidad de extenderse y fusionarse para formar cordones de vegetación continuos (García-Romero et al., 2021; Hernández-Cordero et al., 2012; Hesp et al., 2021a; Viera-Pérez, 2015). La vegetación presente en los sistemas de dunas costeros y su zonificación también está condicionada por la distancia al mar, que genera un marcado gradiente de estrés ambiental (Badreldin et al., 2015; Doing, 1985; Du and Hesp, 2020; Green and Miller, 2019; Rajaniemi and Allison, 2009; van der Valk, 1974a; Wilson and Sykes, 1999). Además de la escasez de agua y de nutrientes, las plantas deben hacer frente a otros factores abióticos restrictivos, como la alta movilidad del sustrato, que produce erosión o enterramiento, y la alta salinidad debida al espray marino y a las inundaciones por agua de mar (Barbour, 1978; Barbour et al., 1985; Du and Hesp, 2020; Maun and Lapierre, 1986; Moreno-Casasola, 1986; Rozema et al., 1985). Estos factores abióticos determinan las adaptaciones que las plantas deben desarrollar para colonizar estos ambientes y condicionan su distribución, su abundancia y su tipología (García-Mora et al., 1999; Hesp, 1991; Luo and Zhao, 2019; Maun, 1998; Moreno-Casasola, 1986). Solo especies adaptadas a las condiciones más duras pueden germinar, crecer y sobrevivir en los lugares más cercanos a la costa (Donnelly and Pammenter, 1983; Ehrenfeld, 1990; Green and Miller, 2019). Una vez estas especies pioneras se instalan, un mecanismo de retención de movilidad de la arena y de disminución de la salinidad se activa para favorecer el establecimiento de nuevas especies, la competencia ecológica y la sucesión de la vegetación (Barbour et al., 1985; Doing, 1985; Hernández-Cordero et al., 2015c).

El papel de Traganum moquinii en la foredune de los sistemas playa-duna de Canarias

La especie pionera predominante en los sistemas playa-duna áridos de las islas Canarias es *Traganum moquinii* (conocida localmente como *balancón*) (García-Romero et al., 2021; Hernández-Cordero et al., 2012; Viera-Pérez, 2015). *T. moquinii (*Figura 4*)* es un arbusto nanofanerófito común en las costas de Canarias, Cabo Verde y el oeste de África (Charco, 2001; Hesp et al., 2021a). Se trata de una especie xerófila y halófila, adaptada al enterramiento y a la moderada/alta salinidad provocada por la escasez de precipitación y humedad (Hernández-Cordero et al., 2019; Viera-Pérez, 2015). En los sistemas playa-duna de Canarias, comunidades de *T. moquinii* aparecen, formando *nebkhas* aisladas o campos de *nebkhas*, en dos ambientes principales: en el interior de sistemas activos, en zonas con acceso al nivel freático o a agua relativamente salobre (e. g. en las depresiones interdunares húmedas entre frentes de dunas móviles de campos de dunas transgresivos) (Hernández-Cordero et al., 2015b; Pérez-Chacón et al., 2010; Viera-Pérez, 2015); y, especialmente, en el área de entrada de los sedimentos a los sistemas de dunas, donde forma las *nebkhas* que estructuran la *foredune* (García-Romero et al., 2021; Hernández-Cordero et al., 2015a; Viera-Pérez, 2015). Así, los ejemplares de *T. moquinii* que se desarrollan en estas áreas de entrada de sedimentos a los sistemas playa-duna también actúan como *especie estructurante e ingeniera de la geomorfología* (Corenblit et al., 2011). En este sentido, la presencia de esta especie vegetal produce cambios relevantes en los procesos sedimentarios eólicos, entre los que destacan: estabilizar el suelo y los sedimentos, modificar la rugosidad de la superficie y contribuir a la disipación de los flujos de energía, atrapar y retener sedimento fino, o evitar la erosión del suelo (Phillips and Lorz, 2008; Viles et al., 2008). Sin embargo, también aparecen ejemplares de *T. moquinii* avanzada la sucesión de especies (Hernández-Cordero et al., 2015c; Marrero-Rodríguez et al., 2020a) a diferencia de lo que sucede en otros ambientes, donde las especies pioneras son generalmente desplazadas por otras (Hesp, 2002).

Se ha documentado una reacción positiva de *T. moquinii* frente al enterramiento por arena (Hernández-Cordero et al., 2012), siempre que este se realice de forma progresiva (Viera-Pérez, 2015), por lo que, al igual que en otras especies vegetales adaptadas el enterramiento (Gilbert and Ripley, 2010; Maun, 1998), existe una relación entre el tamaño y el crecimiento de la planta y la morfología de la *nebkha* generada (Charbonneau et al., 2021; Du et al., 2010; El-Bana et al., 2002; Hesp and McLachlan, 2000; Lang et al., 2013; Toranjzar et al., 2015). Así, en la *foredune* de algunos campos de dunas transgresivos de las islas Canarias, donde el aporte de sedimento es abundante, existen ejemplares adultos de *T. moquinii* que pueden alcanzar hasta 5 m de altura y que dan lugar a *nebkhas* de más de 15 m de diámetro (Alonso et al., 2011; García-Romero et al., 2021). Hesp et al. (2021b) encontraron en las costas canarias una relación entre la disponibilidad de sedimento y el desarrollo de las *nebkhas*, siendo mayor el tamaño de *nebkhas* y menor el número de ellas cuando el aporte es alto, y viceversa.

Figura 4: Ejemplar de Traganum moquinii en la duna costera de Playa del Inglés. Maspalomas (Gran Canaria).

La colonización de la parte alta de la playa por ejemplares de *T. moquinii* supone un obstáculo para el transporte sedimentario eólico, produciéndose retenciones sedimentarias y, en consecuencia, favoreciendo la formación de *nebkhas* y dunas de sombra (Al-Awadhi, 2014; Buckley, 1996; Dupont et al., 2014; Gillies et al., 2014; Hesp and Smyth, 2017; Lang et al., 2013; Luo et al., 2012; Mayaud et al., 2017a; McGuirk et al., 2022; Shumack et al., 2022; Wang et al., 2006; Yang et al., 2019; Zhao et al., 2021, 2020; Zhao and Gao, 2021). Bajo un aporte suficiente de sedimento y dándose una distancia determinada entre dos *nebkhas* adyacentes puede producirse coalescencia entre sus dunas de sombra (Yang et al., 2019), generándose en la parte posterior de la *foredune* una acumulación de sedimento que da lugar a geoformas parabólicas no vegetadas ancladas en sus extremos a las *nebkhas,* en lo que se conoce como dunas de lengua (*tongue dunes)* (Cabrera-Vega et al., 2013b; Domínguez-Brito et al., 2020; Viera-Pérez, 2015). En campos de dunas transgresivos, estas dunas de lengua terminan liberándose de la vegetación de la *foredune*, para dar lugar a geoformas eólicas libres (e. g. barjanas y cordones barjanoides) que avanzan hacia el interior del sistema (Cabrera-Vega et al., 2013b; Hernández-Cordero et al., 2012).

La función de *T. moquinii* como especie fundamental en los sistemas playa-duna áridos de Canarias no es única en lo relativo a generar y estructurar la geomorfología de la *foredune* y regular el paso de sedimento al interior de los sistemas de dunas, sino que también juega un papel fundamental en la sucesión ecológica (Hernández-Cordero et al., 2019). Así, *T. moquinii* aparece formando comunidades monoespecíficas en la *foredune* de los sistemas playa-duna con mayor aporte de sedimento (Hernández-Cordero et al., 2015a; Viera-Pérez, 2015), asociada con otras especies (e. g. *Cakile marítima, Euphorbia paralias, Cyperus ssp.)* en la *foredune* de sistemas con menor entrada de sedimento (Hernández-Cordero et al., 2015c) o desaparece hacia el interior de los sistemas por la sucesión de otras especies (e. g. *Ononis tournefortii, Tamarix canariensis, Launaea arborescens, Suaeda mollis)* (Hernández-Cordero et al., 2019, 2017, 2015c; Pérez-Chacón et al., 2010).

ACTIVIDAD HUMANA Y GESTIÓN EN LOS SISTEMAS PLAYA-DUNA ÁRIDOS

Los sistemas de dunas han sido históricamente utilizados por el ser humano (Marrero-Rodríguez et al., 2022, 2021b, 2020a, 2020b; Martínez et al., 2013; Santana-Cordero et al., 2016a, 2014). Hasta la primera mitad del siglo XX, los principales usos desarrollados en los sistemas de dunas costeros eran la explotación de sus recursos, la agricultura y el pastoreo. Sin embargo, en las últimas décadas se ha incrementado la presión y la amenaza sobre estos sistemas debido al desarrollo industrial y, sobre todo, al urbano-turístico alrededor de ellos (García-Romero et al., 2016; Jackson and Nordstrom, 2011; Martínez et al., 2013).

La ocupación de los ecosistemas costeros

El proceso de *litoralización* se ha potenciado en las últimas décadas, incrementando la presión humana sobre el litoral y su afectación sobre los procesos naturales lo que, a su vez, aumenta la vulnerabilidad de los ecosistemas litorales, incluyendo las dunas costeras (Martínez et al., 2006; Peña-Alonso et al., 2018b). La conversión de los sistemas de dunas en espacios prioritarios para el turismo de masas ha intensificado los procesos de urbanización alrededor de ellos, resultando en un incremento de las alteraciones ambientales que contribuyen a su degradación (Delgado-Fernández et al., 2019b; European Environment Agency, 2006; Jackson and Nordstrom, 2011; Paskoff, 1993). El reconocido conflicto entre el desarrollo y la conservación de los sistemas de dunas (Nordstrom, 2000) se pone de manifiesto con actividades y usos humanos que amenazan los ecosistemas costeros, que incluyen, entre otros, la explotación de los recursos (Fernández Montoni et al., 2014; Kutiel et al., 1999; Marrero-Rodríguez et al., 2022, 2020a; Martínez et al., 2008; Provoost et al., 2009; Santana-Cordero et al., 2016b), las actividades recreativas (Kelly, 2016, 2014; Petch et al., 2018; Prisco et al., 2021) y la urbanización y construcción de infraestructuras (García-Romero et al., 2019a, 2019b; Hernández-Calvento et al., 2014; Salgado et al., 2021; Smith et al., 2017b). Las principales consecuencias de estas actividades en sistemas de dunas son la pérdida de dunas existentes y la inhibición de la formación de nuevas dunas, la creación de nuevas geoformas eólicas que difieren de las que se formarían en condiciones naturales, y la alteración de las características y la dinámica de las dunas preexistentes (García-Romero et al., 2019a; Hernández-Calvento et al., 2014; Hernández-Cordero et al., 2018; Jackson and Nordstrom, 2013, 2011; Marrero-Rodríguez et al., 2020a; Pérez-Hernández et al., 2020).

La actividad humana no solo es susceptible de amenazar la conservación de los sistemas de dunas costeros por la afectación directa sobre las geoformas eólicas, sino también de manera estructural al causar efectos perjudiciales sobre la vegetación dunar. Estas alteraciones sobre la vegetación se traducen, entre otros posibles efectos, en variaciones en el número y la morfología de los ejemplares (García-Romero et al., 2021; Hernández-Cordero et al., 2018), cambios en los procesos reproductivos de las plantas (Viera-Pérez et al., 2019), avance de comunidades de especies exóticas invasoras (Gallego-Fernández et al., 2020; Jørgensen and Kollmann, 2009; Kim, 2005), o reducción de las comunidades de especies pioneras y de la riqueza de especies (García-Romero et al., 2021; Hesp et al., 2010; Kutiel et al., 1999). La reducción en el crecimiento de la vegetación reduce la resiliencia de los sistemas (Keijsers et al., 2016). Así, el tipo y la densidad de la vegetación pueden ser utilizados como indicador de cambios ambientales (Arens, 1996; da Silva et al., 2008; Hernández-Calvento, 2006; Hernández-Cordero et al., 2017; Lancaster and Baas, 1998; Marrero-Rodríguez et al., 2020a; Martínez et al., 2001; Moreno-Casasola, 1986; Peña-Alonso et al., 2019).

Impactos ambientales en torno a la foredune

La *foredune*, como elemento clave para el funcionamiento de los sistemas sedimentarios eólicos costeros, muestra una gran sensibilidad a la alteración de sus procesos naturales debidos a la actividad humana (Bauer and Sherman, 1999). Al ser el nexo entre la playa y las dunas localizadas en el interior del sistema, las *foredunes* se encuentran entre las zonas de más actividad humana dentro de los sistemas de dunas (Figura 5). En las *foredunes* y sus alrededores convergen la mayoría de los usos y servicios urbano-turísticos presentes tanto en la playa como en los sistemas de dunas (p. ej., la instalación de quioscos, construcción de paseos marítimos, y el pisoteo, entre otras actividades descritas en la siguiente sección), incrementando la presión sobre el espacio. Así, el deterioro de la *foredune* tiene como consecuencia, por un lado, la pérdida de su función biogeomorfológica fundamental en el contexto del sistema de dunas en el que se integra, y, por otro lado, el impacto socioeconómico asociado al deterioro de un paisaje característico de estos sistemas y que, en consecuencia, reduce su atractivo turístico y recreativo. Esta íntima relación entre los procesos biofísicos y sociales permite analizar los sistemas sedimentarios eólicos como sistemas socio-ecológicos (Curtin and Prellezo, 2010).

Figura 5: Ejemplo de algunos usos y actividades desarrolladas en torno a la foredune de Playa del Inglés. Maspalomas (Gran Canaria).

A pesar de que la mayoría de los estudios realizados sobre impactos ambientales en dunas costeras se han desarrollado en zonas templadas (Cabrera-Vega et al., 2013a; Corbau et al., 2015; Curr et al., 2000; Martínez et al., 2013; Nordstrom et al., 2007), al igual que en el caso del estudio de los procesos naturales, las características socio-ecológicas de los sistemas sedimentarios eólicos de las islas Canarias los han convertido en un área recurrente de investigación sobre los efectos del desarrollo urbano-turístico sobre sistemas playa-duna áridos (García-Romero et al., 2016; Hernández-Cordero et al., 2019; Marrero-Rodríguez et al., 2020b; Smith et al., 2017b; Viera-Pérez et al., 2019). Las condiciones climáticas de Canarias convierten sus sistemas de playa-duna en lugares ideales para el desarrollo del turismo en su modalidad de sol y playa (Burton, 1991; Lozato-Giotart and Insa, 1990; Soneiro-Callizo, 1991; Vera Rebollo, 1997). Las temperaturas suaves y constantes a lo largo de todo el año, unido a la escasez de precipitación y la cantidad de horas de luz, han convertido las islas Canarias en un destino que recibe turistas de manera constante a lo largo de todo el año (Cabrera-Vega et al., 2013a), no existiendo una estacionalidad marcada, lo cual contribuye a incrementar la presión sobre sus sistemas de dunas que, como otras partes de las islas, están sometidas a la superpoblación constante que se traduce en alta ocupación, urbanización y degradación del litoral (European Environment Agency, 2006).

La amenaza derivada de usos, actividades e infraestructuras

Algunos usos y actividades ligados al desarrollo urbano-turístico susceptibles de alterar los procesos biogeomorfológicos, como la urbanización alrededor de sistemas de dunas (Jackson and Nordstrom, 2013, 2011; Nordstrom and McCluskey, 1984; Wiedemann and Pickart, 2008), la presencia de infraestructuras que alteran la dinámica eólica y los patrones de transporte y sedimentación (Jackson and Nordstrom, 2011; Poppema et al., 2022, 2021; Wijnberg et al., 2021), la extracción de arena para edificación (Dan Gavriletea, 2017; Fernández Montoni et al., 2014) o el mal uso del espacio por parte de los usuarios (Aretano et al., 2017; Delgado-Fernández et al., 2019b; Kelly, 2016, 2014; Kutiel et al., 1999; Schlacher and Thompson, 2008) se han reproducido en los sistemas playa-duna de las islas Canarias (Cabrera-Vega et al., 2013a; Ferrer-Valero et al., 2017; García-Romero et al., 2016, 2019b, 2019a, 2021; Hernández-Calvento, 2006; Hernández-Calvento et al., 2014; Hernández-Cordero et al., 2017; Marrero-Rodríguez et al., 2020a; Peña-Alonso et al., 2019; Smith et al., 2017b). En ocasiones, estos usos y actividades han sido posibilitados por una gestión y planificación ambiental deficiente, traduciéndose estas alteraciones en fragilidad geomorfológica y aumento de la vulnerabilidad de estos espacios (Peña-Alonso et al., 2017).

Las condiciones de alta presión humana que soportan los sistemas playa-duna áridos induce alteraciones que amenazan los procesos geomorfológicos y la vegetación, y que es necesario conocer, reconocer y enmendar para posibilitar su gestión sostenible. Las decisiones de gestión pueden ser factores determinantes para conservar la dinámica sedimentaria eólica natural y la estructura funcional y morfológica de los sistemas de dunas costeros en general, y de su *foredune* en particular (Jackson and Nordstrom, 2011), así como para la recuperación natural o la restauración de los sistemas dañados (Delgado-Fernández et al., 2019a). En este sentido, las particularidades de las regiones áridas no han sido contempladas en las herramientas de gestión desarrolladas en España para la restauración de dunas costeras (Ley et al., 2007), que se han basado en indicadores desarrollados para regiones templadas (García-Mora et al., 2001, 2000). La adaptación de indicadores a las particularidades de los sistemas playa-duna áridos (Peña-Alonso et al., 2018b) son fundamentales para su gestión sostenible.

La aplicación de una gestión óptima de los sistemas playa-duna localizados en regiones áridas del planeta pasa necesariamente por el conocimiento exhaustivo de las dinámicas naturales y sociales presentes en ellos. Acciones enfocadas a alcanzar el equilibrio entre la conservación de estos espacios y la satisfacción de los usos que el ser humano demanda de ellos requiere planificar y regular la actividad desarrollada, permitiendo el funcionamiento de los procesos naturales. Para ello, es imprescindible obtener todo el conocimiento posible sobre dichos procesos naturales y sobre los efectos que la actividad humana pudiese tener sobre ellos en diferentes escalas espaciotemporales. Así, la gestión sostenible de la *foredune* de los sistemas playa-duna áridos debe fundamentarse en la caracterización de sus procesos naturales específicos, y de las actividades y procesos que amenazan, a distinta escala espaciotemporal, la conservación y el mantenimiento de sus funciones ecológicas, geomorfológicas y sociales.

HIPÓTESIS Y OBJETIVOS

De los párrafos precedentes podemos deducir que las condiciones climáticas y ambientales bajo las que se desarrollan los sistemas de dunas costeros áridos, como los localizados en el archipiélago canario, condicionan la biogeomorfología y los procesos sedimentarios que influyen en la formación, desarrollo y funcionamiento de los sistemas playa-duna áridos, en general, y de su *foredune*, en particular. Estos espacios son una importante fuente de recursos y servicios para el ser humano, que a su vez interfiere, a distintas escalas, con la dinámica y evolución de estos sistemas playa-duna. Estas interferencias de la actividad humana en los procesos naturales pueden, en ocasiones, amenazar la formación, el mantenimiento y el funcionamiento de la *foredune*. La gestión integrada de las dunas costeras, a través de un conocimiento profundo de los procesos naturales que las rigen, es un elemento necesario para su conservación o restauración.

HIPÓTESIS DE LA INVESTIGACIÓN

La hipótesis de partida de esta investigación plantea que *el conocimiento detallado de las interacciones naturales entre variables biogeoformológicas y procesos eólicos que dan lugar al establecimiento y funcionamiento de la* foredune *en sistemas sedimentarios eólicos áridos, así como de las interferencias e impactos de las actividades humanas a distintas escalas, permitirán desarrollar estrategias bien informadas para la gestión, la conservación o la restauración de estos espacios*.

OBJETIVOS DE LA INVESTIGACIÓN

El objetivo general de esta investigación consiste en **extender el horizonte de conocimiento** en lo relativo a la **naturaleza**, las **amenazas** y la **gestión** de las ***foredunes*** localizadas en **sistemas de dunas costeros áridos**, dando respuesta a la necesidad de **proponer medidas** de gestión y, en su caso, de **restauración** que atiendan a las **especificidades climáticas, sociales y biogeomorfológicas** de estos espacios y permitan la conciliación del **uso humano** con su **conservación**.

En paralelo a éste, se desarrolla un **objetivo metodológico** y de **escala**, consistente en abordar estudios a un **nivel de detalle**, por métodos **experimentales**, escasos en los estudios llevados a cabo hasta ahora en los sistemas de dunas áridos de las islas canarias.

Objetivos específicos

1. Explorar detalladamente los **patrones de distribución espacial de las distintas variables morfológicas, sedimentológicas y de la vegetación** que afectan a las *nebkhas* que forman parte de la *foredune* de sistemas sedimentarios eólicos costeros áridos, y analizar las **relaciones** que se dan entre dichas variables en condiciones naturales.
2. Caracterizar y analizar los efectos y consecuencias que las decisiones de **gestión** con respecto a los usos y servicios llevados a cabo en las playas tienen sobre los procesos eólicos y biogeomorfológicos de los sistemas playa-duna áridos, y explorar la **evolución espaciotemporal de dichos efectos**.
3. Aislar, caracterizar y analizar en **detalle** los efectos ambientales derivados de **determinados usos humanos e infraestructuras** en sistemas playa-duna, como la construcción de estructuras ***cortavientos*** de piedras en la playa y la *foredune.*
4. Determinar las **consecuencias medioambientales** que actividades humanas realizadas de manera **global** sobre la *foredune* de sistemas playa-duna áridos (e.g. ***extracciones de áridos***) tienen sobre estos sistemas, y analizar la **capacidad de respuesta** que estos tienen hacia la recuperación de las condiciones naturales tras el cese de la actividad.
5. Evaluar **alternativas para la restauración ambiental** de la *foredune* de sistemas de dunas costeros áridos, atendiendo a sus especificidades climáticas, sociales y biogeomorfológicas.

Objetivos transversales

1. Proponer ***recomendaciones para la gestión*** efectiva de los sistemas playa-duna áridos que permitan conciliar el uso humano con la conservación de dichos espacios, así como para la restauración ambiental de estos cuando se encuentren degradados por la actividad humana.
2. ***Transferir el conocimiento*** obtenido como parte de la investigación a los agentes implicados en la gestión de los espacios.
3. ***Promover la divulgación científica*** de los resultados de esta investigación entre la comunidad académica y, especialmente, entre el público general.
4. ***Formular futuras perspectivas de investigación*** derivadas de los resultados obtenidos y que den continuidad a la línea de conocimiento abordada en este estudio.

ÁREA DE ESTUDIO

CARACTERIZACIÓN NATURAL DE LOS SISTEMAS SEDIMENTARIOS EÓLICOS DE CANARIAS

Las islas Canarias conforman un archipiélago volcánico compuesto por ocho islas y cinco islotes. Este archipiélago macaronésico se localiza en el Atlántico norte, sobre la corteza oceánica de la placa Africana, frente a la costa oeste de Marruecos y el Sáhara Occidental. La cadena de islas se extiende entre los 27º-30º norte y los 13º-19º oeste. La edad de las islas se incrementa hacia el este, siendo Lanzarote y Fuerteventura las islas más antiguas del archipiélago (20,5 millones de años, Carracedo et al., 1998). La práctica ausencia de procesos de subsidencia tectónica incrementa la pervivencia de las islas de Canarias, lo cual permite observar su desarrollo en distintas etapas, desde la erupción inicial hasta la etapa final de agotamiento del vulcanismo y predominancia de procesos erosivos que provocan la desaparición de las islas (Carracedo, 1999).

La distinta edad de las islas condiciona la diversidad de su geomorfología costera, aumentando la abundancia de geoformas costeras cuanto mayor es su edad geológica y su estado evolutivo (Ferrer-Valero, 2018). Así, la costa de las islas occidentales está predominantemente compuesta por acantilados rocosos y plataformas costeras, mientras que, en las islas orientales, más antiguas, aumenta la presencia de playas y aparecen los principales sistemas sedimentarios eólicos, al llevar éstas más tiempo expuestas a procesos erosivos. Algunos de estos sistemas se extienden, siguiendo la dinámica eólica, alrededor o a través de islas enteras (Hernández-Calvento et al., 2017). Las fuentes naturales de sedimento que alimentan los sistemas sedimentarios eólicos de las islas Canarias son terrestres, procedentes de la erosión costera y de la descarga de los barrancos, junto con aportes de bioclastos procedentes del fondo marino.

Las áreas costeras de las islas Canarias, dónde se desarrollan los principales sistemas sedimentarios del archipiélago, presentan condiciones climáticas características de las zonas clasificadas como áridas, con precipitación desértica y temperaturas áridas cálidas (KWh) (Köppen, 1900; Kottek et al., 2006). Esta aridez está representada por unas condiciones estables a lo largo del año de altas temperaturas y baja precipitación (Figura 6). Así, la temperatura media anual permanece alrededor de los 20 ºC, mientras que la precipitación media anual no suele superar los 100 mm (Marzol, 2001).

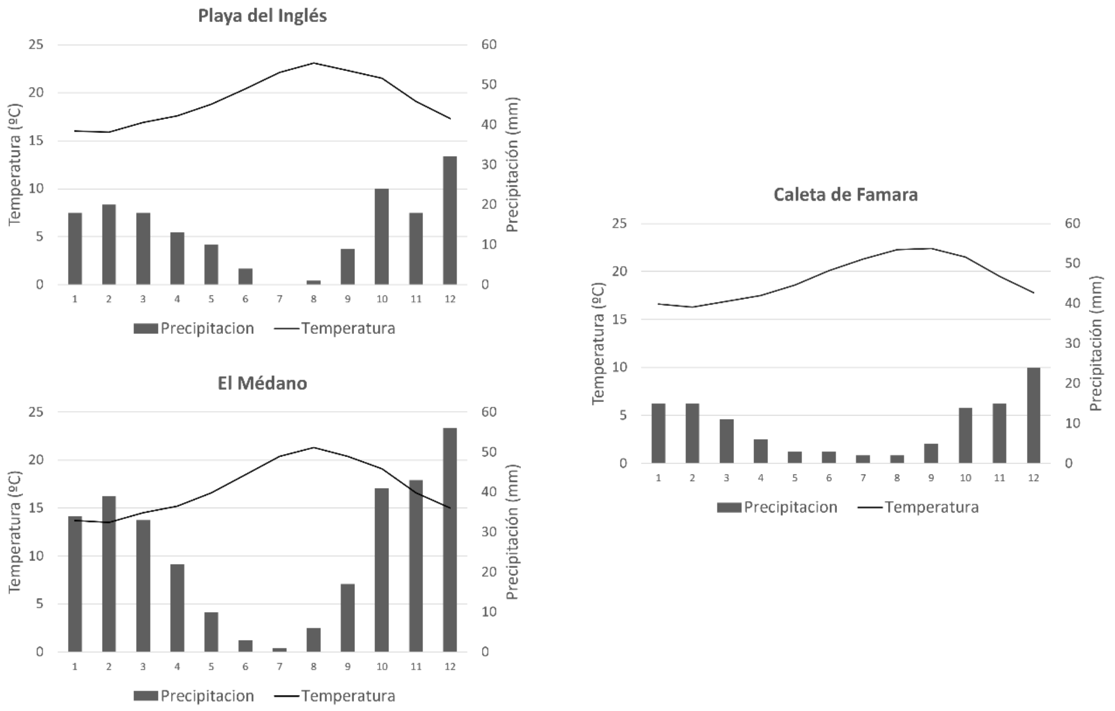


Figura 6: Climogramas en estaciones cercanas a las áreas de estudio para el periodo 1991 – 2021. Fuente: climate-data.org

El viento en las islas Canarias (Figura 7) está influenciado por el anticiclón de las Azores, provocando la predominancia de vientos alisios de componente NE durante la mayor parte del año. Estos son responsables de los vientos efectivos (> 5,1 m/s para sedimento de diámetro entre 0,18 y 0,22 mm) que promueven el transporte sedimentario predominante en los sistemas sedimentarios eólicos de Canarias en dirección NE – SO (Hernández-Calvento, 2006; Hernández-Calvento et al., 2017; Hernández-Cordero et al., 2019; Máyer Suárez et al., 2012; Pérez-Chacón et al., 2007). Sin embargo, en Maspalomas se ha descrito un régimen bimodal, con vientos efectivos del O (Máyer Suárez et al., 2012), que pueden estar influenciados por cambios topográficos de meso-escala debidos al relieve de las islas, originando cambios en la dirección del viento que modifican los procesos eólicos asociados (Smith et al., 2021; Viera-Pérez, 2015).

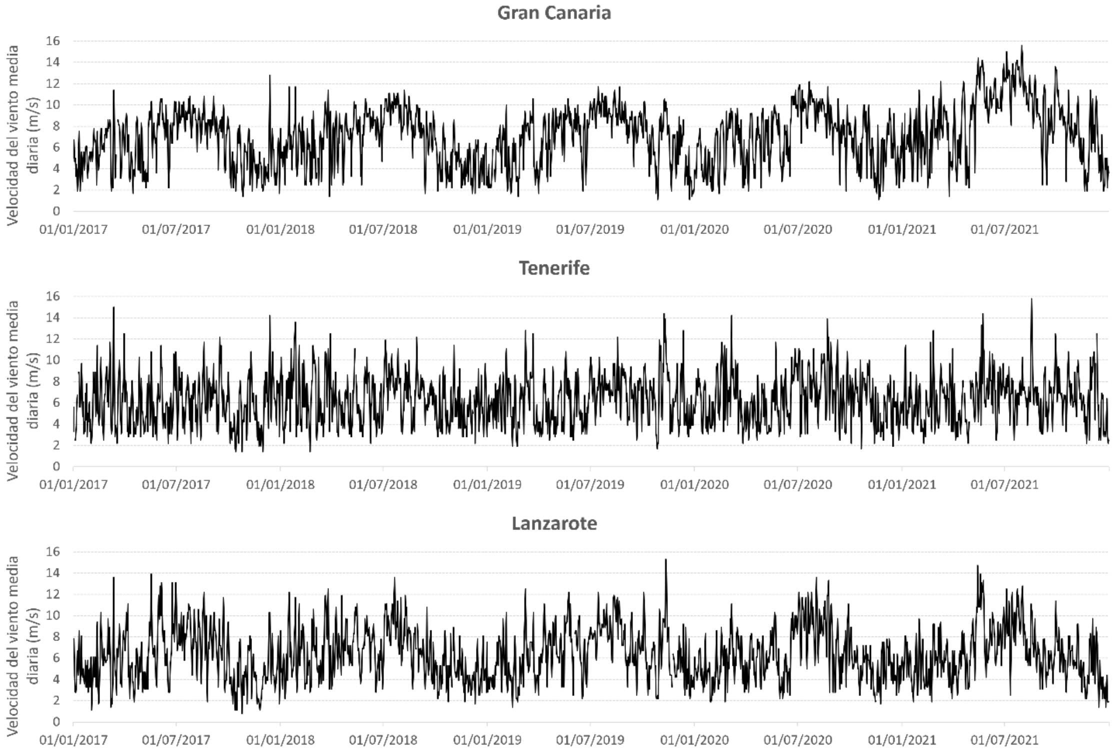


Figura 7:Series temporales de velocidad media del viento diaria en las estaciones meteorológicas localizadas en los aeropuertos de Gran Canaria, Tenerife Sur y Lanzarote para el periodo 2017 – 2021. Fuente: Agencia Estatal de Meteorología (AEMET).

Las condiciones climáticas que se dan en las costas de las islas Canarias permiten considerar las *foredunes* de sus sistemas playa-duna como representativas de las *foredunes* de regiones áridas (Cabrera-Vega et al., 2013a; Hernández-Cordero et al., 2012; Hesp et al., 2021a) (Figura 8). El clima árido, junto con el régimen de vientos intensos y constantes, condiciona el desarrollo de la vegetación y los procesos biogeomorfológicos, que están íntimamente relacionados con la estructura y el desarrollo de la *foredune* (García-Romero et al., 2019c). Así, en regiones áridas, como los sistemas de dunas costeros de las islas Canarias, la escasez de precipitación es el principal factor relacionado con el desarrollo de *foredunes* discontinuas estructuradas por *nebkhas* (El-Bana et al., 2003; Hesp et al., 2021a; Nickling and Wolfe, 1994; Quets et al., 2013). Además de con las características climáticas, el desarrollo de *nebkhas* en ambientes áridos, semiáridos y desérticos está condicionado, de manera natural, por la densidad y tipología de la vegetación, la disponibilidad de sedimento y la actividad eólica (Hesp et al., 2021b; Lang et al., 2013; Wang et al., 2010) y, por otro lado, por la acción humana (García-Romero et al., 2021; Marrero-Rodríguez et al., 2020a; Peña-Alonso et al., 2018b; Rahmonov et al., 2009) y la degradación del suelo (Khalaf et al., 2014; Ravi et al., 2010; Wang et al., 2006).

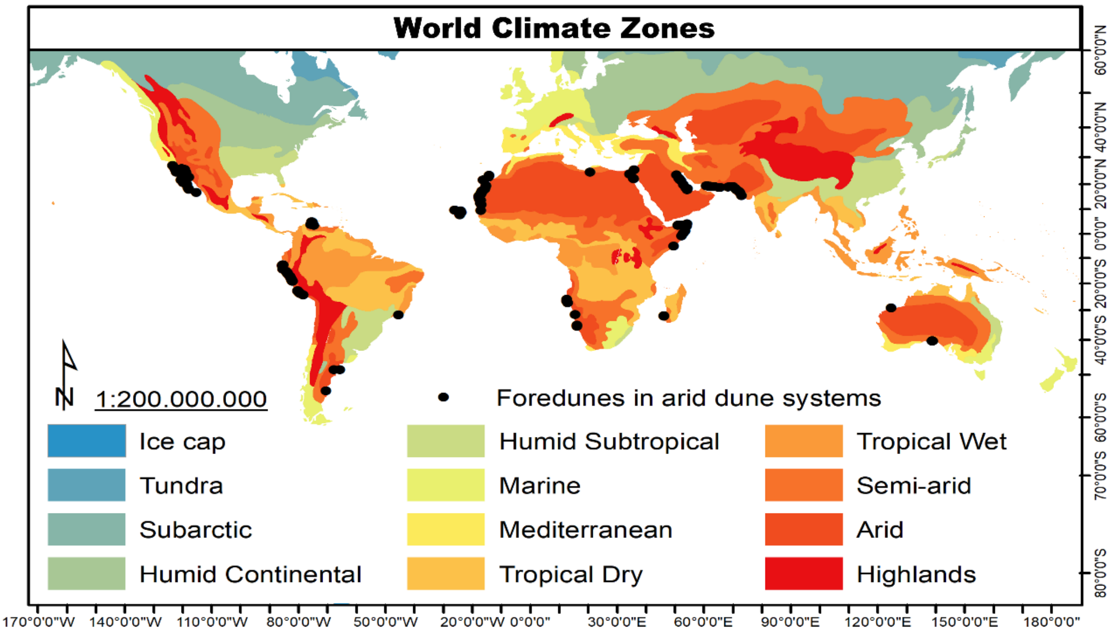


Figura 8. Localización de las principales foredunes identificadas en regiones áridas. Extraído de Peña-Alonso et al. (2018).

La escasez de precipitación limita el desarrollo de las plantas y potencia el transporte eólico, favoreciendo el asentamiento de especies arbustivas halófilas y xerófilas (e. g. *Traganum moquinii*, *Tetraena spp., Suaeda spp., Salsola spp*), que promueven la formación de nebkhas (Hesp et al., 2021a). Esto supone una gran diferencia con respecto a los sistemas sedimentarios eólicos de clima templado, donde las temperaturas intermedias y una mayor precipitación favorecen el desarrollo de vegetación conformada principalmente por especies herbáceas (Hernández-Cordero et al., 2015a).

Hesp et al. (2021a) no solo encontraron relación entre las características climáticas de las costas del oeste africano y de las islas Canarias, sino también en el modo en que se desarrolla la *foredune* (Figura 9A). Sus resultados muestran que en la región climática BWh el principal modo de desarrollo de la *foredune* es con presencia de *nebkhas* (Figura 9B), pudiendo dar lugar a campos de dunas transgresivos cuando el aporte de sedimento es elevado (Hesp et al., 2021b).

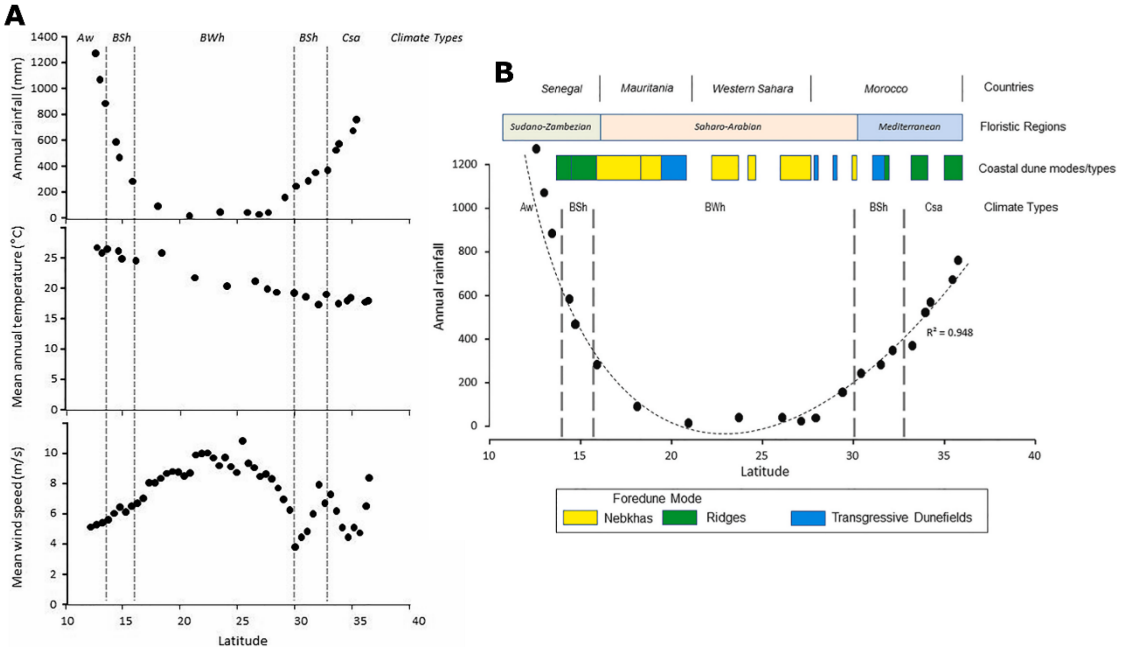


Figura 9. A) Relaciones entre precipitación media anual (Annual rainfall (mm)), temperatura media anual (Mean anual temperatura (ºC)) y velocidad media del viento a 50 m de altura (mean wind speed (m/s)) y latitud para la costa oeste de África y las islas Canarias (latitud 27º-30º). Se indican las zonas climáticas Köppen-Geiger. B) Relaciones entre precipitación media anual, latitud, regiones florísticas, zonas climáticas Köppen-Geiger y modos de desarrollo de la foredune para las costas del oeste de África y de las islas Canarias. Extraído de Hesp et al. (2021a).

De acuerdo con la clasificación establecida por Hesp & Walker (2013), podemos identificar en las islas Canarias sistemas correspondientes a las dos tipologías de sistemas de dunas transgresivos: los mantos de arena transgresivos (e. g. El Jable (Lanzarote), Las Conchas (La Graciosa), El Médano-La Tejita (Tenerife)), y los campos de dunas transgresivos (i. e. Maspalomas (Gran Canaria) y Corralejo (Fuerteventura)).

Los primeros están relacionados con un aporte de sedimento escaso y consisten generalmente en planicies arenosas donde una lámina de arena se acumula alrededor de la vegetación arbustiva predominante, dando lugar principalmente a geoformas eólicas como *nebkhas* y dunas de sombra. La limitación en el aporte de sedimento no permite el desarrollo de formas dunares libres y facilita la colonización de comunidades de plantas hacia el interior de los sistemas. En función del grado de movilidad del sedimento, los mantos de arena transgresivos pueden estar activos, formando campos de *nebkhas* donde se distinguen geoformas como *ripples*, *nebkhas* y dunas de sombra (Cabrera-Vega, 2010; García-Romero et al., 2016; Pérez-Chacón et al., 2010); o estabilizados, donde la movilidad del sedimento se reduce y se incrementa la densidad de la vegetación y se observa la predominancia de procesos erosivos, tanto por el viento como por el agua (Hernández-Cordero et al., 2015a; Marrero-Rodríguez et al., 2020a; Pérez-Chacón et al., 2010).

Por su parte, los campos de dunas transgresivos presentan un amplio abanico de geoformas eólicas, entre las que se destaca la presencia de dunas libres (e. g. dunas barjanas, cordones barjanoides y transversales) que viajan hacia el interior de los sistemas desde las zonas de aporte sedimentario (Alonso et al., 2011; Hernández-Calvento, 2006; Hernández-Cordero et al., 2015c). También aparecen geoformas asociadas a procesos erosivos, como *blowouts* o superficies de deflación (García-Romero et al., 2019a); dunas asociadas a vegetación, como *nebkhas*, dunas eco o dunas de sombra (García-Romero et al., 2021; Hernández-Cordero et al., 2012; Viera-Pérez, 2015); y geoformas eólicas condicionadas por el relieve, como dunas eco, rampantes o de caída (Hernández-Calvento, 2006; Hernández-Cordero et al., 2017). Conforme la movilidad del sedimento va disminuyendo hacia el interior de estos sistemas, la vegetación tiene mayor facilidad para asentarse y colonizar las dunas, generando zonas estabilizadas donde aumenta la densidad de la vegetación que fija las geoformas.

ACTIVIDAD SOCIOECONÓMICA EN TORNO A LOS SISTEMAS SEDIMENTARIOS EÓLICOS DE CANARIAS

Las particularidades climáticas de las islas Canarias no solo condicionan la naturaleza de los sistemas sedimentarios eólicos localizados en ellas, sino también la actividad humana desarrollada alrededor de ellos. Las islas Canarias tienen una población de más de 2 millones de habitantes distribuida de forma muy irregular, concentrándose más del 80% de esta población en las islas de Tenerife y Gran Canaria, que tienen densidades de población de 445 hab/km^2 y 543 hab/km^2, respectivamente (Instituto Canario de Estadística, 2018). En 2009 el porcentaje de la población residente en las provincias de Santa Cruz de Tenerife y de Las Palmas que habitaba en municipios costeros superaba el 90% (Fundacion BBVA, 2010). A la presión sobre el territorio relacionada con la población local se suma la derivada del turismo. En 2019 Canarias recibió 13,1 millones de turistas internacionales, principalmente procedentes de Reino Unido (37,1%) y Alemania (19,1%) (INE, 2020).

Las condiciones ambientales de un espacio están íntimamente relacionadas con el asentamiento humano en cuanto que benefician o dificultan su posibilidad de supervivencia y, una vez garantizada esta, su comodidad en el entorno. Esto convierte los lugares donde se dan condiciones climáticas favorables y estables durante todo el año (en el caso de las islas Canarias temperaturas suaves y escasa precipitación) en zonas ideales para el desarrollo intensivo de infraestructuras urbano-turísticas (Gómez Martín, 2005). Por ello, el turismo se ha convertido en la principal actividad económica de las islas, consideradas un destino idóneo para su desarrollo en la modalidad de sol y playa (Burton, 1991; Lozato-Giotart and Insa, 1990; Soneiro-Callizo, 1991; Vera Rebollo, 1997). La idoneidad del clima de las costas canarias para esta tipología turística redunda en una exposición continua al turismo de masas durante todo el año, a diferencia de otros destinos europeos donde el turismo es estacional (Cabrera-Vega et al., 2013a; Peña-Alonso et al., 2018b). Esta circunstancia ha promovido, a su vez, que alrededor, o incluso en el interior, de los sistemas de dunas de las islas Canarias se hayan desarrollado algunos de los complejos turísticos más importantes de España (Domínguez-Mujica et al., 2011).

Antes del cambio de modelo económico de las islas Canarias hacia el turismo, los principales usos humanos desarrollados en los sistemas de dunas estaban relacionados con la agricultura y la ganadería, la minería de arena, el uso recreativo y la extracción de combustible para uso doméstico y para alimentar hornos de cal (Marrero-Rodríguez et al., 2022, 2021a, 2021b, 2020b; Santana-Cordero et al., 2016b, 2016a). Asimismo, algunos de estos sistemas fueron urbanizados para uso residencial o para albergar infraestructuras (Marrero-Rodríguez et al., 2020a; Pérez-Hernández et al., 2020; Santana-Cordero et al., 2014).

Con el desarrollo del turismo en las islas Canarias a partir de la década de 1960, los sistemas playa-duna se convirtieron en lugares preferentes para la construcción de infraestructuras, alojamientos y equipamientos turísticos, así como para la realización de determinadas actividades y usos relacionados. Esta circunstancia ha expuesto a los sistemas playa-duna de las islas Canarias a distintos niveles de presión antrópica, en función de su exposición a la actividad humana, y ha generado impactos sobre los sistemas, entre los que podemos destacar la desaparición de sistemas completos, o partes de ellos, debido a la ocupación urbana (Alonso et al., 2011; Cabrera-Vega et al., 2013a; García-Romero et al., 2016; Hernández-Calvento, 2006; Santana-Cordero et al., 2014), la alteración de los procesos sedimentarios eólicos, debido a la presencia de edificios e infraestructuras en el sistema y sus alrededores (García-Romero et al., 2019b, 2019a; Hernández-Calvento, 2006; Smith et al., 2017b) y cambios en la distribución, el número y los procesos reproductivos de la vegetación (García-Romero et al., 2021; Hernández-Cordero et al., 2017; Peña-Alonso et al., 2019; Viera-Pérez et al., 2019).

A su vez, las playas de las islas Canarias, expuestas al uso intensivo y a las exigencias de calidad demandadas por la llegada continua de turistas, también se han clasificado en tres tipologías principales de acuerdo con indicadores medioambientales y de usos y servicios (accesibilidad, alojamiento, instalaciones…). Esta clasificación permite adaptar las prácticas locales de gestión en función de sus características, detectándose playas urbanas, semi-urbanas y naturales (Peña-Alonso et al., 2018a). Así, las playas urbanas serían aquellas localizadas en un entorno urbano, con amplia oferta de alojamiento e instalaciones y una buena accesibilidad, donde el interés recreativo suele superar al interés en la conservación. Las playas semi-urbanas están localizadas en zonas de densidad poblacional media o baja, con una accesibilidad reducida que suele moderar el acceso de usuarios, una oferta de instalaciones limitada, y cuyo grado de artificialización suele ser menor que el de las playas urbanas. Por su parte, las playas naturales son generalmente playas bien conservadas al estar lejos de núcleos urbanos y tener una accesibilidad reducida. El acceso suele estar restringido al uso de vehículos privados, barcos o peatones, sin servicios de transporte público, y no disponen de instalaciones para los usuarios. En las últimas décadas las playas urbanas y semi-urbanas han visto intensificado su uso debido a la actividad recreativa, lo cual ha incrementado, a su vez, la presión humana sobre su geomorfología y la necesidad de implementar medidas de gestión.

En lo relativo a la protección de los espacios naturales, aproximadamente el 40% de la superficie del archipiélago canario (301.237 ha) se incluye dentro de los 146 espacios que componen la Red Canaria de Espacios Protegidos (Instituto Canario de Estadística, 2018). Esto incluye una parte significante de los sistemas de dunas de Canarias, que se encuentran protegidos bajo distintas figuras a diferente escala (regional, nacional e internacional). Así, por ejemplo, los sistemas de dunas de La Graciosa, el norte de El Jable (Lanzarote), el islote de Lobos y Corralejo (Fuerteventura) forman parte de sus respectivos Parques Naturales, con el objetivo de preservar los recursos naturales para el disfrute público, la educación y la investigación científica de forma compatible con su conservación, no teniendo cabida usos residenciales ni otros ajenos a esta finalidad. Por su parte, los sistemas dunares de Maspalomas (Gran Canaria) y El Médano – La Tejita se encuentran bajo la figura de protección de Reserva Natural Especial, cuyo objetivo es la preservación de hábitats singulares, especies concretas, formaciones geológicas o procesos ecológicos naturales de interés especial, no siendo compatible con la ocupación humana ajena a fines científicos, educativos y, excepcionalmente, recreativos o de carácter tradicional.

SELECCIÓN DE ÁREAS DE ESTUDIO

Los sistemas playa-duna estudiados en esta investigación (Tabla 1) pertenecen a sistemas sedimentarios eólicos áridos, con sus *foredunes* estructuradas por *nebkhas*, que recogen la diversidad de las islas Canarias en lo referente a su potencialidad para albergar estos sistemas (Objetivo 1). De oeste a este, los sistemas sedimentarios eólicos seleccionados reflejan el gradiente entre islas, tanto en lo referente a la extensión de los propios sistemas como a la longitud de la costa total de la isla que ocupan (Hernández-Cordero et al., 2019).

El sistema playa-duna de la playa de El Médano / Leocadio Machado se localiza dentro del sistema sedimentario eólico de El Médano – La Tejita

(Tenerife). Este es el sistema activo de mayor extensión en la isla de Tenerife, ocupando actualmente alrededor de 103 ha (Marrero-Rodríguez et al., 2020a). El campo de dunas transgresivo de Maspalomas (Gran Canaria), donde se localiza el sistema playa-duna de la Playa del Inglés, es uno de los espacios naturales más singulares del archipiélago canario, ocupando una superficie aproximada de 400 ha (Hernández-Calvento, 2006). Por último, el sistema playa-duna de Caleta de Famara alimenta el sistema sedimentario de El Jable (Lanzarote), que comprende una superficie potencial de aproximadamente 8.000 ha, siendo el sistema sedimentario eólico de mayor tamaño en las islas Canarias (Cabrera-Vega, 2010) (Figura 10).

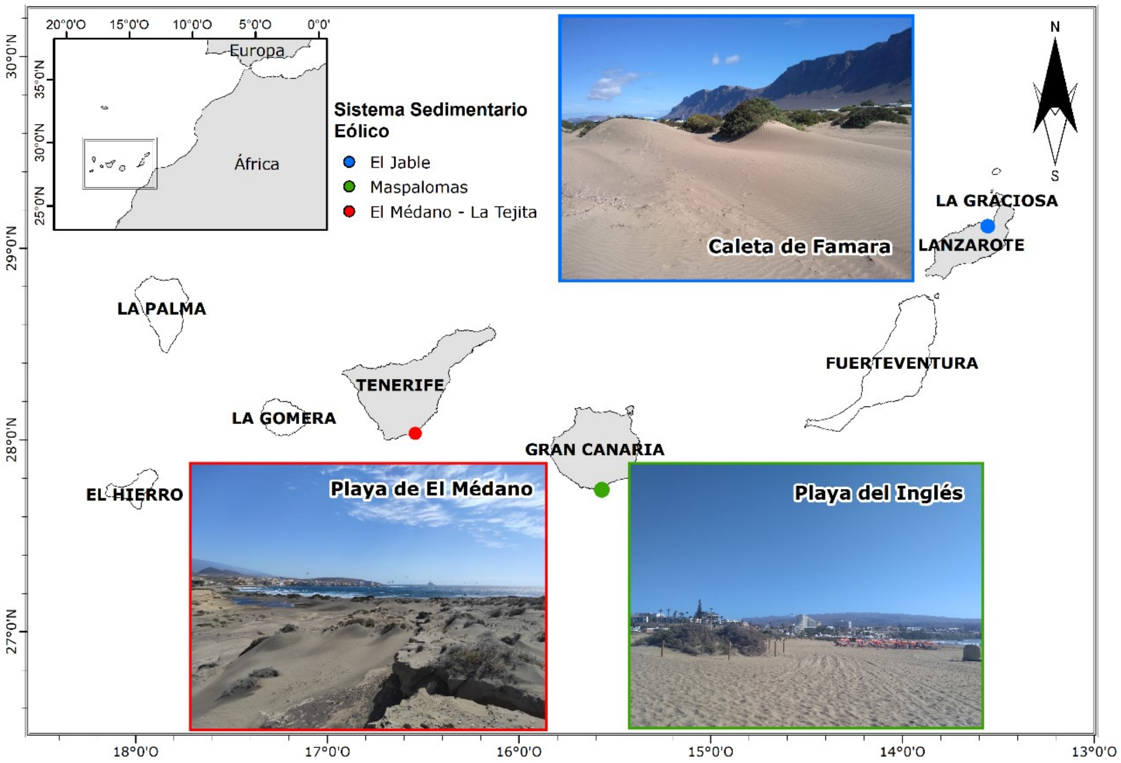


Figura 10. Localización de los sistemas sedimentarios eólicos que albergan los sistemas playa-duna estudiados y vista general de estos: Caleta de Famara (Lanzarote), Playa del Inglés (Gran Canaria) y El Médano (Tenerife).

De igual manera, las áreas de estudio seleccionadas recogen la variabilidad en cuanto al grado de naturalidad/artificialidad que muestran (Tabla 1). Así, se detectó que la *foredune* de Caleta de Famara (especialmente en el sector analizado en el artículo 1) está asociada a una playa semi-urbana (Figura 10, inserto con marco azul) con los procesos biogeomorfológicos naturales menos alterados que los observados en la *foredune* de Playa del Inglés (área de estudio de los artículos 2, 3 y 5; Objetivos 1, 2, 3 y 5), playa urbana muy intervenida (Figura 10, inserto con marco verde), o en la *foredune* de la playa de El Médano (abordada en el artículo 4; Objetivos 1, 2, 4), asociada a una playa semi-urbana (Figura 10, inserto con marco rojo), que muestra procesos aparentemente naturales pero que forman parte de la respuesta al impacto ambiental de determinados usos históricos (Marrero-Rodríguez et al., 2020a).

Tabla 1. Características generales de las áreas de estudio incluidas en la investigación.

Área de estudio (*foredune*)	**Sist. Sed. Eólico**	**Tipología (Hesp & Walker, 2013)**	**Clasificación (Hernández-Cordero et al., 2019)**	**Actividad sedimentaria eólica (Hesp et al., 2021)**	**Tipología de playa (Peña-Alonso et al., 2018)**	**Figura de protección**
Caleta de Famara	El Jable (LZ)	Manto eólico	Campo de nebkhas	Media	Semi-urbana	Parque Natural Archipiélago Chinijo
Playa del Inglés	Maspalomas (GC)	Campo de dunas	Transgresivo	Alta	Urbana	Reserva Natural Especial de las Dunas de Maspalomas
El Médano	El Médano – La Tejita (TF)	Manto eólico	Manto eólico	Baja	Semi-urbana	Reserva Natural Especial de Montaña Roja

Las especificidades locales de las áreas de estudio concretas en las que se ha desarrollado la investigación presentada en cada uno de los artículos científicos que forman parte de esta tesis se encuentran detalladas en el apartado correspondiente al área de estudio de cada artículo.

METODOLOGÍA

Los métodos utilizados en cada uno de los artículos científicos que forman parte de la investigación se encuentran detallados en el apartado correspondiente de cada uno de ellos. Este apartado pretende, pues, aportar información de contexto que permita ampliar el conocimiento sobre los métodos utilizados y presentar la secuencia de trabajo llevada a cabo para dar respuesta a los objetivos planteados en la investigación.

FLUJO DE TRABAJO

El esquema metodológico de la investigación desarrollada (Figura 11) parte del planteamiento de cuestiones relacionadas con los sistemas playa-duna en lo referente a su naturaleza (Objetivo 1), sus principales amenazas (Objetivos 2, 3, 4) y la gestión llevada a cabo en los espacios (Objetivos 2, 5). Los resultados derivados de la investigación desarrollada para dar respuesta a las cuestiones científicas planteadas, a través de la resolución de los objetivos específicos, dieron también lugar a cada una de las publicaciones científicas que componen el *corpus* de esta investigación.

El planteamiento de las cuestiones de partida puso de manifiesto desde el primer momento, por una parte, la necesidad de definir la escala y la *unidad biogeomorfológica* objetivo dentro del sistema playa-duna relacionado. Así, algunas cuestiones están referidas específicamente para ser resueltas a la escala de las *nebkhas*, (‘*plotscale’*) mientras que otras se definen a una escala mayor, que comprende la totalidad de la *foredune*. (‘*landform to landscape scale’*, Walker et al., 2017). El tratamiento de algunas cuestiones concretas se realizó combinando ambas escalas.

¿Cómo se relacionan las variables que intervienen en la formación y el mantenimiento de las *nebkhas* costeras áridas?

¿Qué efectos tiene la actividad urbano-turística sobre esas variables y sus relaciones?

¿Cuál es la respuesta de la *foredune* una vez que cesa la actividad que ha provocado un impacto?

¿Es posible restaurar una *foredune* y sus *nebkhas* tras estos impactos?

1. Explorar detalladamente los patrones de distribución espacial de las distintas variables morfológicas, sedimentológicas y de la vegetación que afectan a las *nebkhas* que forman parte de la *foredune* y analizar las relaciones que se dan entre dichas variables en condiciones naturales

2. Caracterizar los efectos y consecuencias que las decisiones de gestión con respecto a los usos y servicios llevados a cabo en las playas tienen sobre los procesos eólicos y la biogeomorfología de los sistemas playa-duna áridos, y explorar la evolución espaciotemporal de dichos efectos

3. Aislar y caracterizar en detalle los efectos ambientales derivados de determinados usos humanos llevados a cabo en sistemas playa-duna, entre otros, la construcción de estructuras cortavientos de piedras en la playa y la *foredune*

4. Determinar las consecuencias medioambientales que actividades humanas realizadas de manera global sobre la *foredune* de sistemas playa-duna áridos tienen sobre estos sistemas, y analizar la capacidad de respuesta de estos sistemas hacia la recuperación de las condiciones naturales tras el cese de la actividad

5. Evaluar alternativas para la restauración ambiental de la *foredune* de sistemas de dunas costeros áridos, atendiendo a sus especificidades climáticas, sociales y biogeomorfológicas

1. Environmental variables affecting an arid coastal nebkha

2. Spatiotemporal analysis of the impact of artificial beach structures on biogeomorphological processes in an arid beach-dune system

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

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

5. Coastal Dune Restoration in El Inglés Beach (Gran Canaria, Spain): a Trial Study

Figura 11. Esquema metodológico de la investigación desarrollada.

Por otra parte, el planteamiento de las cuestiones iniciales también puso de manifiesto la estrecha relación entre las amenazas derivadas de la actividad humana y la gestión desarrollada en los sistemas playa-duna (Delgado-Fernández et al., 2019b; Jackson and Nordstrom, 2011; Kelly, 2014; Nordstrom et al., 2018, 2007; Palma et al., 2021; Peña-Alonso et al., 2019, 2018b; Prisco et al., 2021).

LA NECESIDAD DE UN ENFOQUE MULTIESCALAR

El rol de la vegetación es fundamental para entender la geomorfología de los ambientes áridos (Cooke et al., 1993; Durán Vinent and Moore, 2013; Lee et al., 2019; Li and Ravi, 2018; Li et al., 2021; Mayaud and Webb, 2017;

Wainwright, 2009). La vegetación ocasiona que la distribución, la dinámica de los procesos y las relaciones en estos ambientes sean irregulares, desiguales y fragmentadas en un amplio rango de escalas espaciales y temporales, por lo que la caracterización de estos espacios debe involucrar conocimiento a diferentes escalas espaciotemporales, puesto que los patrones y los procesos cambian en función de la escala de observación (Figura 12) (Stewart et al., 2014; Wainwright, 2009).

Las variaciones en ecosistemas áridos son especialmente evidentes en el largo plazo, en tanto que pueden modificar el paisaje, reflejándose en cambios en la distribución y en la composición de la vegetación, en la geomorfología o en los procesos. Sin embargo, el entendimiento de los patrones espaciales de la vegetación y de las geoformas eólicas a gran escala debe partir de un enfoque detallado de pequeña escala de los procesos locales para poder evolucionar hacia un enfoque transescalar desde el que poder considerar las dinámicas del sistema (Wainwright, 2009).

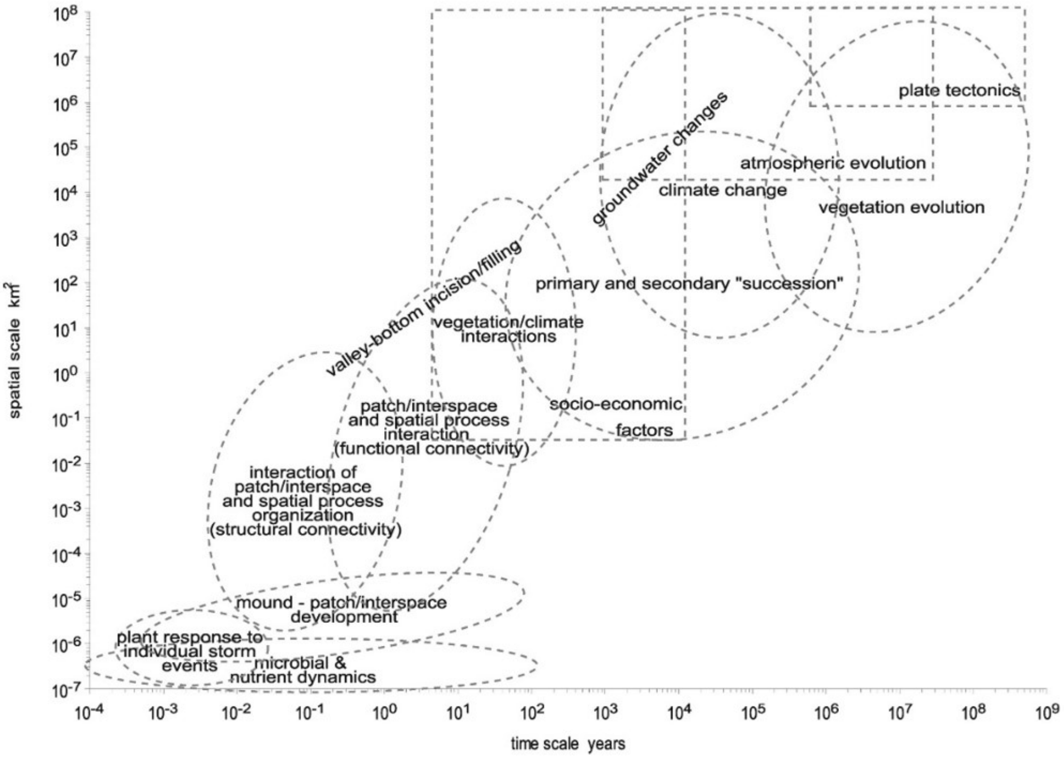


Figura 12. Escalas espaciales y temporales de interacción entre vegetación, geomorfología y procesos relacionados en ambientes desérticos (Wainwright, 2009).

La evolución biogeomorfológica del espacio es fruto de la interacción entre la estructura del entorno y los procesos. En este caso, la estructura del entorno está determinada por la irregularidad y heterogeneidad de la vegetación y es su interacción con la dinámica eólica, como proceso fundamental, lo que determina la distribución espacial en las escalas implicadas. A medida que la estructura del sistema cambia (cambios en la vegetación o en la geomorfología) el proceso se retroalimenta, provocando nuevos cambios en la estructura del sistema (Turnbull et al., 2008). Para caracterizar el espacio y comprender los patrones espaciales resultantes en una escala progresivamente mayor, será necesario comprender cómo los elementos y procesos implicados en las escalas inferiores se comportan de manera individual dentro del entorno, y cómo interaccionan con este y entre sí (Wainwright, 2009).

En el marco de esta investigación, podríamos considerar como punto de partida espaciotemporal la escala intraplanta, en la que la interacción entre eventos eólicos y la vegetación provoca que el material sea transportado desde zonas expuestas y depositado bajo la cubierta vegetal, formando pequeños montículos (Cooke et al., 1993; Gibbens et al., 1983). En una escala de parcela, tanto la planta como las geoformas eólicas generadas en escalas inferiores interaccionan con los procesos del entorno. A esta escala se dan interacciones entre individuos de planta y el viento, que transporta material desde zonas expuestas hacia áreas protegidas. Así, empezarán a tomar relevancia factores como, por ejemplo, el tamaño de la planta, la cobertura vegetal o la porosidad de la planta frente al viento, que afectarán al transporte sedimentario y a la erosión del suelo (Dupont et al., 2014; Gillies et al., 2014; Leenders et al., 2007; Nickling and Wolfe, 1994). Estas interacciones generan patrones de distribución de la vegetación y el sedimento, que dan lugar a geoformas eólicas, como *nebkhas* o dunas de sombra (*shadow dunes*) (Al-Awadhi, 2014; Cooke et al., 1993; Hesp, 1981; Li et al., 2020). En una escala superior, los procesos actuantes determinan la distribución de la vegetación y de las geoformas eólicas, dando lugar a patrones de distribución observables en el paisaje (Bradley et al., 2019; Luo et al., 2021; Quets et al., 2013; Xiaohong et al., 2019; Zhao et al., 2020; Zhou et al., 2015). Las distintas escalas están ligadas de manera jerárquica a través de los procesos eólicos (Delgado-Fernández et al., 2018; Okin et al., 2006). En esta escala, el viento sigue siendo el factor principal, pero entran en juego otros factores, como la sucesión de la vegetación, la competencia entre especies o factores climáticos y socioeconómicos.

También las interferencias que se dan en estos ambientes son espacial y temporalmente heterogéneas, afectando sus consecuencias de manera distinta al entorno en función de la escala en la que se produzcan (Delgado-Fernández et al., 2019b; Hesp and Martínez, 2007; van der Maarel, 1993). Por ello, también deben ser espacial y temporalmente heterogéneas las medidas de gestión que se apliquen para la conservación de estos espacios (Carboni et al., 2009). Debido a interferencias en el entorno, en las escalas mayores se pueden observar cambios en el paisaje, tales como alteraciones en la diversidad biológica y geomorfológica (Ferrer-Valero et al., 2017; García-Romero et al., 2019a; Kutiel et al., 1999; Salgado et al., 2021), fragmentación (Costas et al., 2020a; Hernández-Calvento, 2006; Hernández-Cordero et al., 2012), erosión del suelo (Dan Gavriletea, 2017; Kindermann and Gormally, 2010; Marrero-Rodríguez et al., 2022; Nordstrom et al., 2007) o disminución del número de las poblaciones vegetales (García-Romero et al., 2021; Hernández-Cordero et al., 2017), así como alteraciones de los procesos sedimentarios eólicos que mantienen las funciones del entorno (García-Romero et al., 2019b; Hernández-Calvento et al., 2014; Jackson and Nordstrom, 2011; Nordstrom and McCluskey, 1984; Smith et al., 2017b). Sin embargo, algunos de estos efectos observables a gran escala pueden derivarse de otros en escalas inferiores, por lo que es necesario, de nuevo, un enfoque holístico multiescalar a la hora de abordar estas cuestiones (Walker et al., 2017).

Puesto que los objetivos de esta investigación atienden a la estructura, los procesos, las interferencias y la gestión que se dan en los sistemas playa-duna de regiones áridas, se han utilizado distintas escalas de observación para recoger la heterogeneidad espaciotemporal de estos espacios. Sin embargo, las observaciones que podemos realizar en la naturaleza están a menudo restringidas por factores metodológicos, logísticos o teóricos que condicionan el alcance de lo observado (Sherman, 1995), lo cual se pone particularmente de manifiesto en el campo de la geomorfología dunar costera, que pretende observar la evolución y mantenimiento de sistemas altamente dinámicos como los sistemas playa-duna (Short and Hesp, 1982;

Walker et al., 2017). En este sentido, la evolución de los procesos biogeomorfológicos, a distinta escala, se ha inferido mediante observación indirecta o aproximación estática, con base en el razonamiento "espacio por tiempo" (Pickett, 1989). Este método conlleva limitaciones a la hora de comprender mecanismos en escalas inferiores a la observada, pero ha demostrado ser de utilidad para establecer marcos conceptuales e hipótesis generales para los estudios generales y las observaciones directas (Pickett, 1989). La observación indirecta a gran escala deberá, pues, apoyarse en un contexto adecuado y en el conocimiento derivado de experimentos y observaciones a escalas menores (evento), puesto que de otra forma no proporciona información sobre los procesos intermedios, y no puede utilizarse por sí misma para extrapolar escenarios a largo plazo sobre el mantenimiento o la evolución de los sistemas (Walker et al., 2017).

En el marco de la investigación, cada objetivo planteado ha determinado la escala espacial y temporal de trabajo, condicionando, a su vez, la elección de metodologías y el análisis de variables.

SELECCIÓN DE VARIABLES

El desarrollo de la investigación ha contemplado fundamentalmente dos escalas de trabajo principales, una a largo plazo (*long-term*) y otra a corto plazo (*short-term*) (Bauer and Sherman, 1999).

Los análisis a largo plazo realizados comprenden una escala espacial en el orden de magnitud de las hectáreas y procesos en una escala temporal de varios años. Esta escala se ha utilizado para identificar y analizar cambios ambientales y posibles alteraciones de los procesos biogeomorfológicos relacionados con la evolución de los sistemas playa-duna desde el auge del desarrollo urbano-turístico en las islas Canarias (aproximadamente en los años 60 del siglo pasado) hasta la actualidad. Esta escala comprende unidades biogeomorfológicas como *foredunes* completas, superficies de deflación o parches de vegetación sobre los que se ha realizado seguimiento de su evolución con una periodicidad en torno a la década. Esta escala, que abarca periodos de varios años, ofrece mayor utilidad para observar el mantenimiento y la evolución de las dunas, y para desarrollar las estrategias de gestión relacionadas con la alteración ambiental por actividades humanas (Walker et al., 2017).

Por su parte, los análisis a corto plazo comprenden una escala espacial en el orden de los metros, y se han utilizado para estudiar la evolución ambiental y los cambios en los procesos con una escala temporal eventual. En esta escala se han incluido parcelas que pueden contener una o varias *nebkhas*, sobre las que se han realizado tanto seguimientos de su evolución en periodos temporales inferiores al año, como experimentos de varias horas de duración. La aplicación de enfoques en el corto plazo se centra fundamentalmente en la predicción de patrones de transporte de sedimento en un espacio concreto durante cortos periodos de tiempo, siendo la velocidad y la dirección del viento cerca de la superficie las principales variables independientes (Walker et al., 2017). En esta escala se corre el riesgo de perder la visión holística del sistema, pero esto, a su vez, nos permite realizar observaciones de detalle sobre determinados elementos y procesos, y evaluar su contribución a los hallazgos observados en escalas superiores, ayudando también a rellenar el hueco entre las observaciones realizadas en plazos superiores (Delgado-Fernández et al., 2018).

La escala de investigación determina, por tanto, la relevancia de las variables que intervienen en los sistemas y su dependencia o independencia en relación con el resto. Así, la combinación de variables dependientes e independientes seleccionadas para caracterizar y definir la dinámica de los procesos biogeomorfológicos variará en función de la escala de trabajo seleccionada (Schumm and Lichty, 1965).

La selección de variables concretas para alcanzar los objetivos específicos de cada uno de los artículos científicos recogidos en esta investigación se encuentra detallada en la metodología correspondiente. La Tabla 2 sintetiza la información referente al conjunto de variables utilizadas durante la investigación en función de su naturaleza y de la escala de trabajo planteada.

Tabla 2. Relación de variables analizadas en el contexto de la investigación.

Escala espaciotemporal	Elemento	Variable (unidad)	Métodos de obtención	Publicaciones
Short-term	Topografía	Altura (m)	GPS-RTK, Estación total, Fotogrametría	1, 3, 5
		Orientación (º)	Derivado de MDTs mediante SIG	1
		Pendiente (º)	Derivado de MDTs mediante SIG	1, 3
		Distancia a la costa (m)	*In situ*	1, 4, 5
	Vegetación	Especie	*In situ*	1, 3
		Altura media (cm)	*In situ*	1, 5
		Altura máxima (cm)	*In situ*	1
		Cobertura (%)	*In situ*	1, 4
		Longitud ejes (cm)	*In situ*	5
		Vitalidad (%)	*In situ*	5
	Sedimento	Conductividad (mS/cm)	Análisis de muestras recogidas	1
		Tamaño de grano (mm)	Análisis de muestras recogidas	1, 4
		Carbonatos (%)	Análisis de muestras recogidas	1, 4
		Temperatura (º)	*In situ*	1
	Viento	Velocidad del viento (m/s)	*In situ,* Agencia Estatal de Metorología	3, 4, 5
		Dirección del viento (º)	*In situ*, Agencia Estatal de Meteorología	3, 4, 5
Long-term	Equipamientos y usos de playa	Kioscos (nº)	Fotografía aérea, ortofotos	2
		Kioscos (ha)	Fotografía aérea, ortofotos	2
		Lotes de hamacas (nº)	Fotografía aérea, ortofotos	2
		Lotes de hamacas (ha)	Fotografía aérea, ortofotos	2
		Goros (nº)	Fotografía aérea, ortofotos	2, 3
	Vegetación	T. moquinii (nº)	Fotografía aérea, ortofotos	2, 5
	Topografía	Altura (m)	LiDAR, Modelos Digitales del Terreno.	2, 3, 4
		Foredune (ha)	Fotografía aérea, ortofotos	2
		Superficies de deflación (ha)	Fotografía aérea, ortofotos	2

Puesto que el conjunto de la investigación realizada combina datos de diferente naturaleza procedentes de distintas fuentes de información, se exponen a continuación brevemente las características generales de las metodologías utilizadas para la obtención de los datos y su posterior análisis.

Variables topográficas

En lo referente a la información topográfica, debemos distinguir entre aquella obtenida a partir de fuentes remotas y la obtenida *in situ* mediante trabajo de campo. En la primera, se obtuvieron datos altimétricos a partir de fuentes digitales, como archivos ráster de modelos digitales del terreno (MDT) o de vuelos LiDAR (Light Detection and Ranging) de diferente resolución, a partir de los cuales se derivaron algunas variables relacionadas (e.g. pendiente, orientación) (Moore et al., 1991) mediante herramientas de geoprocesamiento en sistemas de información geográfica (SIG). Las fuentes utilizadas para la obtención de esta información altimétrica incluyeron modelos digitales obtenidos mediante restitución fotogramétrica o mediante sensores LiDAR a bordo de drones (Doyle and Woodroffe, 2018), normalmente suministrados por la Administración Pública (GRAFCAN, S.A. – Gobierno de Canarias, Cabildo de Gran Canaria e Instituto Geográfico Nacional, IGN – Gobierno de España).

La información topográfica en las campañas de campo se obtuvo mediante el uso de diversas técnicas que incluyeron la generación de MDTs mediante SIG a partir de puntos topográficos tomados con RTK-GPS (Łabuz, 2016), estación total o *Structure from motion (SfM)* (Carvalho et al., 2020; Fonstad et al., 2013; Grottoli et al., 2020; Smith et al., 2015).

La identificación de unidades geomorfológicas, como la *foredune* o las superficies de deflación, se realizó mediante la digitalización de vectores a partir de la fotointerpretación de imágenes aéreas (fotografías aéreas históricas y ortofotos digitales) procedentes de bases de datos espaciales. Morgan et al. (2010) recogen las ventajas y desventajas principales del uso de la fotointerpretación de este tipo de fuentes, que ha sido ampliamente utilizada para la caracterización de sistemas playa-duna (Foti et al., 2022; García-Romero et al., 2021; Hesp et al., 2021b; Marrero-Rodríguez et al., 2020b; Vallejo et al., 2006).

Variables de vegetación

Las variables referentes a la vegetación en el corto plazo se obtuvieron principalmente *in situ*, mediante campañas de campo, en las que se tomaron medidas relativas a su tamaño y su estado vital, y se realizó la identificación de las especies y su cobertura, así como la georreferenciación de los datos obtenidos. La evolución del número de individuos de *T. moquinii* en el largo plazo se realizó mediante interpretación visual de ortofotos digitales (García-Romero et al., 2021; Hernández-Cordero et al., 2017).

Variables sedimentológicas

La obtención de datos relativos a las variables sedimentológicas analizadas en el trascurso de la investigación se realizó de dos formas. Por una parte, las medidas de temperatura del sedimento se realizaron *in situ* durante las campañas de monitoreo. Por otra parte, en esas mismas campañas se recogieron muestras de sedimento (aprox. 200 g.) que fueron transportadas a las instalaciones del GFyMA y del Grupo de Geología Aplicada y Regional (GEOGAR) de la ULPGC, donde se realizaron análisis de granulometría, contenido de carbonatos y conductividad.

Variables climáticas

La dirección y velocidad del viento han sido las variables climáticas fundamentales a considerar atendiendo a los objetivos planteados en la investigación. En los experimentos a corto plazo, las medidas de velocidad y dirección del viento se recogieron haciendo uso de los sensores descritos en Domínguez-Brito et al. (2020) y se integraron siguiendo el procedimiento propuesto por Delgado-Fernández et al. (2013). En escalas de tiempo superiores, los datos de dirección y velocidad del viento se han obtenido del registro de estaciones del sistema de observación meteorológica de la Agencia Estatal de Meteorología de España (AEMET).

Variables antropogénicas

La información referente al número, el posicionamiento y el tamaño de las estructuras relacionadas con el uso y gestión del sistema playa-duna para la actividad humana se ha obtenido mediante la digitalización vectorial de los elementos interpretados en fotografías aéreas históricas y ortofotos digitales, de manera similar al procedimiento realizado para las unidades geomorfológicas y las comunidades vegetales.

Análisis espaciotemporales y estadísticos

Los SIG han resultado fundamentales en el desarrollo de la investigación, tanto para la extracción de datos espaciales a partir de fuentes digitales georreferenciadas, como para la realización de análisis espaciotemporales. Para la realización de estos análisis se ha hecho uso de herramientas y funciones implementadas en los SIG para datos vectoriales y ráster. Estas herramientas han incluido, entre otros, procedimientos de conversión, geoprocesamiento, análisis espacial integral, estadística zonal y superposición.

Entre los métodos de análisis espaciotemporal, destaca el procedimiento utilizado para detectar las variaciones del terreno mediante cambios entre MDTs (DEM of Difference-DOD). Este método es ampliamente utilizado para caracterizar cambios del terreno en ambientes costeros (Costas et al., 2020a; Fontán-Bouzas et al., 2019; García-Romero et al., 2019a; Grottoli et al., 2020), pero está sujeto a un error de propagación asociado que deriva de la incertidumbre inherente al uso de los propios MDTs. Para el cálculo de los errores de cada MDT y de su propagación a los DODs generados se utilizó el software Geomorphic Change Detection (GCD) (Wheaton et al., 2010b).

Por otra parte, se ha hecho uso de diversos métodos estadísticos para el análisis de series temporales y la exploración de la dependencia entre variables. Estos métodos se han implementado en distintos lenguajes de programación, principalmente R (R Core Team, 2018) y Matlab

RESULTS

This chapter presents the results of the doctoral thesis, structured into the following 5 scientific publications (Table 3).

Table 3: Characteristics of the scientific publications resulting from this PhD research.

	First submission	**Published**	**Metrics (*)**			**Peer reviews**	**Reviewers**	**Access**
			Impact factor (JIF)	**JCI Category (quartile)**	**SJR Category (quartile)**			
Publication 1(I)	03/Nov/2021	05/Jan/2022	7.963	Environmental Sciences (Q1)	Environmental Chemistry (Q1) Environmental Engineering (Q1) Pollution (Q1) Waste Management and Disposal (Q1)	1	2	Open Access
Publication 2(II)	30/Jul/2020	10/Jan/2021	5.647	Environmental Sciences (Q1)	Environmental Engineering (Q1) Management, Monitoring, Policy and Law (Q1) Medicine (miscellaneous) (Q1) Waste Management and Disposal (Q1)	1	1	Open Access
Publication 3(III)	(Ready for submission)							
Publication 4(IV)	10/Dec/2021	17/May/2022	4.133	Geography, Physical (Q1) Geosciences, Multidisciplinary (Q1)	Earth and Planetary Science (miscellaneous) (Q1) Earth-Surface Processes (Q1) Geography, Planning and Development (Q1)	2	2	Open Access
Publication 5(V)	01/Dec/2020	25/Feb/2021		Area Studies (Q3)		1	2	Open Access

(*) Metrics are referred to moment of publication

(I) Sanromualdo-Collado, A., Gallego-Fernández, J.B., Hesp, P.A., Martínez, M.L., O'Keeffe, N., Ferrer-Valero, N., Hernández-Calvento, L., 2022. Environmental variables affecting an arid coastal nebkha. Sci. Total Environ. 815, 152868. https://doi.org/10.1016/j.scitotenv.2021.152868

(II) Sanromualdo-Collado, A., García-Romero, L., Peña-Alonso, C., Hernández-Cordero, A.I., Ferrer-Valero, N., Hernández-Calvento, L., 2021. Spatiotemporal analysis of the impact of artificial beach structures on biogeomorphological processes in an arid beach-dune system. J. Environ. Manage. 282, 111953. https://doi.org/10.1016/j.jenvman.2021.111953

(III) Sanromualdo-Collado, A., García-Romero, L., Viera-Pérez, M., Delgado-Fernández, I., Hernández-Calvento, L., 2022. Effects of Stone-made wind shelter structures over and arid nebkha foredune. (Ready for submission)

(IV) *Sanromualdo-Collado, A., Marrero-Rodríguez, N., García-Romero, L., Delgado-Fernández, I., Viera-Pérez, M., Domínguez-Brito, A. C., Cabrera-Gámez, J., 2022. Foredune responses to the impact of aggregate extraction in an arid aeolian sedimentary system.* Earth Surf. Process. Landforms, 47 (11), 2709–2725. https://doi.org/10.1002/esp.5419

(V) Sanromualdo-Collado, A., Hernández-Cordero, A.I., Viera-Pérez, M., Gallego-Fernández, J.B., Hernández-Calvento, L., 2021. Coastal Dune Restoration in El Inglés Beach (Gran Canaria, Spain): a Trial Study. Rev. Estud. Andaluces 41, 187–204. https://doi.org/10.12795/rea.2021.i41.10

Environmental variables affecting an arid coastal nebkha

Abel Sanromualdo-Collado, Juan Bautista Gallego-Fernández, Patrick A. Hesp, María Luisa Martínez, Nicholas O'Keeffe, Nicolás Ferrer-Valero, Luis Hernández-Calvento

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Abstract

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

Keywords: Nebkha, Foredune, Coastal dunes, Spatial distribution, Conceptual model.

1. INTRODUCTION

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

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

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

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

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

2. STUDY AREA

The Caleta de Famara beach-dune system (29º06′55′′N, 13º33′36′′W) is located in the north of Lanzarote Island (Canary Islands, Spain), within the Chinijo Archipielago Natural Park (Figure 1A). Weather conditions are constant throughout the year, with average annual temperatures of 21.1ºC and mean annual rainfall below 111mm (AEMET 1981-2010). Prevailing winds are ENE, NE and NNE (Hernández-Cordero et al., 2019). *Caleta de Famara* beach (Fig. 1B) provides the main sediment supply to its adjacent dune field system, and to the *El Jable* sand sheet to the south of it (Cabrera-Vega, 2010). The dune field is approximately 0.45 km^2 and comprises nebkha dunes that range from 1 to 15 m wide and may reach 3.5 m high (Alonso et al., 2011).

Data was collected on a single nebkha representative of the nebkha forming the foredune system, at a landwards distance of 65 m from the high tide limit. The nebkha was typical of the medium size range of the system measuring 6 x 5 x 1.9 m in width, length, and height, respectively and similar to others, its longitudinal axis was oriented 18º N, roughly parallel to the NNE trade winds (Fig. 1C). Like all nebkha in this system, the dune was formed in one plant species, *Traganum moquinii,* which covered 60% of its surface. A shadow dune of 10.5 m in length extended downwind from the leeward top of the nebkha. *T. moquinii* is a shrub that strongly depends on sediment supply, and that grows in an upward direction from buried brunches (Viera-Pérez, 2015). It is also the main dune-building species of foredunes in the Canary Islands (Hernández-Cordero et al., 2019, 2015c) and northwest Africa (Hernández-Cordero et al., 2019; Hesp et al., 2021b). Its marine and climatic conditions, plant growth patterns, natural fragmentation, and the presence of nebkha and shadow dunes, makes the foredune of the *Caleta de Famara* representative of arid regions foredunes generally (Hernández-Cordero et al., 2012). Finally, the system is exposed to moderate human pressure (Peña-Alonso et al., 2018b) due to the proximity to urban areas, its popularity, and the presence of stone windbreaks constructed by recreational users in the foredune (locally referred to as ‘goros’). The selected nebkha was one of the few located far enough away from stone windbreakers to be considered as the standard example of the medium size nebkha of the foredune non impacted directly by human activities.

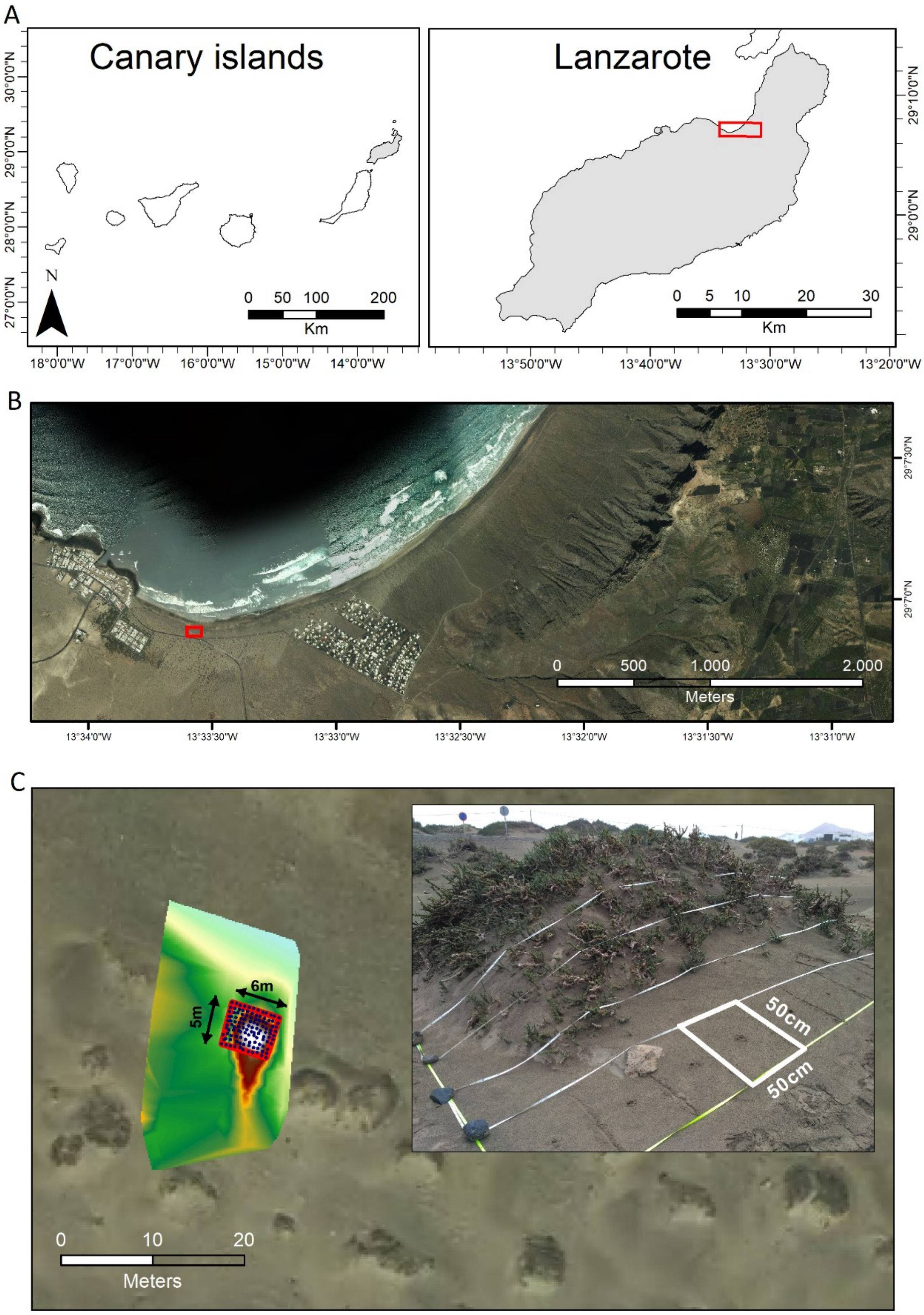

Figure 1: A) Location of the Caleta de Famara (Lanzarote) beach-dune system. B) Aerial view of the Famara coastline showing some of the urban developments to the east and west of the beach-dune system, and with the red square indicating the selected nebkha; C) Digital elevation model (DEM) and close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

3. METHODS

3.1 Field survey

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

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

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

3.2 Laboratory analysis

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

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

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

3.3 Data analysis

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

Pearson’s correlation coefficients were determined to analyze linear relationships between pairs of variables. Multiple Linear Regression analysis (MLR) was performed to predict the distribution of sediment and vegetation properties. MLR analysis are widely used in ecology to describe the influence that certain factors (biological and environmental) have on different aspects of ecology (James and Mcculloch, 1990). To perform the MLR analysis, the set of variables was divided in two groups: 1) a first group including morphological variables (elevation, aspect and slope) and landwards distance from the dune toe (to explore the role played by proximity to the sea); 2) a second group including sediment properties (electrical conductivity, grain size, percentage of carbonates and relative temperature) and vegetation characteristics (plant cover, average height and maximum height).

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

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

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

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

4. RESULTS

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

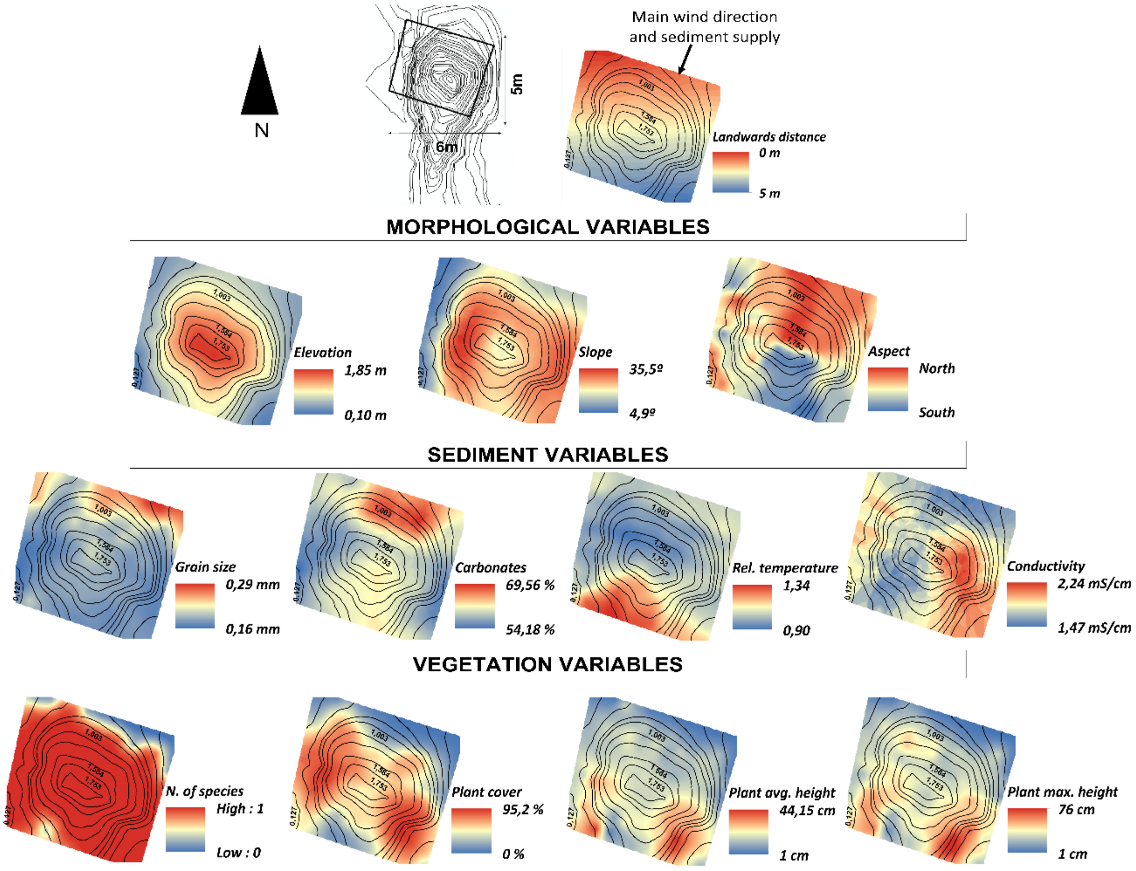

Figure 3: Spatial distribution of variables. Kriging interpolation from 120 survey points.

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

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

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

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

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

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

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

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

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

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

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

5. DISCUSSION

Empirical data collected from the nebkha were used to summarize relations in a conceptual model shown in Figure 4. While the model remains linked to this particular landform, it is worth stressing that the studied nebkha was representative of the nebkha comprising the foredune found at *Caleta de Famara* beach (see section STUDY AREA). This is, however, a pioneer detailed scale (120 plots) comprehensive investigation of morphological, sedimentological, and vegetation patterns on a nebkha foredune, and hence future studies will be needed in order to compare and validate some of the results here.

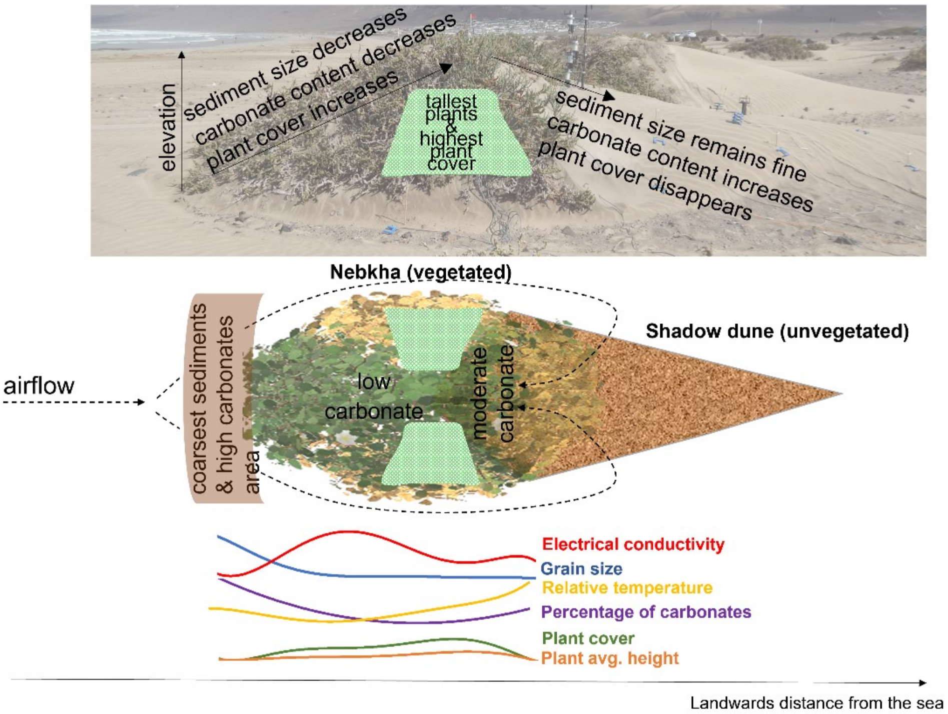

Figure 4: Conceptual model showing spatial patterns of morphological, sedimentological and plant characteristics at a foredune nebkha. Airflow pattern deduced from field visual observations.

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

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

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

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

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

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

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

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

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

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

The introduction of plant cover as an independent variable substantially improved the MLR-2 curves for the spatial distribution of the sediment characteristics. This is in line with multiple studies on the interaction between plants and sediment deposition (Davidson-Arnott et al., 2012; Dupont et al., 2014; Leenders et al., 2007; Mayaud et al., 2016). Wind-sediment-plant interactions were observed cross-shore with larger sediment sizes concentrating in areas of the nebkha facing the sea and the beach in front (i.e., its primary sediment source) and finer sediment sizes towards the interior of the nebkha due to the presence of plants and their effect on slowing the wind and facilitating the deposition of fine sand around them. The increase in plant cover and plant height contributes to the uptake of the finest sediment transported in suspension (Li and Ravi, 2018; Yang et al., 2018), which is deposited in interior and steep areas of the nebkha close to the ridge

(Arens, 1996; Hesp, 2002). However, because sediment sizes found in nebkha were fundamentally transported by saltation and intercepted by the plant a few centimeters from the ground (Li and Ravi, 2018; Yang et al., 2018), the influence of the plant on the grain size distribution was better related to the plant cover than with plant height (Table 3). The influence of plants in the retention of fine sediment also had consequences for the distribution of carbonate grains; hence the introduction of plant cover as a dependent variable in MLR-1 increased its fit and significance.

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

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

6. CONCLUSIONS

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

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

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

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Spatiotemporal analysis of the impact of artificial beach structures on biogeomorphological processes in an arid beach-dune system

Abel Sanromualdo-Collado, Leví García-Romero, Carolina Peña-Alonso, Antonio I. Hernández-Cordero, Nicolás Ferrer-Valero, Luis Hernández-Calvento

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Abstract

The research hypothesis considered in this study is that decisions adopted on beach use and management in arid environments can result in significant changes in the biogeomorphological processes of the beach-dune system of which it forms part. Different information sources and geographical information systems were used to make a spatiotemporal analysis of possible correlations between the presence of beach equipment, services and uses in the backshore area of an arid beach-dune system, such as the beach named Playa del Inglés (Gran Canaria island, Spain) and environmental changes detected in the same area. The period considered in the study covers from 1961 (before the development of the mass tourism on the island) to 2018. Significant variations in vegetation cover over the course of the study period were detected, as well as an overall increase in erosion (topographic and erosive aeolian landforms) and foredune fragmentation and a decrease in geomorphological resilience. The study found not only relationships between management decisions and environmental impacts, but also that environmental impacts of management decisions on beach use made in the 1970s and 1980s continue to be felt today. Moreover, the results also reinforce the idea that management decisions made based on the results of scientific research studies (management-research binomial) can lead to more environmentally sustainable actions.

Keywords: deflation surfaces, geomorphological resilience, environmental impacts, tourism pressure, coastal aeolian sedimentary systems.

1. INTRODUCTION

Coastal dunes are extremely important in socio-ecological terms given the wide range of ecosystem services that they provide (Barbier et al., 2011; Everard et al., 2010; Miththapala, 2008). There has been growing interest in recent decades in the aesthetic and recreational value of these spaces, particularly in view of their frequent use as areas of leisure and relaxation (Ministerio de Medio Ambiente y Medio Rural y Marino, 2008).

The conversion of dune systems into priority spaces for tourism has intensified urbanization processes in the surrounding areas. In turn, this has resulted in environmental alterations that have contributed to the degradation of these dune systems and, in some cases, have brought about the destruction of the ecosystems that they are part of, something that it has been possible to identify in numerous European dune fields (European Environment Agency, 2006; Paskoff, 1993). Functional imbalances have arisen in many dune systems, offering a clear example of the conflict between development and conservation (Nordstrom et al., 2000). The manifestations of these processes may have their origin in the anthropic occupation of water basins or littoral zones that feed the dune systems with sand (Del Río & Malvárez, 2017), in their direct occupation, in dumping, or in the extraction of aggregates, among many others (De Andrés Díaz & Gracia Prieto, 2002). Commonly, one of the key components to the proper functioning of the systems as a whole, the foredune, shows a high degree of sensitivity to anthropic-sourced alteration processes (Bauer & Sherman, 1999). In order to understand the processes in these systems as a whole, spatiotemporal information that reveals behavioural patterns of foredunes and dunefields is required (Livingstone et al., 2007). For this, the use of historical information sources is necessary, especially aerial photography and satellite imagery (Livingstone et al., 2007; Hugenholtz et al., 2012, Cham et al., 2020).

The so-called climatic comfort concept (Gómez Martín, 2005) has been a fundamental aspect in the development of tourism, to the extent that it has conditioned the demarcation of spaces for tourist activities at regional and global scales. Warm and temperate areas (as is the case of the coastal areas of the Canary Islands) are considered optimal for the development of what is known as sun and beach tourism (Burton, 1991; Lozato-Giotart & Insa, 1990; Soneiro-Callizo, 1991; Vera Rebollo, 1997). Unlike other European tourist destinations, the climate of the Canary coasts is stable almost all year round, with mild temperatures, little rainfall, and many hours of sunshine. Mass tourism, a year-round occurrence in the islands with two visitor peaks unlike most other European tourist destinations (Cabrera-Vega et al., 2013a), has in many areas of the islands resulted in a drastic urban over-occupation of littoral areas and, as in other territories, coastal degradation (European Environment Agency, 2006).

Several studies have analysed the impact of human activities, including traditional ones such as grazing, firewood collection and agriculture, on the dune systems of the Canary Islands (Marrero-Rodríguez et al., 2020; Santana-Cordero et al., 2016). Some studies have also considered the impact of more recent land use changes, often carried out with non-existent or inadequately developed environmental planning and management, that have allowed aggregate extraction or given rise to the development of recreational and tourism infrastructures and urbanizations in the immediate surroundings of these systems and occasionally even occupying them (Ferrer-Valero et al., 2017; Hernández-Calvento, 2006; Santana-Cordero et al., 2014). Mass tourism has played a major role in the development of impacts that directly or indirectly affect geomorphological and ecological elements of beach-dune systems of the islands (Peña-Alonso et al., 2018). These impacts include changes to foredune morphology (including their disappearance in some sectors) as a result of alterations to the vegetation (Hernández-Cordero et al., 2012; Hernández-Cordero et al., 2017; Viera-Pérez et al., 2019), occupation by buildings and equipment (García-Romero et al., 2016), and alterations to aeolian sedimentary dynamics due to changes in wind intensity and directions caused by buildings and beach equipment (García-Romero et al., 2019a; Hernández-Calvento et al., 2014; Smith et al., 2017). The foredune and its associated vegetation play an extremely important functional role in dune systems as they regulate sediment transport to the interior of the system and supply the beach with sediments when it is eroded by the actions of the sea (Bauer & Sherman, 1999; Hesp, 2002). Deterioration of the foredune has two main consequences. The first involves a decrease in the geo-ecological effects of the coastal dune in the context of the dune systems in which they are integrated. The second is a socioeconomic impact related to the degradation of the characteristic landscape of these areas and, in consequence, their decreased attraction for tourism and recreation.

The decisions that are taken in terms of their use and management can be determining factors in preserving aeolian sedimentary dynamics and the morphological and functional structure of any dune system, and in particular the foredune area (Jackson & Nordstrom, 2011). For example, the presence of beach equipment can alter the erosion-sedimentation pattern towards the interior of the system, as the flow around barriers is speeded up and zones are generated where sediment transport is increased and local erosion phenomena are created (Jackson & Nordstrom, 2011; Nordstrom, 2000; Poppema et al., 2019). In this respect, on Playa del Inglés beach (Maspalomas, Gran Canaria), the interference of permanent beach equipment (kiosks and sunbeds) and certain beach user activities led to the formation of wind shade corridors and deflation surfaces that extended from the back beach to the foredune area (Hernández-Calvento, 2002; Instituto Tecnológico Geominero de España, 1990; Martínez, 1990). These erosive landforms developed despite some of the barriers being removed years earlier (Díaz Guelmes & Hernández-Calvento, 2004). Subsequent studies also revealed the loss of vegetation to be a factor in foredune alteration (Hernández-Cordero et al., 2012; Hernández-Cordero et al., 2018; Pérez-Chacón et al., 2007).

Along this line, the aim of the present study is to consider in greater depth the relationship between beach management/use and the alterations to the biogeomorphological elements of the beach-dune system of this particular beach, Playa del Inglés, that have taken place in parallel with the tourism development process from the 1960s to the present day. Although there are related studies conducted in temperate environments (Nordstrom et al., 2007; Martínez et al., 2013; Corbau et al., 2015) as well as in arid environments with low human pressure (Amini et al., 2012), the innovation of this research is especially significant due to the specific characteristics of the study area: a fragile arid coastal environment with low plant cover, with a naturally fragmented foredune and subjected to an intensive tourist pressure along the whole year (García-Romero et al., 2021), where the biogeomorphological processes are rapidly changing. The hypothesis considered in this study is that the decisions that have been adopted on the use and management of Playa del Inglés have induced changes in the aeolian sedimentary dynamics of the beach-dune system that have had significant repercussions on the dimensions, structure and functionality of the foredune. For this purpose, an analysis is undertaken of the correlations between, on the one hand, the presence of beach equipment, services offered and activities undertaken on the backshore of the beach and, on the other, the biogeomorphological transformations that took place in the period between 1961 and 2018. Based on this analysis, an evaluation is then made of how the land use and management measures adopted by administrations can affect and compromise the conservation of coastal dune systems. In the next section, a description of the study area is introduced. In the third section, the information sources and the methodology are described in detail. In the fourth section, the main results about the evolution of biogeomorphological elements and their relationships with beach equipment are presented and widely discussed. Finally, the conclusions are gathered in the fifth section.

2. STUDY AREA

The Maspalomas dunefield (27°44’24.73’’N;15°34’26.19’’W) is a 360.9 ha transgressive arid dune system situated on the south coast of the island of Gran Canaria (Fig. 1). It was declared a Special Nature Reserve by the Canary Regional Government and a Special Area of Conservation (SAC) by the EU. Beaches are not included in these protected areas.

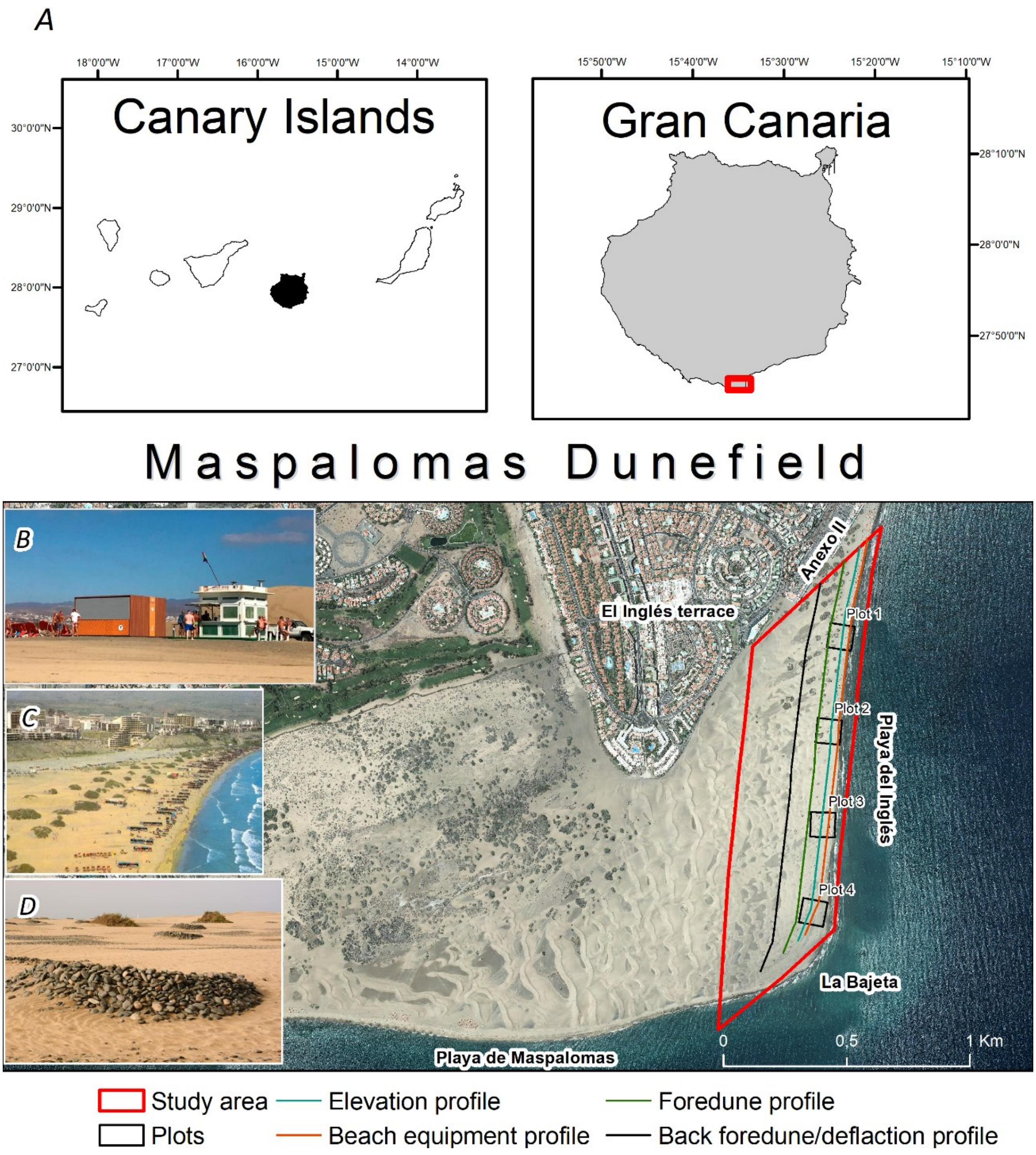

Figure 1. A) Study area, profiles used to analyse the variables studied in this work and plots established for the geomorphological resilience study. Source of orthophoto: IDECanarias, GRAFCAN, S.A.-Canary Islands Government (2018). Coordinates UTM. Zone 28 N. Ellipsoid WGS 84. Datum REGCAN95. B) Kiosk type until 2019 (white on the right) and new kiosk from 2019 (orange on the left) (source: Canarias7 newspaper). C) Kiosk and sunbed distribution in the 1970s. D) Goro (artificial windbreak structure) and examples of T. moquinii (Source: Masdunas project).

Mean annual rainfall in the dunefield is less than 100 mm and mean annual temperature is 21ºC, with only slight variation throughout the year (Hernández-Cordero et al., 2019). The effective prevailing winds are NE, ENE and E, favouring sedimentary transport (Máyer Suárez et al., 2012). In consequence, the dunes move from NE to SW, from their access to the system through Playa del Inglés. The foredune is situated on the backshore, comprised of nebkhas, shadow-dunes and tongue dunes (parabolic-shaped, unvegetated, arcuate ridges) (Viera-Pérez, 2015) which are formed by colonization of the plant species *Traganum moquinii* (Hernández-Cordero et al, 2012). This shrub species contributes to the accumulation of sand, favouring the formation of nebkhas which regulate the transport of sediment to the interior of the dunefield. In between these nebkhas, tongue dunes are formed which evolve into barchan dunes as they advance towards the interior of the system (Cabrera-Vega et al., 2013b; Domínguez-Brito et al., 2020; Hernández-Cordero et al., 2012).

Playa del Inglés is a space with year-round intensive tourism use. In the northern half of the beach the density of equipment such as kiosks, parasols and sunbeds is high, while other equipment for the rental of small recreational watercrafts can be found in the most elevated section of the profile protected from tidal effects. In the southern half, from the backshore to the interior of the system, an abundant number of windbreak structures, locally known as *goros*, can be found. These circular structures, constructed by beach users with large pebbles for protection against wind and sand, can generate impacts at local scale by modifying aeolian transport and damaging *T. moquinii* specimens, behind which the *goros* tend to be constructed.

The 71.6 ha study area extends, from east to west, from Playa del Inglés towards the interior of the system and, from north to south, from the Anexo II shopping centre towards the tip of La Bajeta. The northern area of the beach, where some human impacts have previously been studied in detail (Hernández-Cordero et al., 2017; Peña-Alonso et al., 2018b; Viera-Pérez et al., 2019) has been excluded from the study, as much of its surface was built on towards the end of the 1980s and so it is not possible to analyse the biogeomorphological evolution of the foredune. For the purposes of this study, four 100 x 100 m plots, separated from each other by an approximate distance of 400 m along the N-S profile of the beach (see Fig. 1) were established and used for an analysis of geomorphological resistance.

3. METHODOLOGY

A decade-based analysis was carried out of the spatiotemporal correlations between the geomorphological transformations of the foredune and its immediate surroundings and the presence and distribution of beach equipment (mainly kiosks and groups of sunbeds) and *goros* (Fig. 1D). The years of the study period selected for this analysis were 1961 (before the development of tourism in the area), 1977, 1987, 1998, 2006 and 2018. The information used (Table 1) was collected mainly from historical aerial photographs, digital orthophotos and digital elevation models derived from LiDAR flights, using the maximum resolution of each information source and geographic information systems (GIS). Fieldwork was also undertaken for the more recent dates. The WGS84-UTM 28-N reference system was used. The delineation error was calculated according to Robinson et al. (1987).

Table 1. Characteristics of the information sources used.

Type (source)	Year	Spatial resolution (m)	Use	Delineation error (m)
Historical aerial photographs (1, 2)	1961 (RMS: -) web map service	0.12	*	0.12
	1977 (1:6,500) (RMS: 1.54 m)	0.9		1.3
Orthophotos (1, 2, 3)	1987, 1998, 2006, 2018	0.15, 0.25 and 1	*	0.15, -, 1
DEMs (1, 2, 4)	10/2006, 03/2011, 11/2018	1	^{a}	^{a}

(1) IDECanarias, GRAFCAN, S.A.-Canary Islands Government (web map service or LiDAR flights); (2) Grupo de Geografía Física y Medio Ambiente (IOCAG, ULPGC); (3) Instituto Geográfico Nacional (IGN); (4) LiDAR flights (file .las) (2006, 2011, 2018). *eco-anthropogenic variables; ^{a}elevation profile; - missing data.

From these information sources, eco-anthropic variables related to beach equipment, vegetation and geomorphological elements were identified and digitalised to analyse spatiotemporal relationships, topographical changes and geomorphological resilience in the study area (Fig. 2).

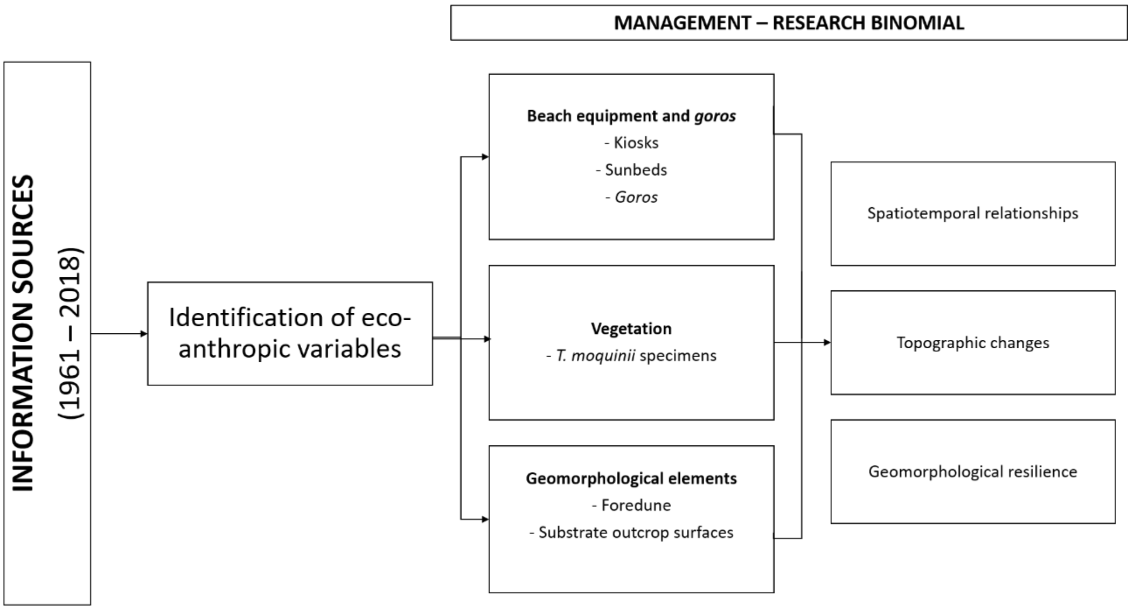

Figure 2. Flowchart of the methodology carried out in this research.

3.1 Identification of eco-anthropic variables

3.1.1 *Beach equipment and goros*

The kiosks and groups of sunbeds were digitalised in polygon-type vectors to obtain the number, surface area and distance between them for each studied year. The *goros* were also digitalised in point-type vectors to count their number and determine the distance between them.

3.1.2 *Vegetation*

The only plant species that grows in the study area is the nanophanerophyte *Traganum moquinii* (Hernández-Cordero et al., 2012; Hernández-Cordero et al., 2015). The presence of individual *T. moquinii* specimens was digitalised creating a point-type vector shapefile in the centroid of the each specimen. The following procedure was undertaken to know the spatiotemporal evolution of the *T. moquinii* specimens: i) detection of the disappearance of individual specimens between 1961 and 2018, and ii) calculation of the Euclidean distance using specific GIS tools. The distance to the coastline and to the equipment situated on the beach was determined from the eastern boundary of the study area (Fig. 1) towards the interior of the system. Similarly, the northern boundary was used to determine the existence or otherwise of a relationship with the main entrance to the beach-dune system, situated in the Anexo II commercial centre of Playa del Inglés (Fig. 1).

3.1.3 *Geomorphological elements*

3.1.3.1 Foredune

The foredune extends from the first *T. moquinii* specimens and their sedimentary accumulations (nebkhas, shadow dunes and tongue dunes; Hernández-Cordero et al., 2012; Viera-Pérez, 2015) in the first line of the backshore to the last examples of this species which are situated towards the interior of the system, following the prevailing direction of the aeolian sedimentary dynamics (NE-SW). The foredune was digitalised through a polygon-type GIS vector layer.

3.1.3.2 Substrate outcrop surfaces

These erosive depressions of aeolian origin are identified as outcrops of the underlying substrate (wet sand, alluvial deposit and palaeo-reefs, among others) wetted by capillary action. Depending on their origin, they can be interdunal depressions or deflation surfaces.

Interdunal depressions are outcrops of the underlying substrate situated between free dunes (barchan dunes or barchanoid ridges) and associated to displacement of the dunes themselves (natural origin). They are located in mobile dunes found behind the foredune, more than 300 m inland and at some distance from the structures that alter the aeolian sedimentary dynamics (> 100 m). They are oriented parallel to the coast (130°-180°). They were digitalised using a polygon-type GIS vector layer. The information about these landforms was unified and is shown together with the deflation surfaces as a single category (substrate outcrops) in Figure 3. This information was not used for the spatial analyses.

The deflation surfaces are substrate outcrops situated on the backshore and associated to interferences in the aeolian sedimentary dynamics (anthropic origin). They appear near to the foredune (< 300 m) and the artificial structures of kiosks, sunbeds and *goros* (< 100 m). They are oriented perpendicular to the coast (100°-130°) and have a larger surface area than the interdunal spaces. They were mapped using a polygon-type GIS vector layer. Due to their anthropic origin, the information about these erosive landforms (Figs. 5 and 6) was used for the analysis of spatiotemporal relationships with the rest of the variables.

3.2 Analysis of spatiotemporal relationships

3.2.1 *Relationships between foredune, beach equipment and deflation surfaces*

A bivariate correlation analysis (Pearson correlation coefficient of 0.95) was undertaken of the spatiotemporal evolution between beach equipment and biogeomorphological elements of the dune system. For this purpose, three N-S profiles were drawn, coinciding with the beach, foredune and back foredune/deflation, separated by a distance of 85 m (Fig. 1, orange, green and black lines). The following were registered each 2 m in the direction of the sedimentary dynamics (NE-SW): i) the presence or absence of kiosks or groups of sunbeds in the first profile (beach equipment profile); ii) the presence or absence of foredune in the second profile (foredune profile); and iii) the presence or absence of deflation surfaces in the third profile (back foredune/deflation profile).

3.2.2 *Topographic changes and their correlation with beach equipment*

The topographic profiles were obtained using digital elevation models (DEMs) for 2006 and 2018. The 2011 profile was added to allow better observation of the trends and to reduce the temporal scale. The profiles are located between the back beach and the foredune front (Fig. 1, blue line, elevation profile). The mean density of the original LiDAR data was 1.20 points/m^2, with mean planimetric and altimetric precision ranging around 0.60 and 0.2 m, respectively. The profiles were taken with an elevation datum each 2 m. On this basis, the topographic variations (accumulation and erosion) were detected for this 12-year period.

3.3 Analysis of geomorphological resilience

To facilitate the analysis of the capacity of the dune system to preserve its functionality and to support the external agents to which it was exposed over the course of the study period (geomorphological resilience), four plots were established along Playa del Inglés. The plots were situated in areas that were representative of the different spatial combinations of parameters of height, vegetation cover, coastal dune surface area, exposure to wave action, aeolian incidence and anthropic pressure (area occupied by kiosks, sunbeds and parasols). A bivariate analysis was undertaken of pairs of variables between the six selected dates using GIS-based spatial measures on the orthophotos. The calculation of resilience was performed using a set of indicators and following the concepts and metrics set out in Peña-Alonso et al. (2018), which are based on the evaluation of the geomorphological vulnerability of coastal dunes of arid regions. The variables considered and the measurement criteria are represented in Table 2.

Table 2. Variables used to calculate geomorphological resilience

GEOMORPHOLOGICAL RESILIENCE (GR)	**0**	**1**	**2**	**3**	**4**	**Reference**
1. Foredune zone surface variation (%)	<-30	-11/ -30	-	0/-10	>0	Peña-Alonso, 2015
2. Dry beach surface variation (%)	<-100	-16/ -100	-	0/-15	>0	Abuodha & Woodroffe, 2010
3. Shoreline variation (m)	<-100	-26 / -100	-	0/-25	>0	Gornitz et al., 1994
4. Variation in the continuity of the first line of nebkhas (%)	<-30	-11/ -30	-	0/-10	>0	Bodere, 1991
5. Variation of maximum distance between individual plant specimens in the first line of nebkhas (%)	>30	21-30	-	0-20	<0	Peña-Alonso, 2015
6. Vegetation cover variation in the foredune zone (%)	<-50	-26/-50	-	<0/-25	>0	Bodere, 1991

After the results of the variables for each year and plot had been obtained, the Geomorphological Resilience (GR; Eq. 1) value was calculated as the ratio between the sum of the values assigned to each variable (Vi) and the sum of the maximum possible values of geomorphological resilience (Vp max.), following Peña-Alonso et al. (2018) :

$$GR = V_i/V_{p\,max} \qquad \text{(Eq. 1)}$$

4. RESULTS AND DISCUSSION

4.1 Spatiotemporal evolution of the geomorphological and anthropic elements

Between 1961 and 2018 several variations were detected in the different eco-anthropic variables studied in the dunefield. These variations are principally related to the role played by beach equipment and user activities, as well as measures taken by the competent authorities. These management actions have, in turn, been based on advances in scientific knowledge acquired in recent decade, especially in reference to how the aeolian sedimentary systems of the Canary Islands function and the impacts generated by human activities. Knowing the evolution over time of the management of this protected nature area is key to understanding the environmental changes that have been detected.

Initiatives began in the 1970s to protect the dunefield, but it was not until the 1980s that measures were enacted in law to protect and preserve the system. Such measures included municipal subsidiary regulations (1986) on land use, the first law that established Nature Areas in the Canary Islands (1987), which included Maspalomas as a protected area, and the Coastal Act of 1988 which placed restrictions on the use of beaches and sandy areas. The 12/1987 law on Nature Areas was replaced by a law (12/1994) which declared the dune system and its immediate surroundings to be a Special Nature Reserve and an Area of Ecological Sensitivity. As a result of this law, a Nature Reserve Master Plan was drawn up in 1999, which oblige to the declaration of ecological impact of any management activity on its beaches, as well as the taking of measures that affect the back beach and the foredune, such as the *goros* removal. In the early 2000s, the approval of new land-use planning laws leaves beach management out of the ecological impact statement. In 2004, a new Master Plan was approved promoting the planting of specimens of *T. moquinii* where they had disappeared, and management of the beach became the responsibility of the Coastal Authority and the Local Council of San Bartolomé de Tirajana who intensified management actions concentrating on using heavy machinery to correct the alterations that had been detected as the result of the impact of beach equipment. A new project, established by the Ministry of the Environment (2007) integrated all the knowledge that had been acquired on the Maspalomas dune system, establishing a new scenario based on the need for a more environment-centred focus and management strategy. Some of the proposed management measures are presently being put into action through the Masdunas+ programme (2018) established by the *Cabildo Insular de Gran Canaria*.

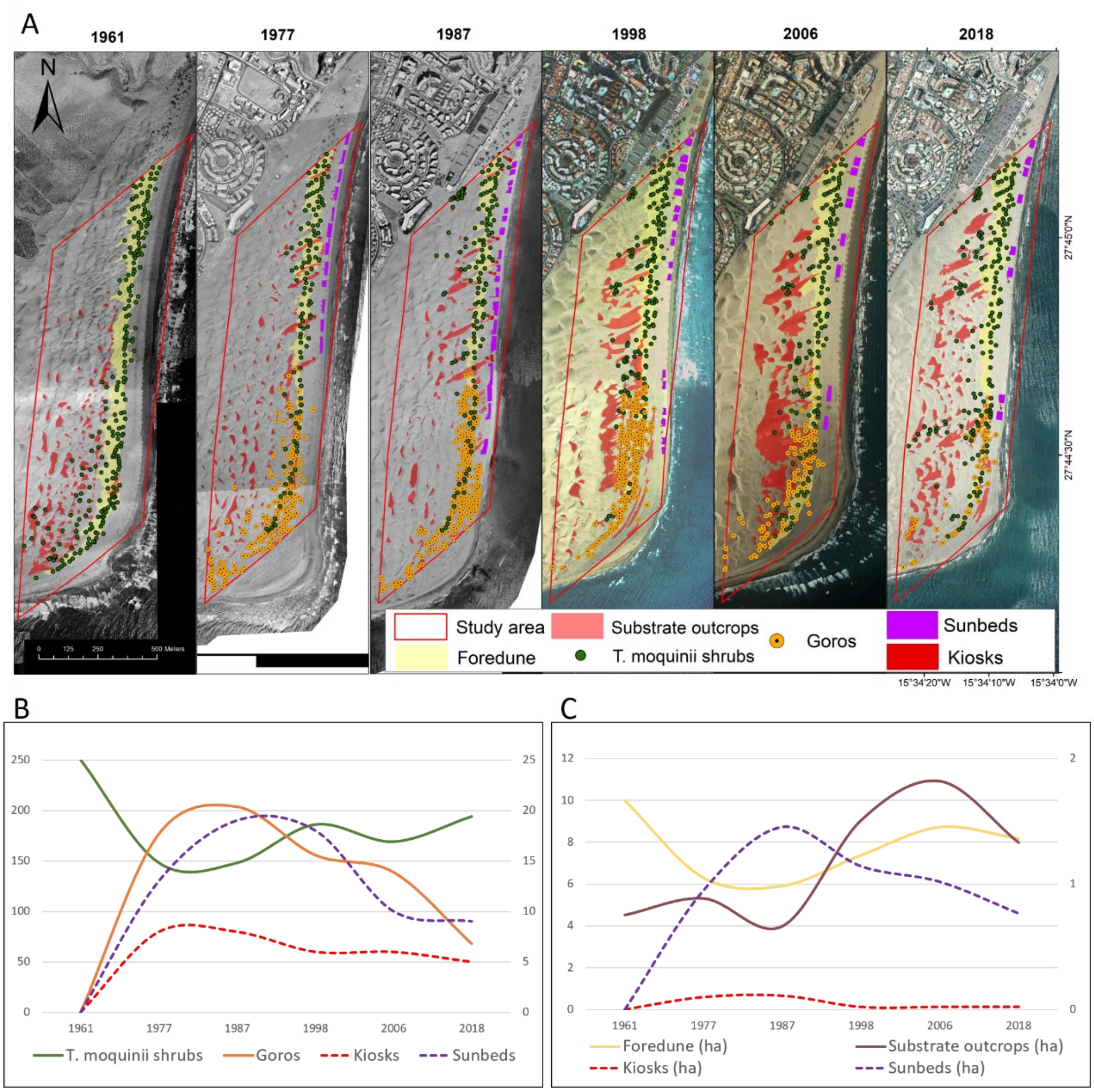

Figure 3. A. Cartography of the variables. B. Evolution (no.) of variables. C. Evolution (ha) of the variables. Dotted lines are read along the secondary y-axis.

4.1.1 *Beach equipment*

As tourism began to develop in Playa del Inglés in the 1960s, so too did the installation of beach equipment on the backshore. The number of groups of sunbeds and, consequently, the surface area occupied by them grew constantly up to 1987, initially in the northern and central area of the beach and then extending southwards during the 1980s (Fig. 3). A redistribution of the groups of sunbeds took place between 1987 and 1988, with a subsequent reduction in the area occupied by them through the disappearance one of the groups of sunbeds. A further reduction in these groups of sunbeds took place in the following years, with the most important of the measures that were taken in this respect being the obligation that was established in 2007 to stack the sunbeds when not in use. As a result, in 2018 a total of 9 groups of sunbeds occupied a surface area of 0.75 ha.

Analogously, the presence of kiosks increased in the 1970s, reaching their maximum number and maximum occupied surface area in 1977 (Fig. 3). These values remained virtually constant up to 1987. The kiosks in this first period ranged in size between 105 m^2 and 120 m^2. Between 1987 and 1998 the number of and surface area occupied by the kiosks fell. The designation of Playa del Inglés as an Area of Ecological Sensitivity (1994) resulted in new measures being taken with respect to the kiosks in the first decade of this century. The position of a total of 6 modular and detachable kiosks (smaller than 20 m^2) had to be changed on a regular basis. A study conducted by the Spanish Ministry of the Environment (2007) recommended a redesign of the kiosks, using a more aerodynamic form. Despite this, in 2018, 5 rectangular-shaped kiosks occupying a surface area of 0.02 ha were detected in the present study.

4.1.2 *Goros*

Between 1961 and 1977 there began to appear in the central and southern areas of the beach windbreak structures known locally as *goros.* The highest number of these structures (over 200) was detected for 1987, after which they gradually decreased in number until 1999 when the Nature Reserve Master Plan expressly prohibited their construction and existing structures began to be removed. The 2004 Nature Reserve Master Plan focussed again on the need to eliminate these structures, although only those which were not associated to specimens of *T. moquinii* were removed.

4.1.3 *Traganum moquinii*

As reported in previous studies, an overall reduction in the number of specimens of *T. moquinii* in the Maspalomas dunefield has taken place since

1961 (Hernández-Cordero et al., 2017, 2012). This evolutionary dynamic is observed even if only the area included in the present study is considered (Fig. 3A). The highest decrease of 40.8% took place between 1961 (before the development of tourism) and 1977. Since then, there has been a series of rises and dips in the numbers of specimens: an increase between 1987 and 1998 of 25.7%, a decrease of 9.1% between 1998 and 2006, and an increase of 14.8% between 2006 and 2018.

Two spatial patterns can be observed in the evolution of the populations of *T. moquinii* (Fig. 4). Firstly, most of the losses take place in the first 200 m from the coast. Most beach users are concentrated in this strip, either on or close to the beach, sunbeds and kiosks. In this respect, the grouping together of beach equipment in certain areas of the beach (generally the kiosks are situated between groups of sunbeds) generates user focal points of concentration. Beach user access to areas where beach equipment is concentrated is liable to generate other impacts on biogeomorphological elements of the systems, caused by stepping or trampling on the vegetation making the growth of new specimens and the formation of embryonic dunes more difficult (Hernández-Cordero et al., 2017). Secondly, the reduction is greater in the northern and southern sections of the study area compared to the central section. Previous studies have reported that these higher reductions in the northern and southern sections may be related to the degree of tourist activity (Hernández-Cordero et al., 2017). That is, the reduction in the northern area may be associated to its closeness to the urbanised area of the resort and therefore to a greater number of beach users affecting individual specimens of *T. moquinii*. The reduction in the southern section may be related to the alteration of aeolian dynamics as a consequence of the development of the touristic resort on the Playa del Inglés terrace. It is also possible that the plants were directly destroyed at some point to expand the beach area available for tourists.

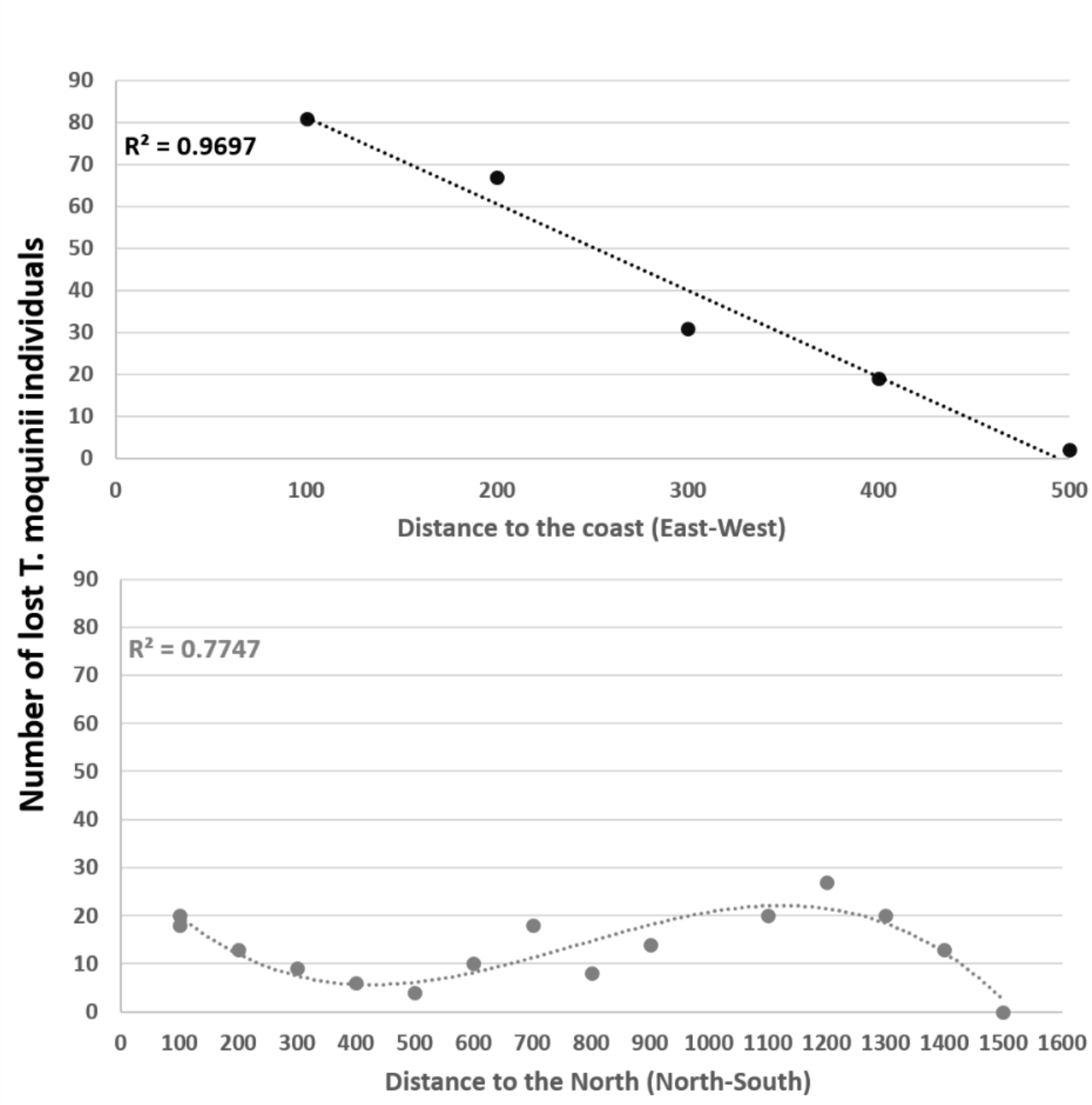

Figure 4. Spatial analysis of T. moquinii individuals lost between 1961 and 2018.

4.1.4 *Substrate outcrops*

Outcrop areas of the underlying substrate in 1961 were detected principally in the southern section of Playa del Inglés. These areas were small and produced no fragmentation of the foredune. Between 1977 and 1987 an increase was observed in the number of deflation surfaces, although the area they occupied decreased. In this period, however, these deflation surfaces began to fragment the foredune in the northern and central sections. A decrease in the surface area occupied by these outcrops was detected for 1987. Between 1987 and 2006 the number of deflation surfaces decreased but increased in size. Their displacement towards the interior of the system was also observed, with large deflection surfaces detected behind the foredune. The area occupied by substrate outcrops recovered slightly between 2006 and 2018, amounting to almost 8 ha in the latter of the two years (Fig. 3).

The formation of these substrate outcrops, perpendicular to the coast and located on the beach, on the foredune and in the back foredune (Fig. 3) indicates an erosional process (Díaz Guelmes & Hernández-Calvento, 2008; Hernández-Calvento et al., 2014). This occurrence is comparable to the formation of blowouts that occurs commonly in temperate regions (Leatherman, 1976; Saunders and Davidson-Arnott, 1990; Mir-Gual et al., 2013). The fact that blowouts have not been observed around, or on the foredune of this environment is related to the differences between arid and temperate foredunes, as the vegetation cover is lowest in the arid systems and bushes predominate (García-Romero et al., 2021).

4.1.5 *Foredune*

In 1961, the foredune of Playa del Inglés situated in the study area occupied a continuous extension of 10 ha. A continuous north-to-south foredune was observed with no fragmentations, although some 14 small-sized deflation surfaces appeared in the south. Progressive fragmentation of the foredune took place in the following years at the same time as the number of individual *T. moquinii* specimens decreased, as determined in previous studies (Hernández-Cordero et al., 2012). The management measures that were taken during the study period were at least partly responsible for the changes detected (Fig. 3). The reduction in the area occupied by the foredune that took place between 1977 and 1987 was greater than between 1961 and 1977. This higher foredune loss coincides with the period of the highest loss of *T. moquinii* specimens in the study area. In 1977 the first discontinuities appear in the foredune, concentrated in the northern and central section of the beach. In 1987, the area occupied by the foredune is the lowest in the whole study period. There are clear discontinuities along the beach which resulted in a foredune surface area of less than 6 ha. The management measures adopted in the 1990s appear to have favoured a gradual recovery of the area occupied by the foredune up to 2006. Between 2006 and 2018 this trend is reversed, and once again there is a loss of surface area occupied by the foredune (Fig. 3).

Unlike the foredune of temperate regions, where the main indicator of degradation is the presence of blowouts (Hesp, 2002), these results show that the effect of degradation of an arid foredune is the reduction of *T. moquinii* specimens and nebkhas, as well as the formation of deflation surfaces and free mobile landforms (small barchan dunes with less than 1 m high and sand sheets) (Hernández-Cordero et al., 2012; Hernández-Calvento et al., 2014; Hernández-Cordero et al., 2018).

4.2 Spatiotemporal relationships between biogeomorphological and anthropic elements

Analysing the joint spatiotemporal distribution of beach equipment and biogeomorphological variables of the dunefield between 1961 and 2018 enables determination of cause-effect relationships in the historical transformations observed in Playa del Inglés (Figs. 5 and 7).

As this is a transgressive dune system, where sedimentary transport is initiated on the beach, the characteristic natural processes that take place in beach-dune, foredune and interior area subsystems are connected, with any interference that is produced in the beach having possible repercussions throughout the system.

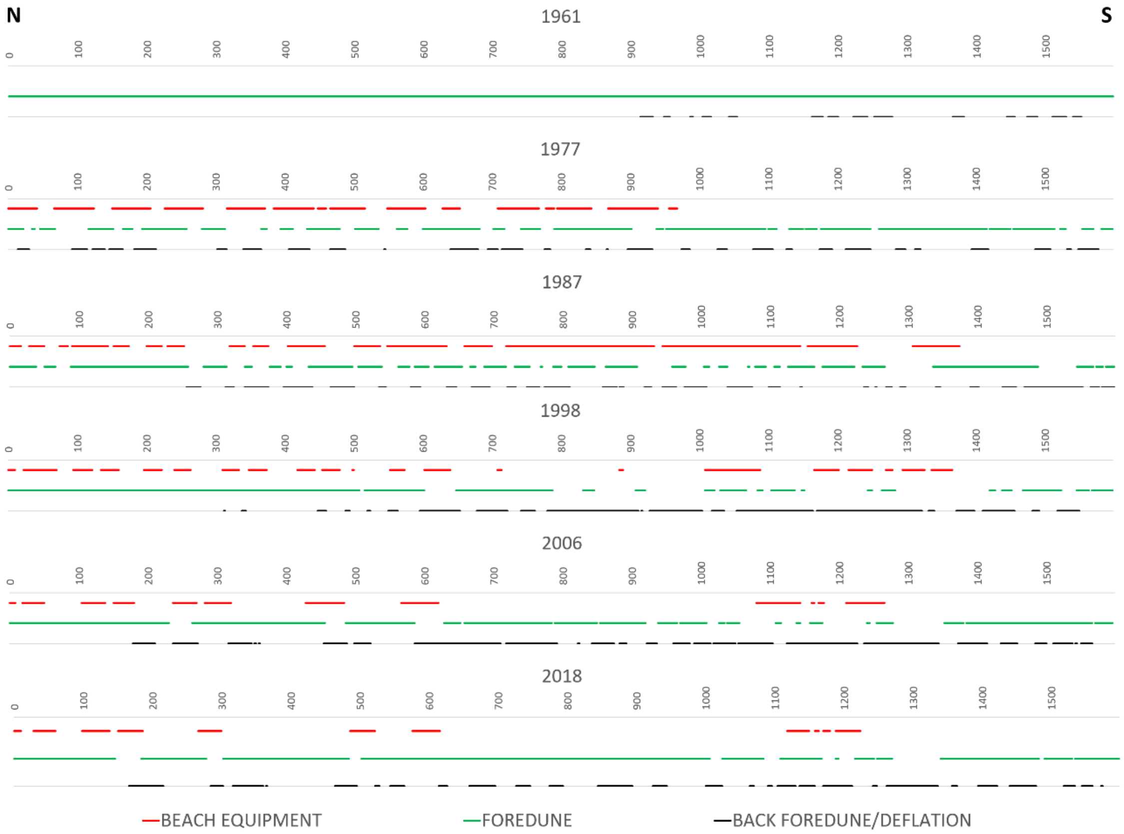

Figure 5. Spatiotemporal analysis of the presence of beach equipment (red, in the beach equipment profile), foredune (green, in the foredune profile) and deflation surfaces (black, in the back foredune/deflation profile).

The maximum joint presence of *T. moquinii* and foredune over the course of the study period was in 1961 (Fig. 3), and the minimum 16 years later in 1977, with this period coinciding with the expansion of tourism and the maximum number of kiosks (1977) and *goros* (1977-1987) on the beach (Figs. 3 and 5). The pattern described by this joint presence coincides with the appearance and increase between the 1960s and 1987 of the number of *goros,* kiosks and sunbeds and in the amount of surface area occupied by kiosk and sunbeds (Fig. 3 B, C). From 1987 to 2018, the *T. moquinii* shrubs and the foredune tended to progressively recover at the same time as the presence of beach equipment (sunbeds and kiosks) and *goros* tended to decrease (Fig. 3 B, C), which coincides with the declaration in 1987 of the Maspalomas dunefield as a protected natural area. These beach structures decreased from 1987 onwards, which is when an incremental trend in the number of *T. moquinii* specimens is also detected. The inverted correlation between vegetation cover/foredune size and the presence of *goros* is especially notable in the southern section of the beach (Figs. 3 and 5), where it is also possible that the decrease in *T. moquinii* is related to alteration of the aeolian sedimentary dynamics of the urbanisation of the Playa del Inglés terrace, and/or their direct removal to expand the beach area available for tourists (Hernández-Cordero et al., 2017).

The deflation surfaces followed a trend of progressive expansion from 1961 to at least 2006, despite the progressive decrease from 1987 onwards of beach equipment (kiosks and sunbeds) and *goros* and the progressive recovery of the foredune and *T. moquinii* specimens (Fig. 3 B, C). The coastal sections most affected by the deflation processes over time strongly coincide with the location of the main beach structures (kiosks, groups of sunbeds and *goros*) and with the sections where there was a greater decrease in surface area occupied by the foredune and in the number of individual *T. moquinii* specimens (Fig. 4). In the case of Playa del Inglés, plastic netting was on occasions positioned around the sunbed sectors to protect users from the wind. This netting would have constituted an added obstacle to aeolian sedimentary transport and contributed to the development and permanence of deflation surfaces. Their persistence may be due to the strong inertia of this type of erosive landform, which once the process for their development has been triggered tends to be difficult to invert. These deflation surfaces may well be inherited effects from the 1970s and 1980s of the first kiosks and groups of sunbeds (Suárez Rodríguez & Hernández-Calvento, 1998).

The origin of the deflation surfaces is nevertheless difficult to precisely determine given that, as previously indicated, they are erosive aeolian landforms which are not easily reversible. Henández-Calvento (2006) suggests that beach equipment, comprised mainly of kiosks, sunbeds and parasols, and windbreaks constructed by beach users, would have altered over the years the aeolian sedimentary dynamics, impeding sedimentary transport, causing deterioration to the foredune, and generating deflation surfaces. Although the deflation surfaces may decrease in number, generally they tend to increase in size over time (Fig. 3C). It can be seen in Figure 6 that in 1961 (yellow), these deflation surfaces (frequency and area percentages) were principally situated 200 m or more from the coastline.

However, between 1977 and 1998 (pink, blue and orange), the areas occupied are displaced towards the first 100-150 m from the coastline, and in 1987 and 1998 deflation surfaces are even found in the first 50 m. These years coincide with an important increase in the services offered to beach users in Playa del Inglés. With respect to this coastal strip, there is also a correlation with the areas where the main beach equipment (kiosks, groups of sunbeds) and *goros* are situated and where the highest loss of *T. moquinii* specimens was detected, as explained previously (Fig. 4). In this respect, in combination with the results shown in Figure 5, there are clear signs that these environmental changes are related to beach equipment and man-made windbreaks, with a cause-effect process altering biogeomorphological processes in the Maspalomas beach-dune system. The impact of beach equipment is similar to that of rigid structures like buildings (the effect of which has been studied in greater detail), altering the incidence of the wind and thereby affecting aeolian sedimentary dynamics and transport in the areas that surround them (Smith et al., 2017b). At the same time, complex airflow patterns are generated, causing sediment to diverge around and above the structure and creating turbulence, particularly behind it (Fackrell, 1984; Hunt, 1971; Peterka et al., 1985). These latter processes can also alter biogeomorphological elements, generating deflation surfaces downwind of the structure (García-Romero et al., 2019b). In 2006 (light red) and 2018 (dark red), a slight inland displacement is again seen of the deflation surfaces (200 m + from the coast). This displacement, especially in terms of area percentage, coincides with the foredune recovery that can observed in Figure 5. However, the recovery process tends to be slow and at the present time this coastal strip (200 m + from the coast) is more affected than in 1961 with a higher number of eroded surfaces. This deterioration could be the result of effects inherited from the installation of kiosks and sunbeds in the 1970s and 1980s , with the impact of these structures continuing over time despite the reduction in the surface area they occupy and their relocation on the beach (Suárez Rodríguez & Hernández-Calvento, 1998).

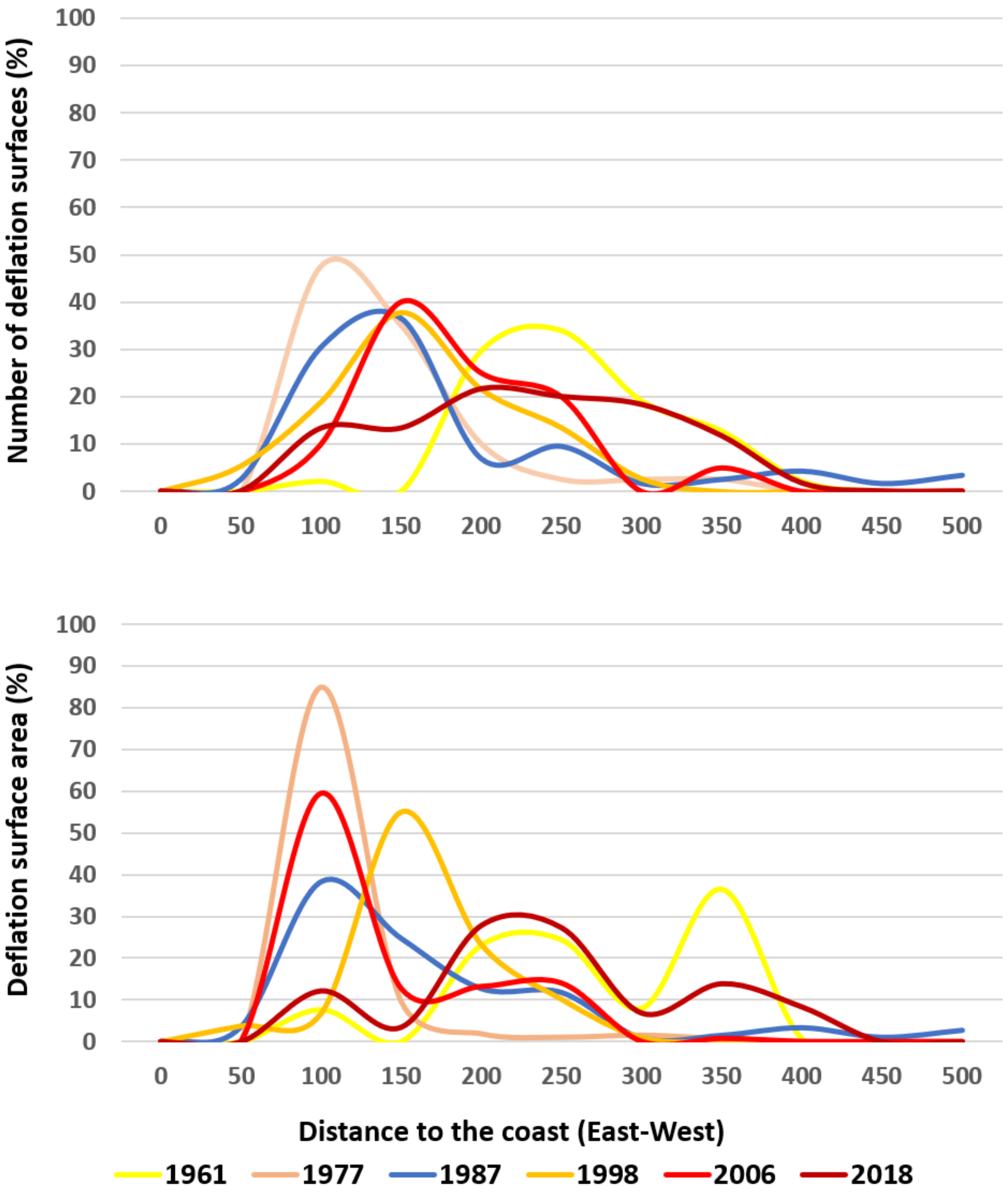

Figure 6. Location and displacement of deflation surfaces and occupied area.

All the above reinforces the idea of the relationship between these artificial beach structures and their impact not only in the distribution and presence of *T. moquinii* specimens, but also in the size and morphology of the foredune. This relationship was hypothesised in previous studies (Hernández-Calvento, 2006; Hernández-Cordero et al., 2012; García-Romero et al., 2021), but not directly analysed. In general, it can be seen that the fragmentation of the foredune and the reduction in the number of *T. moquinii* specimens is related to the greater presence and abundance of beach equipment. The same behaviour is observed with the growth in the number and size of deflation surfaces. In addition, in the case of the southern section of the beach the correlation is increased due to the presence of *goros*.

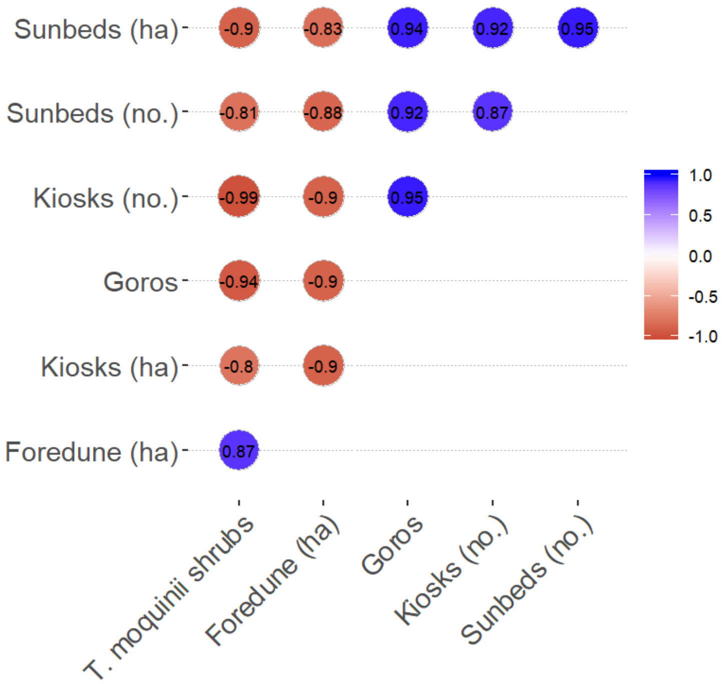

Figure 7. Pearson correlations between the studied variables (p-value < 0.05).

The Pearson coefficients (Fig. 7) provide further evidence of the relationships observed between biogeomorphological transformations of the dune systems and the variables associated to human activity on the beach. The backshore presence of structures, in the form of kiosks, groups of sunbeds and *goros*, is inversely correlated to the number of *T. moquinii* specimens and the surface area occupied by the foredune. Particularly notable are the correlations between the numbers of kiosks (R^2 = -0.99) and *goros* (R^2 = -0.94) and the abundance of *T. moquinii* specimens.

4.3 Recent topographical evolution of beach and foredune

Figure 8 shows the topographic variations (Fig. 1, elevation profile) (accretion and erosion) and their correlation with the presence or absence of beach equipment along the beach (Fig. 1, beach services profile) between 2006 and 2018. In this period, 27.75% of the profile shows accretion and 72.25% erosion, and it was also observed that the losses mainly coincide with areas permanently occupied by beach equipment. However, where no such equipment was detected the topographic profile remains stable or even shows accumulation (especially in the central sector). In the southern tip, an irregular profile is observed with zones of accretion and accumulation. Like buildings, beach equipment are obstacles that can spatially divide beach and dune and, consequently, reduce the area where aeolian sedimentary transport takes place (García-Romero et al., 2016; Morton et al., 1994). That is, a barrier is formed that separates the dunes and foredune from its sediment sources (Jackson & Nordstrom, 2011).

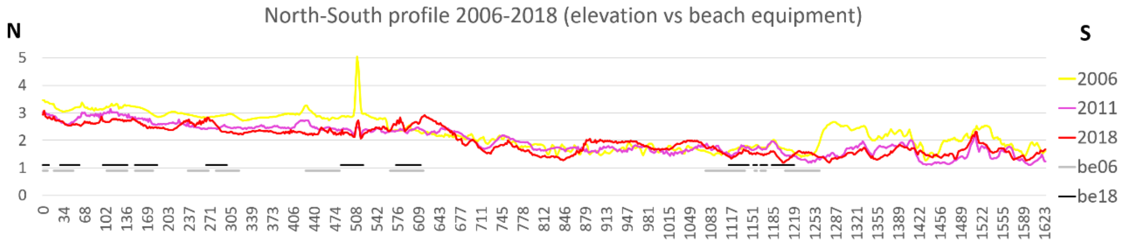

Figure 8. Elevation profiles (m) (N-S) from 2006 to 2018 and the presence of beach equipment in the study area. Key: be-beach equipment

4.4 Geomorphological resilience

The results of the analysis by plots show a very low degree of beach-dune resilience according to the variations in foredune surface area, continuity in the first line of nebkhas and foredune vegetation cover (Table 3). These three variables are related to the functional structure of the coastal dune, indicating that its capacity to support the natural and anthropic impacts that might affect it is being weakened. This loss of capacity is particularly notable in the southernmost plot of the study area (Plot 4), where there was a 43.34% loss in surface area, a 25.38% loss in the continuity of the foredune front, and a 27.66% loss in foredune vegetation cover in the final period analysed (2006-2018).

Table 3: Main results in geomorphological resilience variables (degrees of freedom=4)

Geomorphological resilience variables	**Mean**	**Standard deviation**
1. Foredune zone surface variation (%)	2.56	1.46
2. Dry beach surface variation (%)	3.00	0.89
3. Shoreline variation (m)	3.25	0.77
4. Variation in the continuity of the first line of nebkhas (%)	2.63	1.50
5. Variation of maximum distance between plant specimens in the first line of nebkhas (%)	3.00	1.41
6. Vegetation cover variation in the foredune zone (%)	2.75	1.44

These negative results obtained in the last of the periods analysed are related to the trend observed in all the plots (Fig. 9). While geomorphological resilience may have experienced other dips (as in the period between 1977 and 1987), the last decade analysed shows the worst result. In general, an enduring geomorphological deterioration is observed of beach and backshore at functional level, with detection of foredune fragmentation and the ongoing development of deflation surfaces.

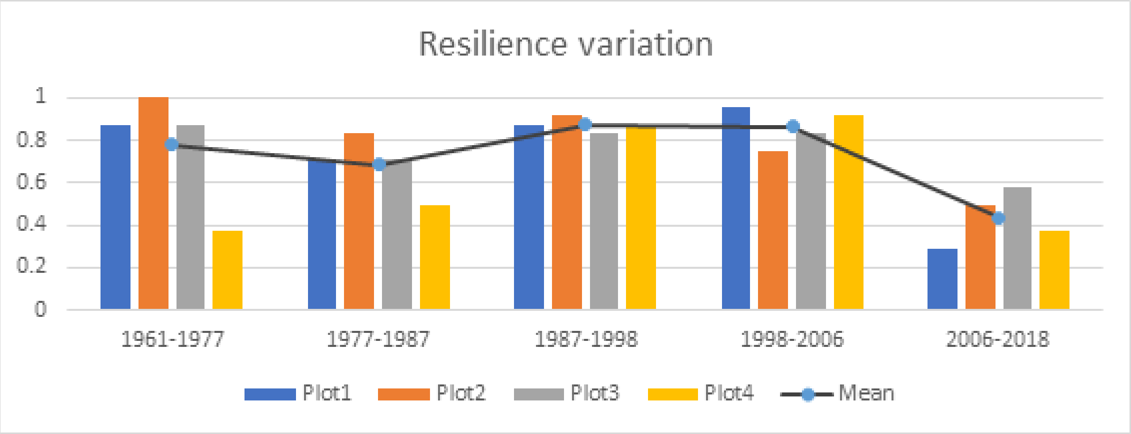

Figure 9: Geomorphological resilience variation of representative plots along Playa del Inglés.

This is additionally verified in the study of topographic profile variations (Fig. 8), foredune fragmentation (Figs. 3 and 5), and the evolution and displacement of deflation surfaces, with the latter analysis also reflecting the difficulty that these landforms have to recover or disappear (Fig. 6). In this respect, future studies should be considered for the construction of indices that integrate both environmental and anthropic variables, as they may provide more critical results closer to the actual reality. Additionally, if the intention is to provide integrated management and at the same time undertake the restoration and/or preservation of a system (in this case the beach-dune system of Maspalomas and particularly the foredune), special attention should be paid to processes that integrate all of its natural and socio-economic elements (Gracia Prieto et al., 2009; Lithgow et al., 2015; Peña-Alonso et al., 2018), as well as consider strategies to the respond to different environmental scenarios, such as sea level rise (Nazarnia et al., 2020).

5. CONCLUSIONS

This research presents innovative results about the impacts of beach equipment on an arid beach-dune system subjected to an intensive and continuous human pressure. Significant transformations have been found in the morphology and physical structure of the foredune of an arid dunefield, as well as statistically significant spatiotemporal correlations between these biogeomorphological transformations and beach equipment installed in the area. This supports the initial hypothesis of the potential influence of beach management on the transformation of the beach-dune system. Moreover, the biogeomorphological processes have responded to different management measures over the years, and it was found that some of the effect on these processes that had their origin in the 1970s and 1980s (development and increase in tourist activities in Gran Canaria without environmental protection) are not only detectable but have been inherited in the present day. Although that some of the considered variables seem to demonstrate a degree of recovery in the study area when analysed individually, coinciding with some of the improvements that have been made in terms of environmental protection (declaration as protected natural area since 1987) and management measures (since the 1990s), it should be noted that when integrated in an index designed to evaluate geomorphological resilience it was found that the system has been deteriorated and not recovered.

The results obtained in this study are conducive to a reflection on how environmental management measures can have a determining influence on the conservation or degradation of environments and ecosystems and, in particular, of arid beach-dune systems. It is important to underline the close collaboration that must exist between management and research organisations to ensure the effective management of these spaces (management-research binomial). This ensures the application of management strategies based on scientific knowledge and know-how, as well as the undertaking of further research studies aimed at continuously and efficiently improving the management of such areas.

Acknowledgements

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

Abel Sanromualdo-Collado, Leví García-Romero, Manuel Viera-Pérez, Irene Delgado-Fernández, Luis Hernández-Calvento

(***Ready for submission***)

Abstract

Beach users often use a range of strategies to shelter from the wind. On many cases, this involves building structures made of stacking stones to protect people behind them from strong winds. Different from other portable wind blockers such as umbrellas or tents, stone-made wind shelters remain in the landscape after people leave. 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 discontinuous nebkhas are naturally fragmented. This is the case of *Playa del Inglés* beach (Gran Canaria Island, Spain), the main sediment input to the Maspalomas dunefield (Special Nature Reserve), where the presence of windbreak pebble structures (locally named *goros*) made by beach-dune users has increased in recent decades following an increase of visitors to the island.

This research investigates the effects of stone wind shelters (stone shelters henceforth) on the dynamics of an arid beach-dune system at various spatiotemporal scales. We first study the increase of stone shelters in *Playa del Inglés* and its effects on foredune evolution over the last sixteen years. We then 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 dune landform as we progressively remove pebbles from a previously built stone shelter over a period of six months.

Results show that stone stacking impacts airflow and sediment transport dynamics and changes patterns of sand accumulation and delivery to nebkha foredune systems. Our results also show that the impacts of these artificial structures can be reverted following their removal but that the process of dismantling stones has to be carefully planned. We elaborate some recommendations here to avoid damaging foredune vegetation.

Keywords: Stone-stacking, Coastal aeolian sedimentary system, Shadow dune, Human impacts, Beach-dune management.

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, displacement and stacking of stones can disturb microhabitats and rock-dwelling organisms, promote soil erosion, and lead to vegetation damage (Rocha et al., 2020). However, the effects of structures made by stacking stones on biogeomorphology have been not studied, even though they may be modifying the biogeomorphological evolution of large conservation areas such as those found along many sedimentary coastlines.

The 1960s marked the beginning of mass tourism 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., 2017b; Viera-Pérez et al., 2019). Among other alterations to biogeomorphology, 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)also related with 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., 2021a). *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 the paleo-barriers, mostly phonolites, and sometimes are located over the foredune and annexed to the *T. moquinii* plant specimens to take advantage of the windbreak effect of the plants (Figure 1). These structures are common in Maspalomas and elsewhere in the Canary Islands, to the point that their presence has been used as an indicator of human pressure on these systems (Peña-Alonso et al., 2018b).

Nebkha is the main dune mode of arid foredunes (García-Romero et al., 2019c; Goudie, 2022; Hesp et al., 2021a), which are naturally fragmented. As coastal vegetated dunes, these ecosystems play a fundamental role in the regulation of sediment transport inland (Hernández-Cordero et al., 2015c), as well as in the protection of the coast against storms (Feagin et al., 2019). Arid coastal nebkhas are biogeomorphological units that result from the interdependence between plant characteristics, sediment dynamics and attributes, and geomorphology (Sanromualdo-Collado et al., 2022).

Wind flow and aeolian sediment transport around nebkhas and shadow dune formation have been studied (Domínguez-Brito et al., 2020; Gillies et al., 2014; Viera-Pérez, 2015; Zhao and Gao, 2021) and modelled by wind tunnel and computational methods (Hesp and Smyth, 2017; Yang et al., 2019; Zhao et al., 2020, 2019a). 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). However, little is known about the effects of roughness elements on nebkha formation, with no studies (to the knowledge of the authors) conducted on the limitations imposed by the presence of pebbles and other obstacles to sand transport on nebkha foredune growth and evolution.

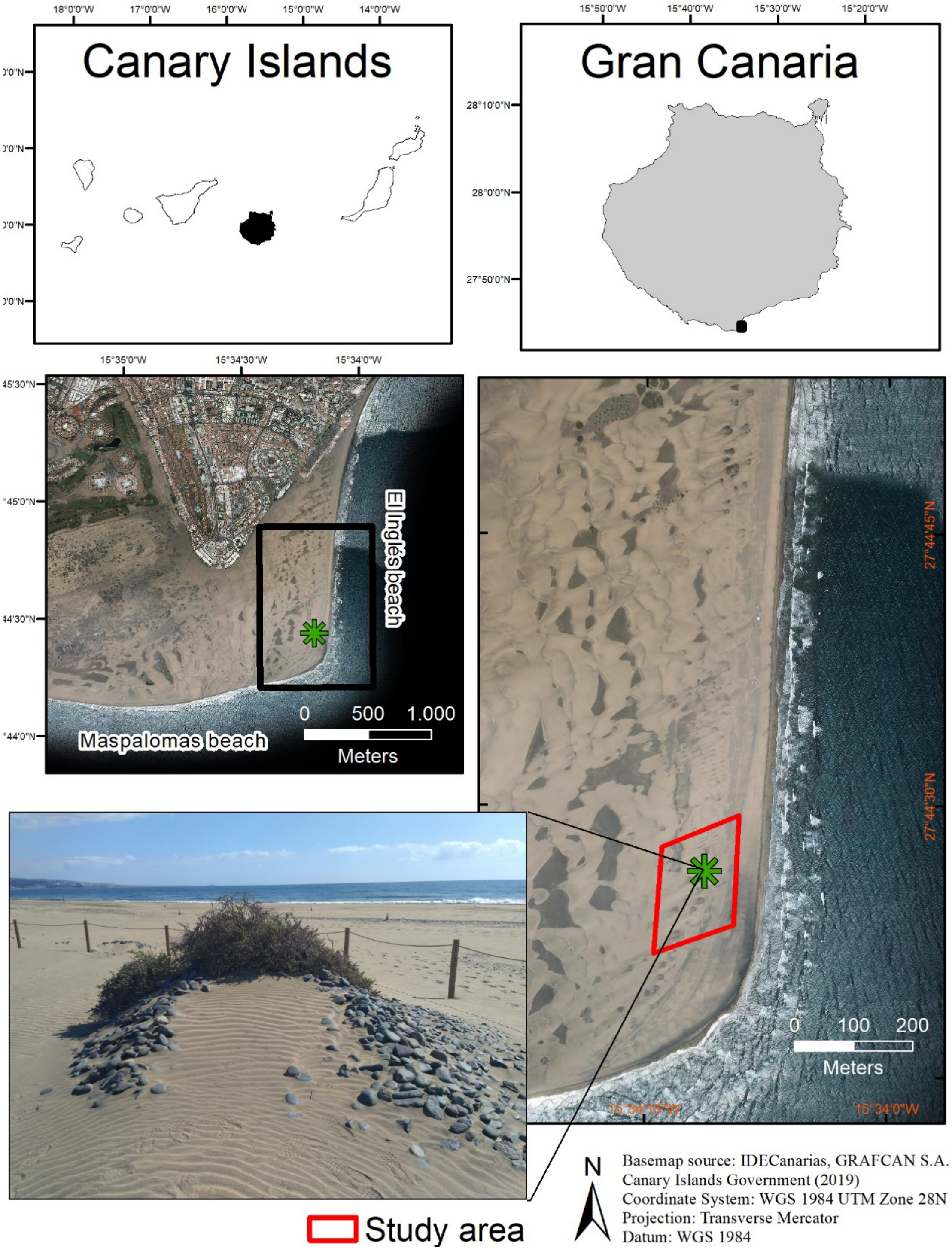
The impact that buildings have on wind flow and sediment deposition patterns around them (Fackrell, 1984; Hunt, 1971; Peterka et al., 1985; Poppema et al., 2021; Pourteimouri et al., 2021) and at the beach or beach-dune interface (Hernández-Calvento et al., 2014; Jackson and Nordstrom, 2011; Nordstrom and McCluskey, 1984; Sanromualdo-Collado et al., 2021a;

Wijnberg et al., 2021) has been well studied, but there is a lack of knowledge about the impact of relatively smaller structures such as stone-made wind shelters built by users. There is also a notable gap on policies regulating the presence of these stone-made structures at beaches and foredunes.

Sanromualdo-Collado et al. (2021) observed a direct correlation between the increase in the number of *goros* in *Playa del Inglés* and a decrease in *T. moquinii* specimens and foredune area. The hypothesis of the research presented here is that the pebbles stacked around the vegetation of the foredune prevents the natural development of the plants and their associated landforms, such as nebkhas and shadow dunes. On the one hand, the stones constrict the growth of the plant and its ability to retain sediment. On the other hand, they change the wind flow and sediment transport dynamics around the landform, limiting sediment accumulation and therefore foredune growth.

2. STUDY AREA

Playa del Inglés (27º44’26.4’’N, 15º34’11.2’’W) is a sandy beach to the east of Maspalomas dunefield (Gran Canaria Island, Spain) (Figure 1). This beach stretches 2.5 km in the north-south direction and is the main source of sediment of the dunefield. The effective prevailing winds from NE, ENE and E (Máyer Suárez et al., 2012) return the sediment to the sea through the southern *Maspalomas* beach, after crossing a transgressive dunefield where dunes were over 20 m height prior to the development of mass tourism (Hernández-Calvento, 2006). 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 into deep marine zones leading to an overall sedimentary deficit in the system (Hernández-Calvento, 2006; Hernández-Calvento et al., 2014).



Basemap source: IDECanarias, GRAFCAN S.A.
Canary Islands Government (2019)
Coordinate System: WGS 1984 UTM Zone 28N
Projection: Transverse Mercator
Datum: WGS 1984

Figure 1: Location of the study area in Playa del Inglés beach and detail of the studied windbreak pebble structure (goro) built over a nebkha (green asterisk) before the study period.

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 21º C, and the mean annual precipitation is around 81 mm (Hernández-Cordero et al., 2019). These conditions favour halophytic shrub species in the foredune (Hernández-Cordero et al., 2015c) 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., 2021a; Viera-Pérez et al., 2019). Moreover, the beach and its associated foredune is an area of intensive tourist use throughout the year (Hernández-Calvento, 2006). While in the north of the beach the density of equipment such as kiosks, parasols and sunbeds is high, in the southern half, from the backshore to the interior of the system, there is a significant number of *goros* (Sanromualdo-Collado et al., 2021a). *Goros* (human-made stone wind shelters) began to appear in central and southern beach areas from 1961 to 1971 as touristic resorts developed. Circa 1987 the number of *goros* in *Playa del Inglés* was over 200, with most located towards the southern half of the beach (Sanromualdo-Collado et al., 2021a). Despite publication of the first Nature Reserve Master Plan in 1999, which identified the impact of *goros* and led to the removal of many of them, some stone shelters still remained in *Playa del Inglés*. In 2018, more than 50 *goros* were identified along the beach (Sanromualdo-Collado et al., 2021a). They tend to persist over time because users continuously rebuild them as the pebbles and stones are removed or buried.

3. METHODS

3.1 Landscape change analyses

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

Table 1: Characteristics of the cartographic sources used.

Type (source)	Year	Spatial resolution (m)
Historical aerial photographs (1, 2)	1961 (1:5,000)	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).

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 error (%) from DEMs between 1987 and 2019 were: Accumulation (15.45, 9.99, 11.07, 4.21) erosion (18.22, 8.71, 5.78, 7.12) [respectively]; the above DoD errors are shown in order (1987-2003, 2006-2011, 2011-2018 and 2018-2019).

3.2 Field experiment: goro removal and nebkha evolution

For more detailed spatiotemporal scale analyses, we focused on a single nebkha located inside the study area during a 6-month period (November 2020 to May 2021; Figure 1). The objective at this scale was to monitor the evolution of the nebkha following the progressive removal of the *goro* previously built on it, and to investigate the effect that the *goro* had on wind dynamics around the landform. A 20 x 10 m plot was established around the selected 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 with a laser device was carried out on 5 November 2020. An intensive field experiment was carried out 5 days later, on 10 November 2022 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 too exposed to incoming winds. Instead, we chose to manually and carefully remove only the stones that were in sight on the 10 Nov (and then allow the wind to deposit fresh sand during the next 3 weeks). Stones within a random area of 1 x 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 measurement of wind data following 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 damage the plant (Figure 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 on the previous year. Finally, regional wind characteristics from October 2018 to June 2019 and from Oct 2020 to June 2021 were obtained from the Gran

Canaria Airport (LPA) met station, located 25 km northeast of the study area (Smith et al., 2017b). Daily averages for wind speed and wind direction recorded by the Agencia Estatal de Meteorología (AEMET) were used to compare conditions during the study period.

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

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 used to derive 0.3 m pixel resolution DEMs. DoD error (%) from LiDAR data (file .las) between 2018 and 2019: Accumulation (7.86) erosion (5.63). DoD error (%) from topographic survey between 2020 and 2021: Accumulation (4.32) erosion (3.98).

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).

Digital elevation models (DEM) were obtained from the field photographs using structure-from-motion (SfM) photogrammetry, 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 were low due to the high resolution of the photographs. At the initial and final states, 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 less than 0.003 m.

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

Three orthogonal profiles were drawn to obtain the topographical evolution of the nebkha: one along the central axis and two transversal profiles, one on the top of the nebkha and one behind the plant, where shadow dune should be formed.

3.2.3 *Wind data*

Airflow data were collected on 10 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) (Figure 3).

Airflow was measured by 10 wind stations consisting of an anemometer-vane-data logger system (Figure 3, C) with wireless communication (Domínguez-Brito et al., 2020; García-Romero et al., 2019b). Wind speeds and directions were initially sampled every 2 s and 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 data were collected at each location for 15 min, 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., 2019).

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 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 Figure 3 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 spatial patterns of wind data (Figure 3, B). Despite some differences, the range of incident wind directions at the fixed location was narrowest for T23 (15º or less between all runs) and showed the lowest standard deviation (78.984 ± 5.324º). 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.

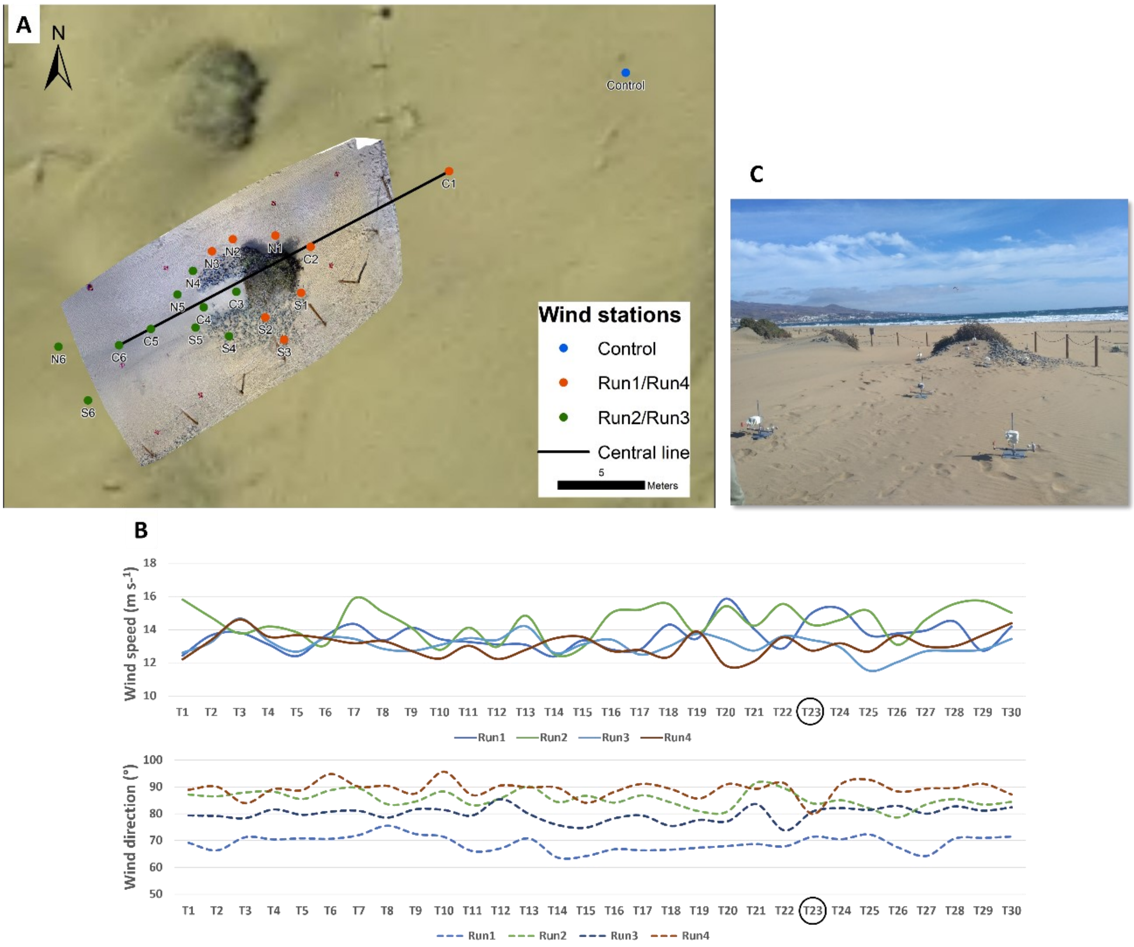


Figure 3: A) Grid of sampling points around the selected nebkha. B) Average wind speeds and directions recorded by the control fixed station for Run 1 (STARTING TIME: 09:48) and Run 2 (STARTING TIME: 10:33), prior to the removal of the goro, and for Run 3 (STARTING TIME: 11:20) and Run 4 (STARTING TIME: 11:49) following the removal of the goro. C) Anemometers deployed around the nebkha during the field experiment.

4. RESULTS AND INTERPRETATION

4.1 Combined effects of windbreak pebble structures over foredune (long-term evolution)

Playa del Inglés beach and its associated foredune is an area of intensive tourist use throughout the year (Hernández-Calvento, 2006). While in the north of the beach the density of equipment such as kiosks, parasols and sunbeds is high, in the southern half, from the backshore to the interior of the system (Figure 4), there is a significant number of *goros* (Sanromualdo-Collado et al., 2021a). According to Figure 4, in 1961 there were no windbreak structures in the study area. In this sense, the observations show that the foredune was formed by isolated nebkhas, producing a continuity as a geomorphological unit because of the union of the shadow dunes that formed downwind of each nebkha, called tongue dunes due to their parabolic shape (Viera-Pérez, 2015). This year 1961 is precisely the moment in which the greatest joint presence of nebkhas and shadow dunes is detected in the Maspalomas foredune from the record of available aerial photographs. This pattern is very common in foredunes of arid regions, especially in those formed by the *T. moquinii* species (García-Romero et al., 2021; Sanromualdo-Collado et al., 2022; Viera-Pérez, 2015). According to Sanromualdo-Collado et al. (2021), as of 1961 the windbreak pebble structures began to appear in the central and southern areas of the beach, and normally replace or are built on nebkhas. Of those more than 200 *goros* built on the foredune of *Playa del Inglés* beach in 1987, more than 40 (20%) were located in the study plot (Figure 4). In spite of Law 12/1987 on Natural Spaces was replaced by Law 12/1994 that declared the dune system and its immediate surroundings as a Special Nature Reserve and Ecological Sensitivity Zone, and from this law, in 1999 a Master Plan for the Natural Park was drawn up, which adopted measures to correct effects on the back beach and the dune by structures, such as the removing of *goros* (see the situation in 1996, Figure 4, top row), and for that reason a decrease is detected from 1999 when the Master Plan of the Natural Park also expressly prohibited their construction and began to remove the existing structures. However, *goros* are still present today due to two reasons: i) sometimes they had been buried by the sand and were not removed by the cleaning campaigns at the time of the action, being appeared months and even years later after the advance of the sand; ii) they are still built by beach-dune users due to the lack of system management-surveillance, even over old *goros* partially covered by sand, accumulating large amounts of pebbles. In this sense, it is observed that the number of these has increased and decreased irregularly in the last 16 years (Figure 4, medium row). Previous studies, such as Díaz Guelmez and Hernández-Calvento, (2004) and Sanromualdo-Collado et al. (2021) observed a correlation between the presence of artificial structures on the beach with the greater loss of specimens of *T. moquinii* and the presence of deflation surfaces. These are clear indications that these environmental changes are related with artificial windbreaks that could also modify wind transport and damage *T. moquinii* specimens, close which *goros* are usually built. All of the above would give rise to a cause-effect process that alters the biogeomorphological processes in the beach-dune system of Maspalomas.

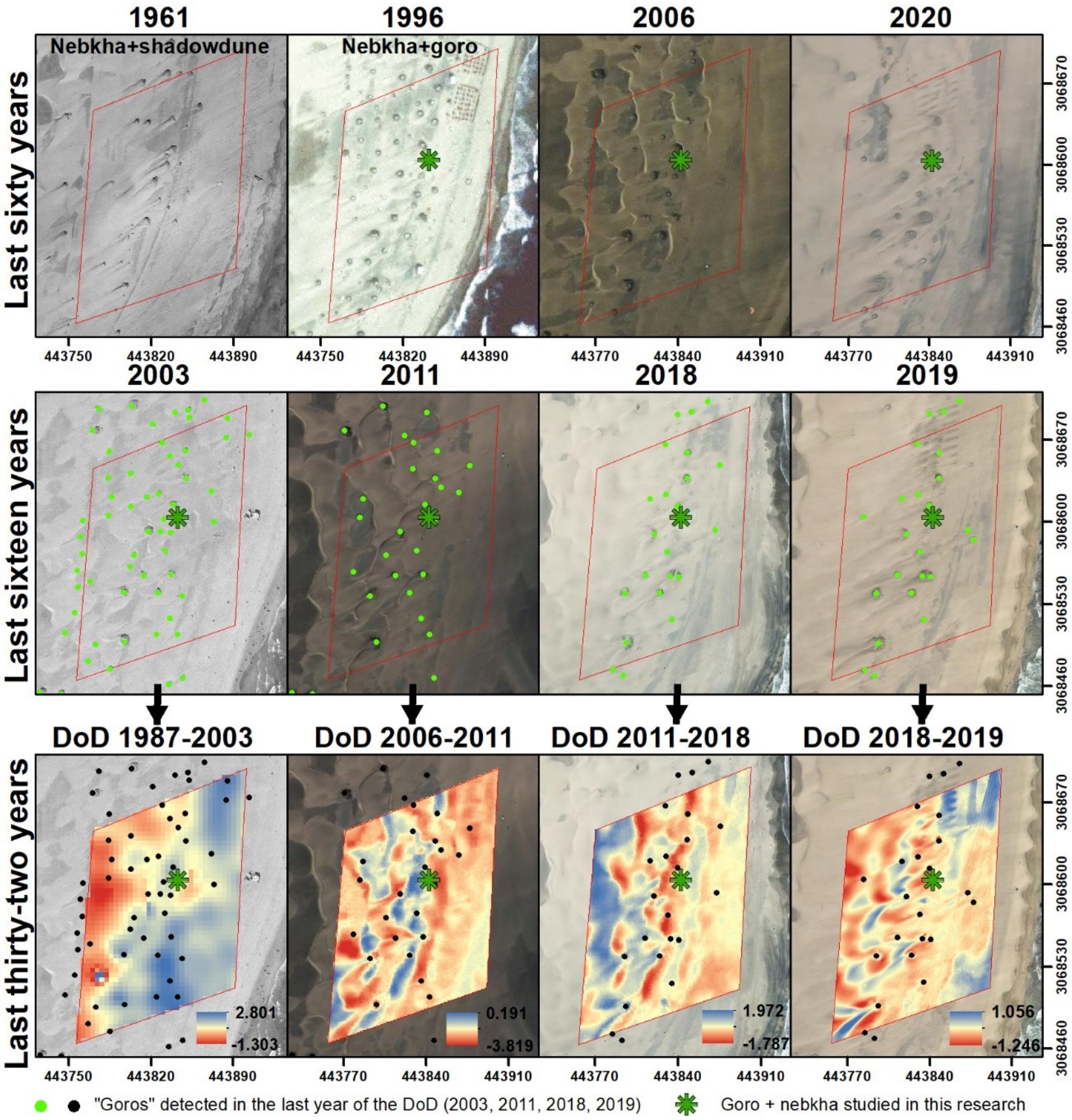


Figure 4: Long term evolution of the study area in Playa del Inglés beach. Top row: Evolution of the study area from 1961 to 2020. Medium row: Evolution of the study area and goros detected from 2003 to 2019. Bottom row: topographic evolution over 32 years (1987-2019) obtained through DoDs. (Orthophotos source: SDI Canarias – Canary Islands Government-Grafcan S.A.)

Among the changes on the topography and, therefore, on the geomorphology from 1987 (Figure 4, bottom), in general, an increase in erosion was detected in the study plot, which is one of the areas with the highest number of *goros*. Furthermore, increasing the scale, it was observed that, around the *goros,* normally built on nebkhas, erosion processes usually took place, especially downwind of the nebkha and its associated shadow dune, which does not develop under normal conditions. All these observations reinforced the idea of the relationship between these artificial structures and their impact, not only on the distribution and presence of *T. moquinii* specimens, but also on the size and morphology of the nebkhas and their associated shadow dunes, and therefore on the development of the foredune. This relationship had been hypothesized in previous studies (García-Romero et al., 2021; Hernández-Calvento, 2006; Hernández-Cordero et al., 2012) and was analysed directly in Sanromualdo-Collado et al. (2021). These studies observed that, in general, the fragmentation of the foredune, the growth in the number and size of the deflation surfaces and the reduction in the number of *T. moquinii* specimens are related to the greater presence of *goros*, especially in the south of *Playa del Inglés* beach.

4.2 Detailed effects of windbreak pebble structures over nebkha (short-term experiment)

4.2.1 *Geomorphological evolution*

The estimated number of stones removed at the end of the experiment reached more than 2,200 kg of with approximately 1,000 kg were removed in the first campaign. The surface covered by pebbles, of 18 m^2 in the first campaign, was reduced throughout the study period and was adopting a more fragmented distribution as the most superficial stones were removed, especially on the south side of the plant (Figure 5).

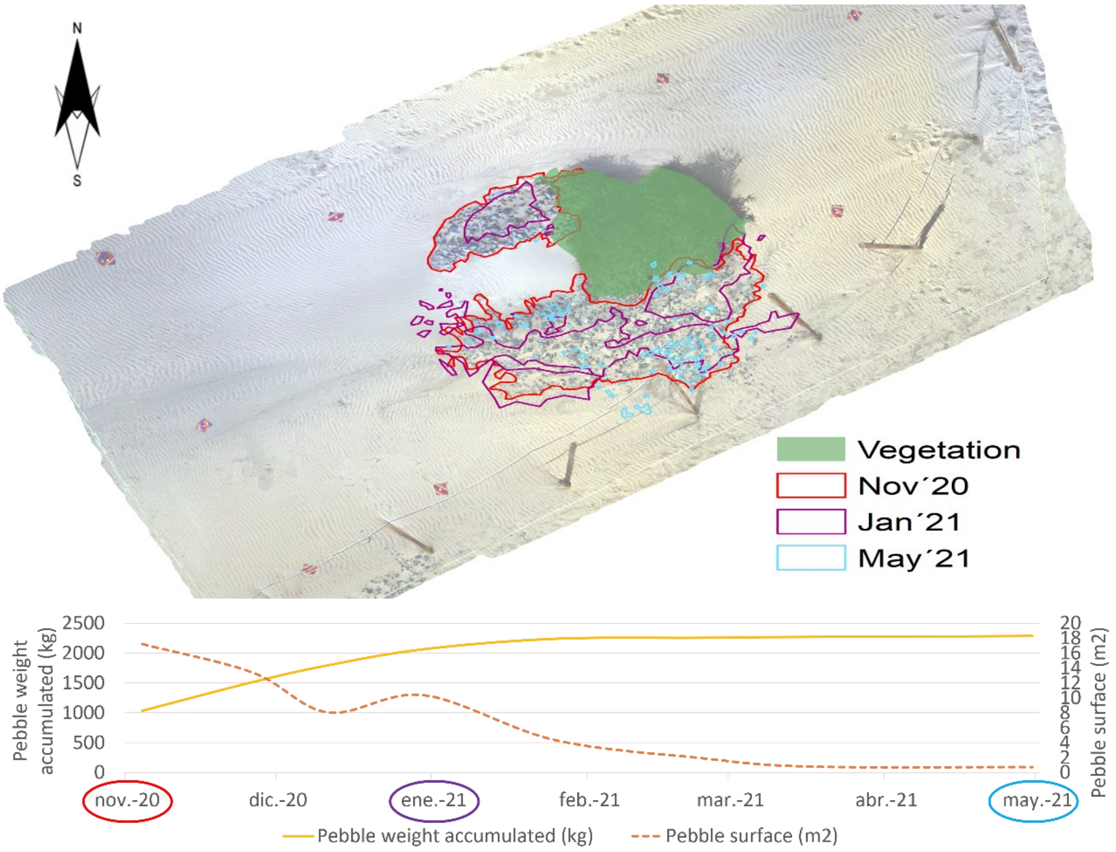


Figure 5: Spatial evolution of surface covered by pebbles in initial, intermediate, and final states of the experiment. The base map is an example of the ortho-mosaics obtained using Structure from Motion (SfM) photogrammetry.

The progressive removal of the pebbles that conformed the *goro* between November 2020 and May 2021 leaded to significant changes in the morphology of the nebkha and its surroundings (Figure 6). The maximum altitude of the nebkha hardly varied between 2018 and 2019, while there were no actions taken over the *goro*. From the start of the field experiment and the pebbles removal, an increase of more than 20 cm in the maximum height of the topography was leaded in six months. This increase in height by sand accumulation was especially noticeable in the central region of the plant, which is a sign of nebkha evolving (Lang et al., 2013; Sanromualdo-Collado et al., 2022).

After the pebble's removal campaigns, an eroded zone was identified at the southern flank of the nebkha (Figure 6, bottom right). This zone corresponded with the area where the higher number of pebbles was removed. The extraction of stones by itself produced a decrease in topography that should be replenished by sand, but also promoted the avalanche of sand in the flanks that was artificially supported by the windbreak structure. The volume gap left by the extracted pebbles is hardly refilled by sand because of the flanks of the nebkha are zones where high wind velocities are promoted (Hesp and Smyth, 2017; Zhao et al., 2019a). Flanks are generally poor vegetated and steep zones of the nebkhas which are constantly eroded to feed the shadow dune downwind (Hesp, 1981; Sanromualdo-Collado et al., 2022). Sand avalanching after stone removal can maintain high slopes in the sides of the nebkha, promoting wind velocities that become sediment fill complicated in these zones. In addition to being the area with the highest concentration of pebbles, the higher erosion in the southern flank of the nebkha than in the northern one can be explained by incident wind directions during the study period, which were slightly oriented to the east and that could increase the shear stress in this zone (Luo et al., 2012; Zhao et al., 2020; Zhao and Gao, 2021). Moreover, the northern flank of the nebkha could be influenced by the proximity of another nebkha, which could interfere in the aeolian sedimentary dynamics and resulting in the formation of a tongue dune (Domínguez-Brito et al., 2020; Viera-Pérez, 2015; Yang et al., 2019)

The topographical monitoring between 2018 and 2019 (Figure 6, top) showed two well differentiated zones: a uniform zone of slightly accumulation (max. +0.168 m) in the windward and around the vegetation; and an erosive zone (max. -0.475 m) behind the plant, in the leeward area where sediment should had been retained to form the shadow dune (Hesp, 1981; Hesp and Smyth, 2017; Yang et al., 2019). The maximum height of the nebkha was behind the plant (at the place of transect C), which could be due to the pebbles were modifying reversing flows at the edges of plant and retaining sediment in an artificial way in this area, preventing sand avalanching which feed the shadow dune.

After the field experiment, in May 2021, the maximum height of the nebkha was displaced windwards to an inner zone of the plant, more sheltered from wind erosion (Dupont et al., 2014). The topographical evolution of the nebkha during the experiment period (Figure 6, bottom) showed a homogeneous sand accumulation around the nebkha (max. 0.227

m), both windward and leeward, and erosion (max. -0.443 m) was only observed in the aforementioned zone where pebbles were removed.

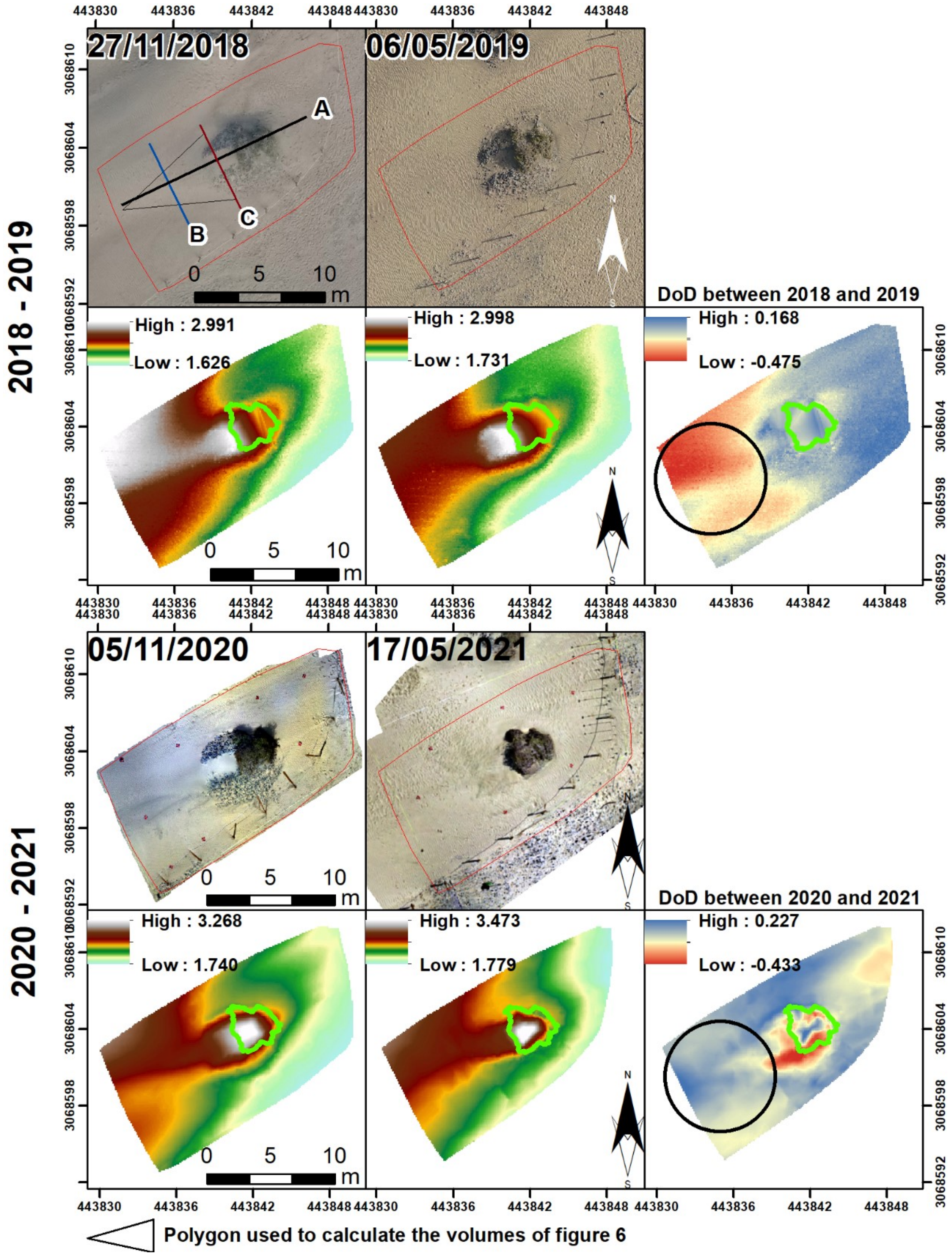


Figure 6: Initial (left column) and final (second column) states of the nebkha during the study periods. Right column shows DoDs between initial and final states, where plant contour is highlighted. Black circle marks the potential zone for shadow dune formation.

The shadow dune should had been formed leeward the plant, with a triangular morphology due to the sand accumulation on the shadow zone behind the vegetation and symmetrically sharped in the flanks because of the reversing vortices generated by the obstacle (Hesp and Smyth, 2017; Zhao et al., 2019a). While locations with high variation in wind direction are likely to form more rounded nebkhas with short tails (Li et al., 2021; Zhang et al., 2020), zones with less variable wind regimes, as the case of Maspalomas, where prevailing winds come from the first quadrant (Máyer Suárez et al., 2012), lead the formation of large tails in the prevailing wind direction, as can be seen in other areas of *Playa del Inglés* beach (García-Romero et al., 2021) or in the study area in 1961 (Figure 4, top row). Once the stone removal action took place, an increase of sediment accumulation in the potential zone for shadow dune formation was observed, changing the sedimentary dynamics of this zone from erosive to cumulative.

The topographical evolution of the longitudinal profile (Figure 7, A) showed sand accumulation in the parts of the nebkha covered by the plant and behind as the *goro* was being removed. This could evidence that the pebble structure was interfering in the wind-sediment-plant interactions, limiting the capacity of the plant to intercept sediment and retain it protected from wind action. This widely studied interaction between plants and sediment deposition (Davidson-Arnott et al., 2012; Dupont et al., 2014; Leenders et al., 2007; Sanromualdo-Collado et al., 2022) was pronounced after the pebble removal. Furthermore, the stones located over the plant entailed an extra weight that prevented the plant to grow and develop in a natural way. Thus, the remotion of these stones leaded the plant to achieve a bearing that increases the interception of sediment transported by saltation and also in suspension (Li and Ravi, 2018; Yang et al., 2018).

Regarding the transversal profiles, it was the closer to the plant the one which presented major variations during the experiment (Figure 7, C). The initial profile presented a nearly symmetrical shape with steep flanks and a plain behind the plant. This plain was due to that this zone sheltered by the plant and the windbreak is where beach users usually lie down. The steep flanks were artificially held by the pebble structure, modifying the angle of repose of the sand and avoiding avalanches (Mehta and Barker, 1994; Parteli et al., 2014), thus, the sand in this zone was confined inside the windbreak pebble structure, forcing an artificially steady-state landform. After the removal of the stones that support the slope, the sand surface slope in the flanks relaxed through avalanches, and sediment was at wind's dynamics disposal to be redistributed (Durán et al., 2010; Hesp, 1981). The combined action of sand avalanches and sedimentary dynamics over a bare sand zone were responsible of the changes in the flanks to be less steep and more rounded, as well as of the progressive reduction of sand on this profile. Part of the sediment eroded from this zone by those dynamics was relocated inside de plant due to reversal flow at the edges of the shrub or transported to the shadow dune (Figure 7, B) where it could be seen an accumulation at the end of the study period.

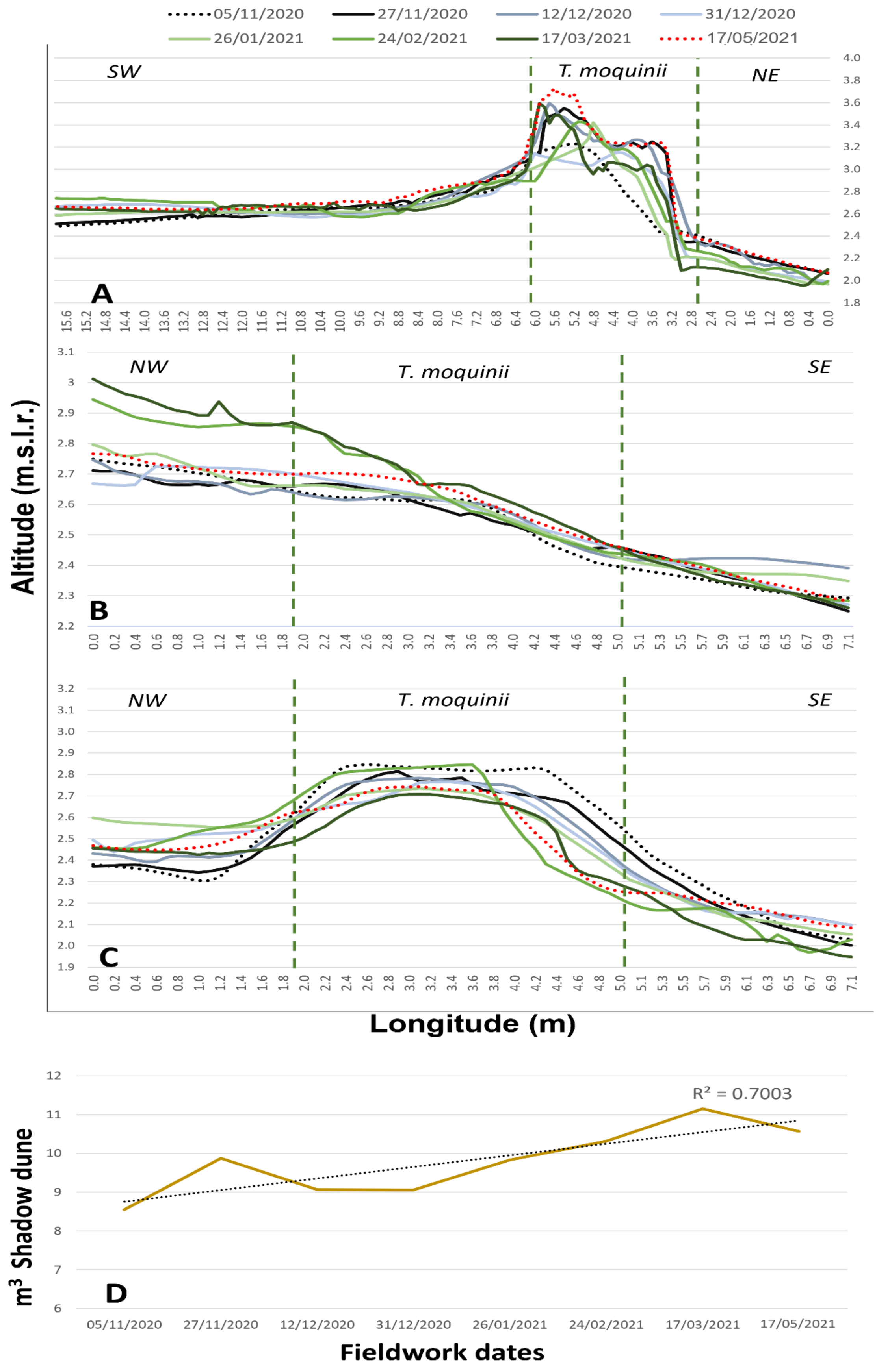


Figure 7: Landform profiles evolution. A) Longitudinal profile. B and C) Transversal profiles. D) Volume evolution in the shadow dune. Note that dotted lines represent the initial (blue) and final (red) profiles.

In terms of volume of sand accumulated in the potential zone for shadow dune formation (Figure 7, D), an ascent trend was observed during the field experiment. There was a noticeable rise after the first campaign, when the large amount of removed pebbles released a considerable volume of sand which could be transported to the shadow dune by the wind. Then a progressive sand accumulation in this zone was observed from January 2021, when the effective winds from the NE begun to be more constant.

4.2.2 *Wind dynamics*

Nebkhas act as obstacles that interfere with wind dynamics. Flow patterns surrounding these obstacles have been widely studied and different flow regions have been identified (Burkow and Griebel, 2016; Hesp and Smyth, 2017; McKenna Neuman and Bédard, 2015; Walker et al., 2021; Zhao et al., 2021). Results of the pebble removal experiment showed that stone-stacking over the foredune, and specifically over nebkha, modified the flow patterns that lead the shadow dune formation (Figure 8).

As the timeslot selected to evaluate the effects of the pebbles was those with less input wind flow variations, both in speed and direction (Figure 8, B), airflow pattern in front of the nebkha hardly varied during the experiment. The effect of the *goro* in airflow patterns was patent comparing the streamlines in different regions of the nebkha before and after pebble removal (Figure 8).

In the north side of the plant (1) it was identified a flow acceleration zone when pebbles are still present. This could be in line with the described flow region where flow is separated and accelerated by the effect of the obstacle possibly leading a horseshoe vortex (Hesp and Smyth, 2017; McKenna Neuman and Bédard, 2015; Sutton and McKenna Neuman, 2008). However, the presence of this vortex in wind direction was hardly appreciated before pebble removal and streamlines in this zone seemed to blow the wind outside the north limit of the study area. Thus, it was after the pebble removal when the maximum wind speed moved to the edge of the plant (Leenders et al., 2007; Mayaud et al., 2016) and the changes in the wind direction by the described reversal flow were more appreciated, leading sediment transport to the wake zone (3). A similar pattern was observed in the south side of the nebkha (2), where airflow was accelerated at the edge of the plant once the pebbles had been removed, transferring momentum from this area to the edge of the wake zone (3) and transporting sand for the shadow dune formation (Hesp, 1981; Hesp and Smyth, 2017; Zhao et al., 2019a; Zhao and Gao, 2021). The wake zone in the lee of the plant (3) at the beginning of the field experiment was completely sheltered from the wind by the effect of the *goro*, contributing to the stagnation of the sand retained in this zone. Moreover, it has been described that those obstacles higher than the sand saltation height, as could be the case of windbreak pebble structures, lead a massive stagnation of particles and reduce the amount of sand particles transported into the wake which contribute to the formation of shadow dunes (Zhao et al., 2019a; Zhao and Gao, 2021). Once the pebbles were removed a slightly increase in wind speed in the weak zone (3) was observed. The pebble removal also leaded an increase in wind speed in the potential zone for shadow dune formation (4), due to the airflow recovery downwind nebkha. The airflow recovery in these zones contributes to sediment transport leeward through the ridge of the shadow dune and its subsequent elongation (Zhao and Gao, 2021).

As elements that modify the porosity of the obstacle, pebbles alter the bleed flow and the sand transport processes at the leeside, influencing the morphology of the shadow dune (Dong et al., 2008; Gillies et al., 2014; Mayaud et al., 2016; Mayaud and Webb, 2017; Zhao et al., 2019a). The porosity of nebkhas vegetation permits sand flow go through the shrub, which also affects the airflow recovery at the lee (Cheng et al., 2018; Latif Bhutto et al., 2022). However, the presence of the windbreak pebble structures transforms nebkhas in nonporous obstacles, limiting this bleed flow and forcing the horizontal and vertical separation flow around them. This effect not only prevents the sand accumulation at the leeside for the formation of shadow dunes, in a similar way that occurs with non-vegetated man-made nebkhas showed in Zhao and Gao (2021), but also can result in sand erosion around the obstacle, as occurs with other solid roughness elements like tree trunks, woody debris or buildings (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).

These isolated effects observed in a single *goro* built over a nebkha are enhanced and affects overall the foredune as the activity is replicated by users, and the windbreaks are scattered all over the beach-dune system. However, more detailed research about the wind dynamics in areas plenty of windbreak pebble structures are necessary to better understanding the combined effects of these obstacles over the foredune. Similarly, detailed studies on the different types of *goros* that appear in these systems and their associated impacts are recommended, as well as the deployment of 3D wind data meshes around these obstacles, or the use of wind tunnels and Computational Fluid Dynamics (CFD) to discriminate in detail their effects on airflow dynamics. In this sense, the required efforts to the parameterization and modelling of wind flow of surface roughness and around shrub vegetation (Fu, 2019; Smyth, 2016) could help to better evaluate the effects of windbreak pebble structures over vegetated dunes.

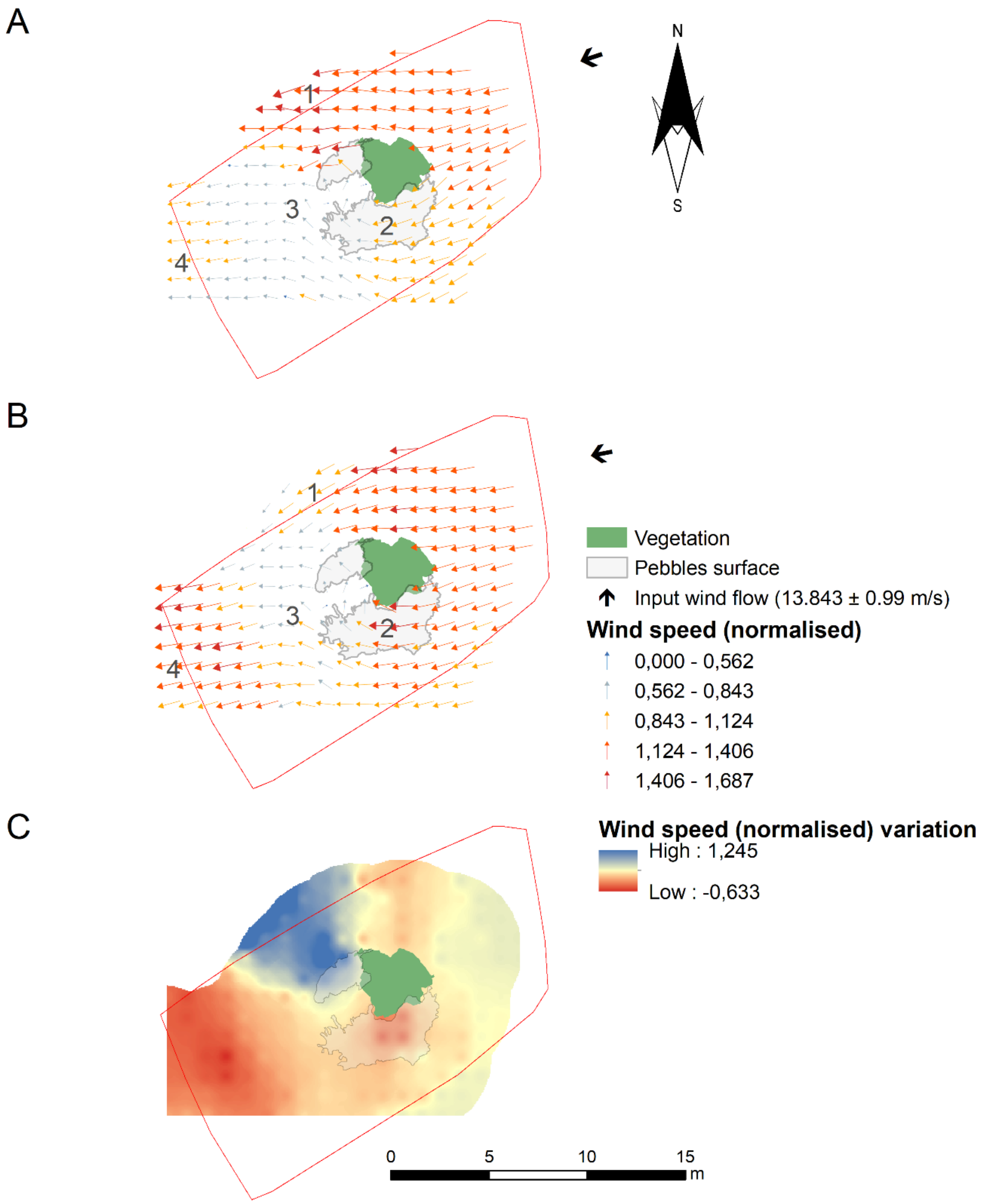


Figure 8: Streamline distribution around the nebkha before pebble removal (A) and after pebble removal (B). Differences in wind speed after pebble removal (C). Input wind flow speed = 13.843 ± 0.99 m/s; Input wind flow direction = 78.984 ± 5.324º)

5. GENERAL DISCUSSION

The changes observed in the geomorphological characteristics and sedimentary dynamics of the studied combination of nebkha and *goro* as a result of the pebbles removal action revealed that the presence of these windbreaks has harmful consequences over the functioning of the nebkhas and therefore over the foredune. Ultimately, because of the stone-stacking over an arid beach-dune system a domino effect is produced leaded by the no-formation of the shadow dunes which, in turn, avoids the formation of tongue dunes, formed by the union of those shadow dunes. The absence of shadow dunes and tongue dunes increases the fragmentation of the foredune and makes it more fragile (Viera-Pérez, 2015).

The widely studied patterns that regulate the formation of shadow dunes by the presence of nebkhas in natural conditions were not identified until the pebble removal experiment was performed. Thus, at the end of the field experiment, in May 2021, the typical morphology corresponding to a nebkha and its associated shadow dune was recognizable in the study area. However, the performance of the experiment in an arid and, thus, highly dynamic beach-dune system as Maspalomas (Jackson et al., 2013) had predicted a faster response to natural conditions as the disturbance was removed. In this sense, there are two main reasons that could explain this response delay. Firstly, the continuous reconstruction of windbreaks as they are buried or destroyed results in large accumulations of pebbles, so after the removal campaigns there were not long time until a new underlying sheet of pebbles were uncovered, returning the nebkha in some extent to the unnatural state. On the other hand, the weather conditions during the field experiment period were not the optimum. Wind directions between October 2020 and May 2021 slightly turned to the East and, moreover, effective wind events from NE with speeds over the threshold of sand mobility were scarce until January 2021 (Figure 9).

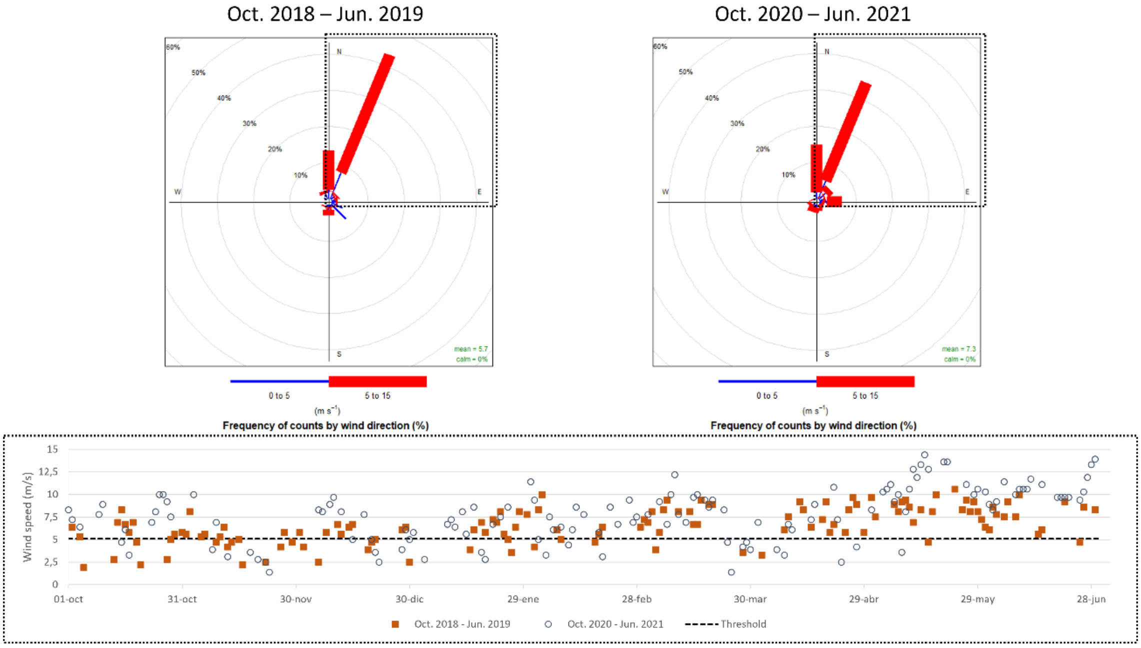


Figure 9: Wind variability in Gran Canaria Airport (LPA). The graphics at the bottom shows only wind events from the first quadrant.

In spite of the inconvenience, it was validated that the removal of the pebble structure leaded a reversal process to the natural conditions of the landform, although it is present that more favorable weather conditions during the experiment, in terms of wind speeds and directions, would have led a clearer and faster response. However, due to the recovery action of the massive pebble removal, even once the study period was over and the periodic removal campaigns have ended, the nebkha and the shadow dune evolved to a more natural-like morphology. This was obvious almost one year after the beginning of the field campaigns, during the elaboration process of this manuscript, when a well-defined shadow dune could be identified at first sight on the study area (Figure 10). The morphology of this landform resembled the one of non-impacted nebkhas and shadow dunes described in other arid beach-dune systems of the Canary Islands (see Fig. 2 in Sanromualdo-Collado et al. (2022)). That confirms that once the main stressor has convenient ceased, and under favorable weather conditions acting for a certain period, the harmful effects of the windbreak pebbles structures over arid foredunes could be reverted.

Figure 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).

Recommendations to remove stacking stones (*goros*)

From the action carried out in this investigation (removing of the *goro* or stacking stones), recommendations are suggested due to concerns related to the health status of the vegetation, that is, the analysed individual of *T. moquinii*, and that were detected in the field work. In this sense, the removing of pebbles must be carried out for a long time and in different campaigns and not in a single campaign. The reason is because the initial *goro* (the one observed on the surface on Nov. 2020) was simply the last visible stratum of the total structure, which has been built over decades (explained in long-term section). This accumulation of stones around the *T. moquinii* specimen has altered its growth and morphology. The buried stratums of the windbreak act as a flowerpot that have limited the natural growth of adventitious roots, which are essential for the plant growth and nebkha development in arid environments (Luo and Zhao, 2019). On the other hand, pebbles hold the branches in a cylindrical height growth and prevent, with their weight and limited available space, the normal growth of branches (bonsai effect). The result of removing the windbreaks in a single campaign would lead to the collapse or breakdown of the *T. moquinii* specimen in a short period of time due to its own weight and gravity, breaking branches and even its roots at the same time. However, prolonged removal over time would lead to the stones being gradually replaced by sand naturally (through aeolian transport) so that *T. moquinii* finds a settlement on the sand, and at the same time finds itself progressively buried, which produces the reactivation and rejuvenation of this plant species (Viera-Pérez, 2015). As a complementary impact associated to this activity, the removal and displacement of pebbles from the paleo-barriers for windbreaks construction affects the geological record of the *Playa del Ingles* beach, complicating the interpretation of the sedimentary dynamics that formed those paleo-barriers. Trying to mitigate this impact, during the windbreak's removal campaigns, it is recommended to identify the source of the pebbles that form the *goros* in order to return them to their original paleo-barrier in the most natural way.

6. CONCLUSIONS

The construction of windbreaks by stacking stones over the foredune is a common practice on beach-dunes systems. This practice is even more popular in areas subject to intense tourism activity. In the Canary Islands, where coastlines are subject to an intense touristic pressure, the presence and complexity of stone windbreakers (locally called *goros*) exponentially increased from a limited amount in the 1960s to large numbers in the 1980s and to date. Although the negative effects that stone-made windbreakers have on beach-dune systems has been reported, there is a lack of legal frameworks to manage their presence, partially due to a gap in scientific knowledge about their specific biogeomorphological impacts.

Our results show that *goros* prevent the natural functioning of nebkhas. The stones made the flanks slopes steeper and preventing sand avalanches, limiting sediment transport to the nebkha lee-side, 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. The *goro* acted as a ‘flowerpot’, limiting the capacity of *T. moquinii* to develop roots and branches, that are key for plant growth and sand burial, and modified the porosity of the nebkha, affecting wind and transport dynamics around it. Speedup of airflow along the steep flanks and the inability of the plant to trap sand that in turn will favour plant growth, complicated sand transport patterns, limited the formation of a shadow dune, and even led to the development of erosional zones in the foredune. These effects could be enhanced when the number of *goros* in the foredune increases.

Our experience in dismantling a *goro* suggests that a) it is possible to restore nebkha foredunes negatively affected by the presence of stone-made windbreakers; b) restoration should be made gradually, allowing the vegetation to adapt to a return to more natural growing conditions; c) restoration is straightforward and inexpensive, and when combined with appropriate identification of pebble original source areas, it can also lead to additional benefits such as the partial restoration of paleo-barriers. Results presented in this study provides a biogeomorphological understanding of the effects that *goros* have on arid coastal dunes, and hence helps future management in *Playa del Inglés* and other areas. The removal of stone-made windbreakers in combination with improved management of arid foredunes involving controls on visitors pressure will favour conditions for passive restoration of nebkha and the formation of shadow dunes associated to them.

Acknowledgements

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FOREDUNE RESPONSES TO THE IMPACT OF AGGREGATE EXTRACTION IN AN ARID AEOLIAN SEDIMENTARY SYSTEM

Abel Sanromualdo-Collado, Néstor Marrero-Rodríguez, Leví García-Romero,
Irene Delgado-Fernández, Manuel Viera-Pérez, Antonio C. Domínguez-Brito,
Jorge Cabrera-Gámez

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ABSTRACT

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

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

1. INTRODUCTION

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

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

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

As sand is indispensable for construction and urbanization, the demand for aggregate extraction has grown exponentially in many aeolian sedimentary systems in developing regions (Dan Gavriletea, 2017), as was the case of the Canary Island in the last decades of the 20th century, before the prohibition of extracting sand from the dune systems (Marrero-Rodríguez et al., 2021b, 2021a; Santana-Cordero et al., 2016a). Knowing the effects of aggregate extractions and the response capacity of impacted environments is key to minimize and mitigate the environmental impacts of this activity, even more so when the extractions are carried out in fragile ecosystems like arid coastal aeolian sedimentary systems (Cabrera-Vega et al., 2013b; Peña-Alonso et al., 2018b). The evolution and response environments after disturbances are not only restricted to recovery of the original functions, but to the adaptation to the element to the new situation (Kombiadou et al., 2019). Thus, the main aim of this work is to analyse the response process of the arid aeolian sedimentary system of El Médano after the cessation of this activity, especially in an area affected by the historical extraction of aggregate located on the foredune. For this purpose, two temporal approaches are employed: i) a long-term analysis to identify topographical changes from historical and current sources, including oral interviews with technicians; ii) a short-term experiment to characterize the present functioning of the system through the analysis of the airflow dynamics and the spatial distribution of vegetation and sediment. The ultimate objective of this research is to help to understand the environmental consequences of aggregate extractions on the foredunes of arid aeolian sedimentary systems and to contribute to the decision-making process to make better-informed management decisions.

2. STUDY AREA

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

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

The sediments are a mixture of biogenic and terrigenous sands that are produced by the erosion of palaeodunes, along with marine contributions as well as contributions from local ravines during episodes of intense rainfall. These sediments enter from the Leocadio Machado beach and are blown into the system by the prevailing ENE winds, generating nebkhas and shadow dunes (Marrero-Rodríguez et al., 2020a).

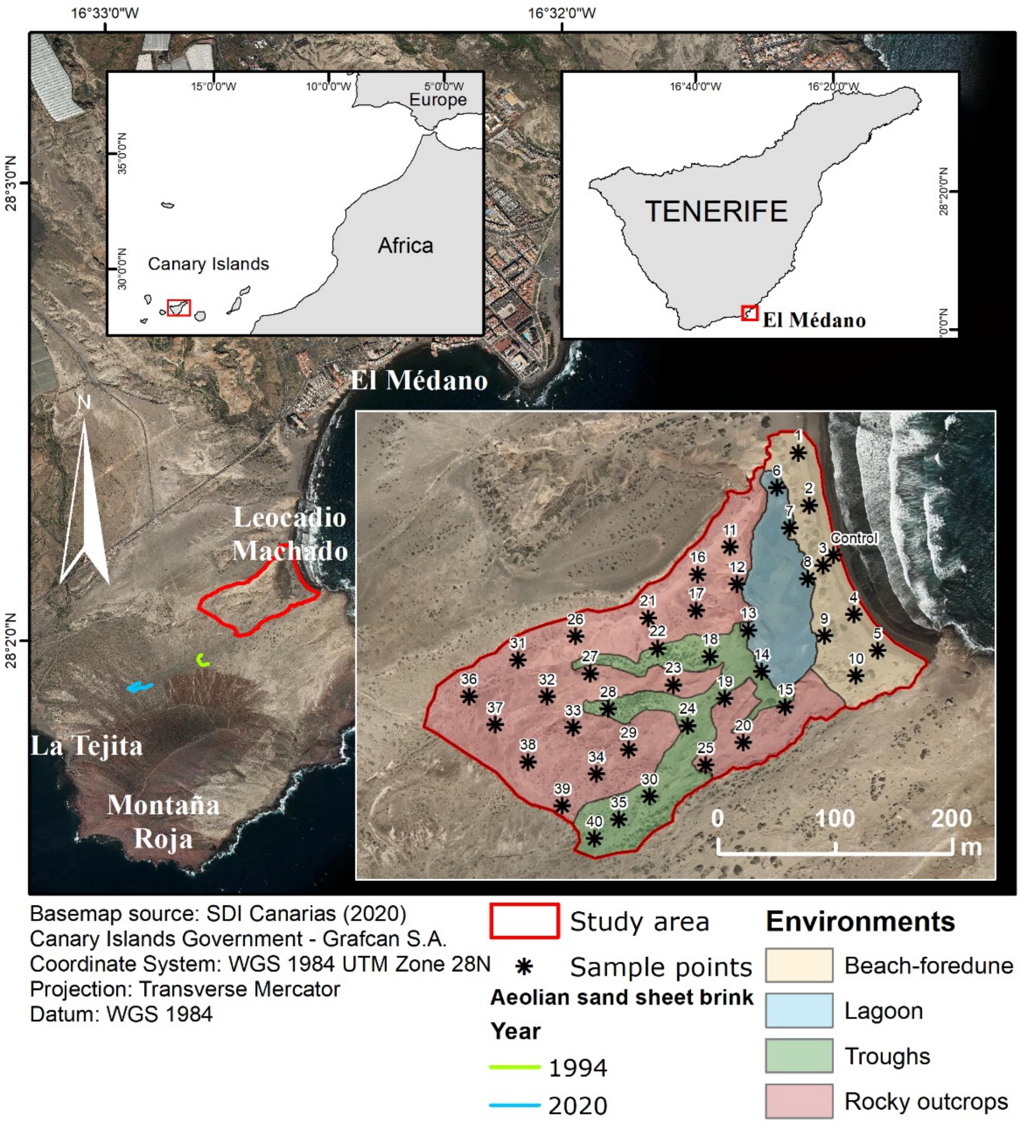

Figure 1. Location of the study area, environment identification and position of the field experiment sampling points.

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

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

3. METHODS

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

3.1. Long-term approach

3.1.1. Aggregate extraction zone and foredune evolution

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

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

Table 1. Inventory of cartographic sources used in this research.

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

* RMS = Root mean square. ^ flight with ground sample distance (GSD) of 22.5 cm/píxel. [1]SDI Canarias (Canary Islands Government-Grafcan S.A.) [2]National Geographical Institute (Spain).

3.1.2. *Interviews with technicians*

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

3.2. Short-term approach

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

3.2.1. Sediment and vegetation data

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

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

Table 2. Characteristics of plant species present in the study area (modified from Marrero-Rodríguez et al., 2020a and based on García-Casanova et al., 1996, Hernández-Cordero et al., 2015a, Hernández-Cordero et al., 2017 and Hernández-Cordero et al., 2019).

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

3.2.2. Wind data

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

4. RESULTS AND DISCUSSION

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

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

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

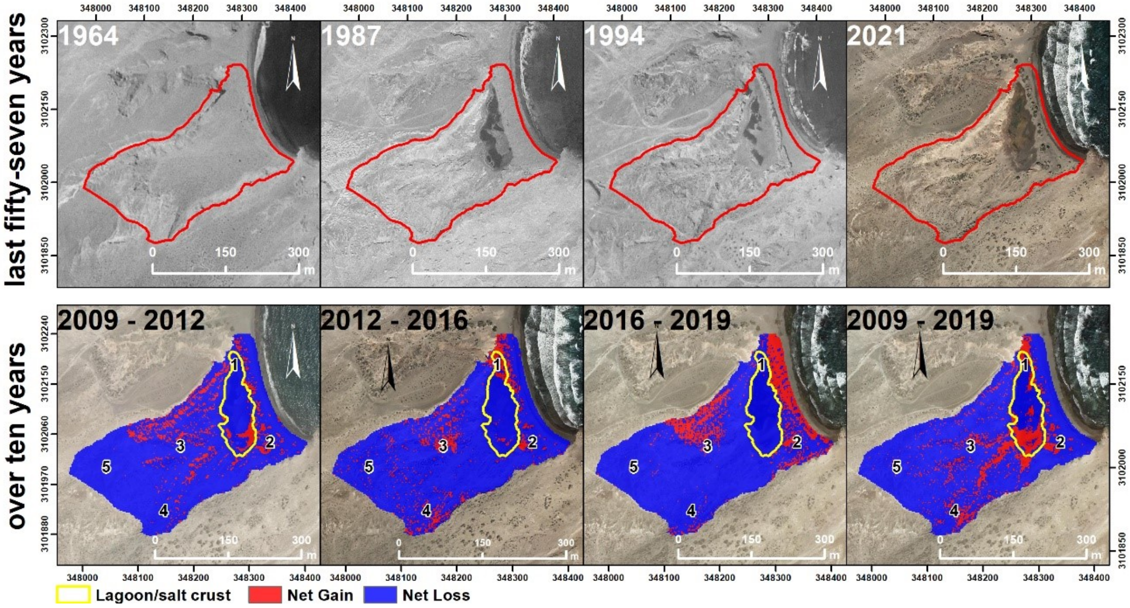

Figure 2. Top: Evolution of the study area (aggregate extraction) from 1964 (before extraction begins) to 2021 (orthophotos source: SDI Canarias (Canary Islands Government-Grafcan S.A.). Bottom: Topographic evolution over 10 years (2009-2019) obtained through DoDs and showing Cut Fill results.

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

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

4.2.1. Vegetation and sediment spatial distribution

The beach-foredune (Figure 3, A), with a surface area of 10,680.85 m^2, has sediments characterized by poorly sorted medium sands (Figure 4, B and C) and the vegetation cover is determined by the presence of *T. moquinii* in the foredune. *T. moquinii* responds to sand burial by accelerating its growth

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

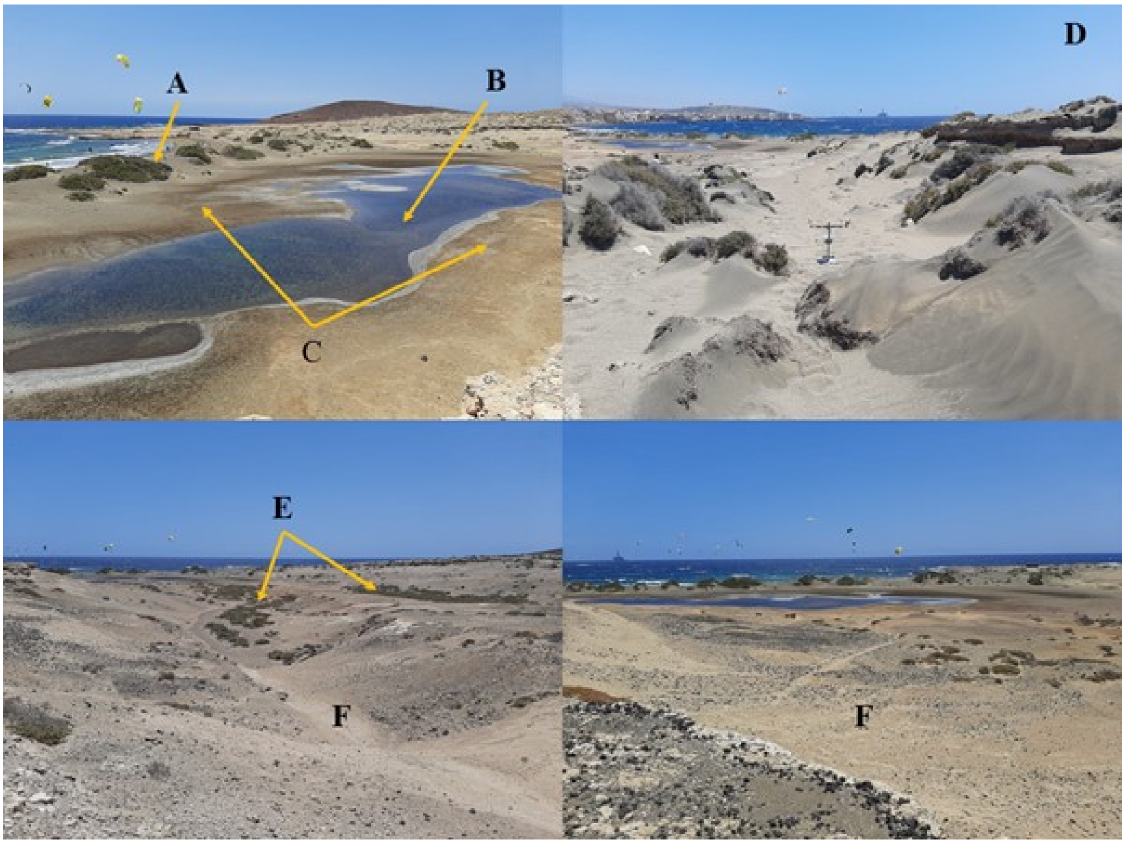

Figure 3. Environments present inside the area affected by the extraction of aggregates. A: Beach-foredune; B: permanently flooded lagoon sector; C: sector flooded in high tides that presents an important saline crust; D: Troughs with accumulation of sand, sparse vegetation and active aeolian landforms (ripples, nebkhas and shadow dunes); E: Troughs without active aeolian landforms and high density of vegetation; F: Aeolian deflation zones without vegetation or sand accumulation.

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

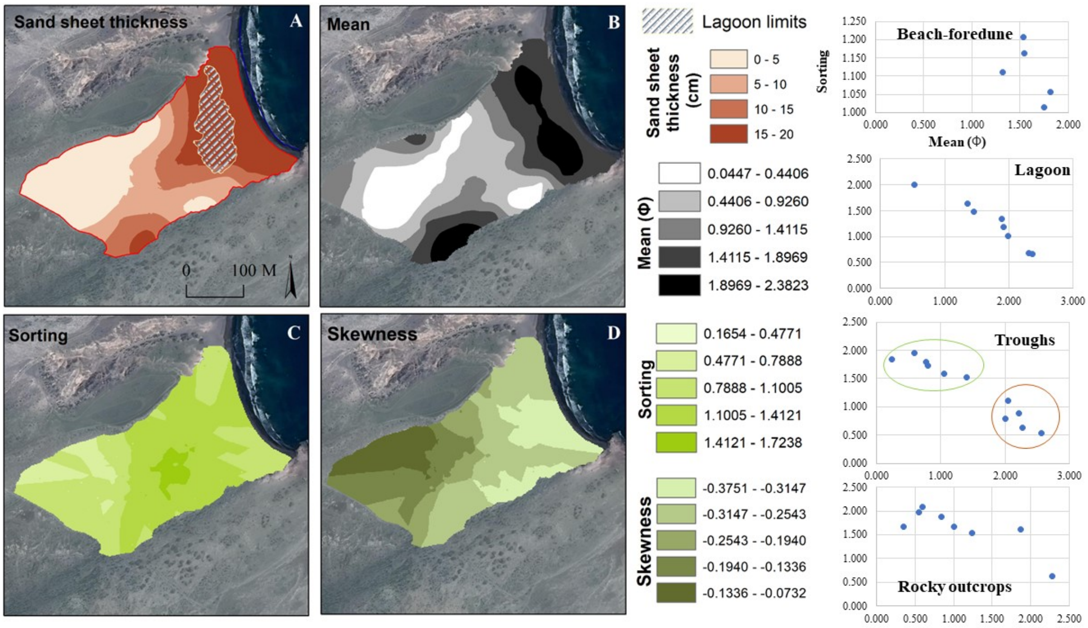

Figure 4. Sand sheet thickness, mean grain size, sorting and skewness in the aggregate extraction area. Sorting and mean grain size values represented in graphs on the right by environment present in the area. Green circle: troughs with vegetation cover between 50% and 70%. Brown circle: troughs with vegetation cover under 50%.

The troughs present in the rest of the study area show a more limited sedimentary activity (Figure 3, E). The thickness of the sediment varies between 10 cm and 20 cm (Figure 4, A) and they are mostly coarse and poorly sorted sands (Figure 4, green circle). The sediments of the central troughs are finer than those of the troughs located in the southern sector of the study area, as coarse sands are likely to fall into the lagoon when they are transported by the wind. These troughs can also experience sediment transport during runoff, as the samples present pyroclastic fragments from Montaña Roja. The vegetation cover (Figure 5) is very high (between 50% and 70%) and the species present are S. sericea, L. sessilifolius, K. neriifolia, A. glauca, L. pectinatum and A. frutescens. These plants do not tolerate burial by large volumes of sand and some of them, including K. neriifolia and A. frutescens, do not tolerate substrate mobility. Therefore, active aeolian landforms are almost absent, although sporadic nebkhas associated to S. sericea and L. sessilifolius can be found.

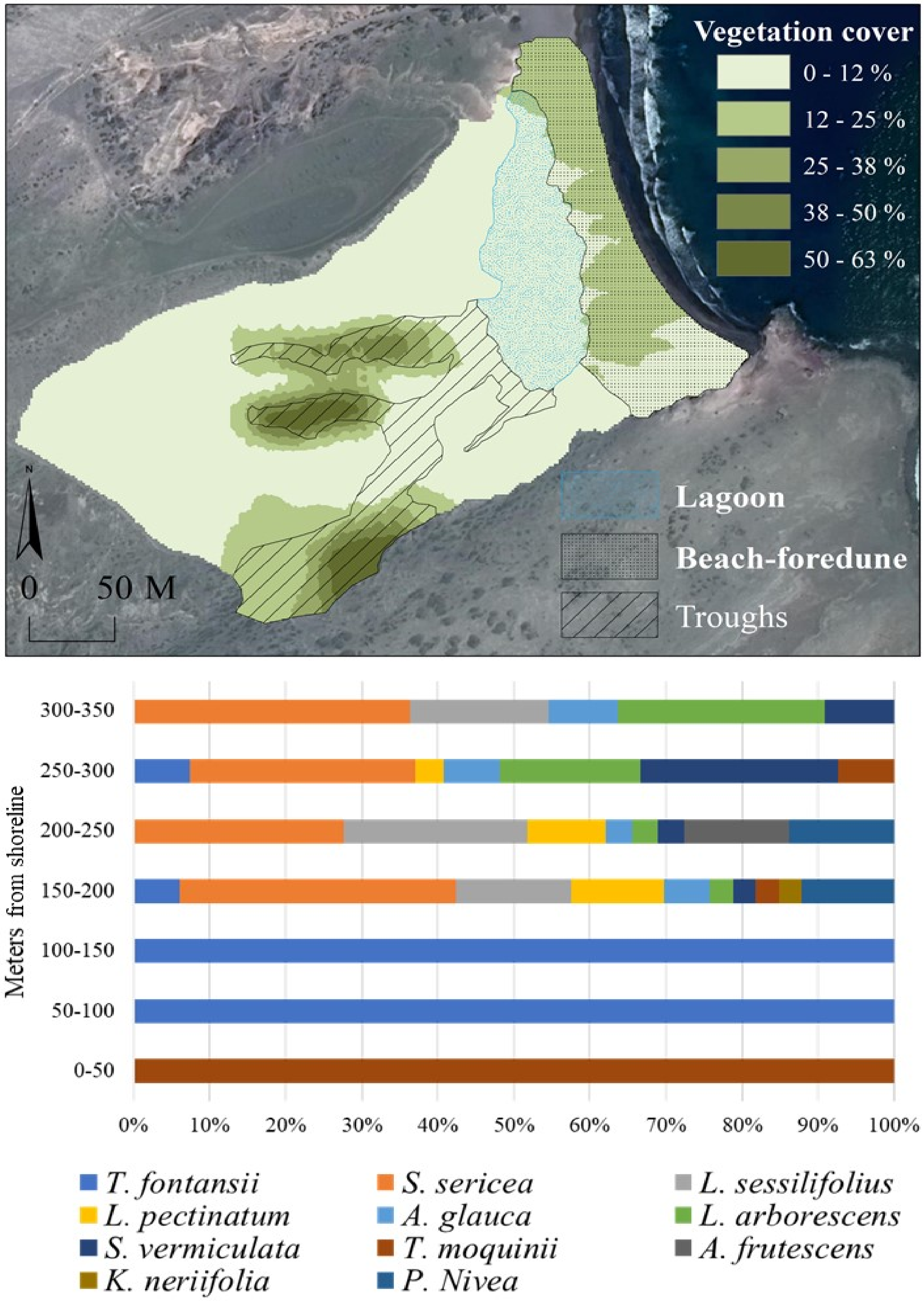

Figure 5. Vegetation cover and species distribution from the shoreline.

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

4.2.2. Airflow dynamics

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

In Run 1, there was a noticeable difference in wind speed between the sample points located in the backshore (SP1 to SP5), where wind speeds generally reached 70% of the input wind speed, and between the sample points located in the second row, behind the foredune, where wind speeds varied from between 30% and 60% of the wind speed at the control point. With respect to SP10, although it is located in the second row, wind speeds were similar to those in the first row, reaching speeds that exceeded 80% of the input wind speed. In this southern zone of the beach-foredune environment, the foredune more closely resembles the mounded morphology typical of arid coastal dune systems (Hernández-Cordero et al., 2019; Hesp et al., 2021a; Viera-Pérez, 2015), instead of the nearly continuous sand ridge of the foredune in the north. While the foredune in the northern area blocks the wind and reduces its speed when entering the system, the naturally fragmented foredune in the southern area allows the wind to enter between the vegetated mounds, transporting sediment to the rear areas of the foredune and forming nebkhas and shadow dunes that enable the foredune to develop in height and width (García-Romero et al., 2021; Hernández-Calvento, 2006; Hernández-Cordero et al., 2012; Viera-Pérez, 2015).

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

Wind speeds at the sample points recorded in Run 3 varied between 25% and 90% of the input wind speed. Three sample points presented wind speeds under 50% of the input speed. As was the case in SP18 and SP19, wind speeds at SP22 and SP28 were reduced by the presence of vegetation at the bottom of the troughs. Additionally, the reduction of wind speeds at SP26, located as in the case of SP16 in an elevated rock outcrop close to the northern limit of the extraction, could be caused again by the topography of the scarp, but in this case due to a rocky ledge that blocks the wind. The highest wind speeds for this run were recorded at SP24, due to its location at the bottom of a denuded trough where the wind is channelled in the absence of vegetation to slow down the airflow.

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

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

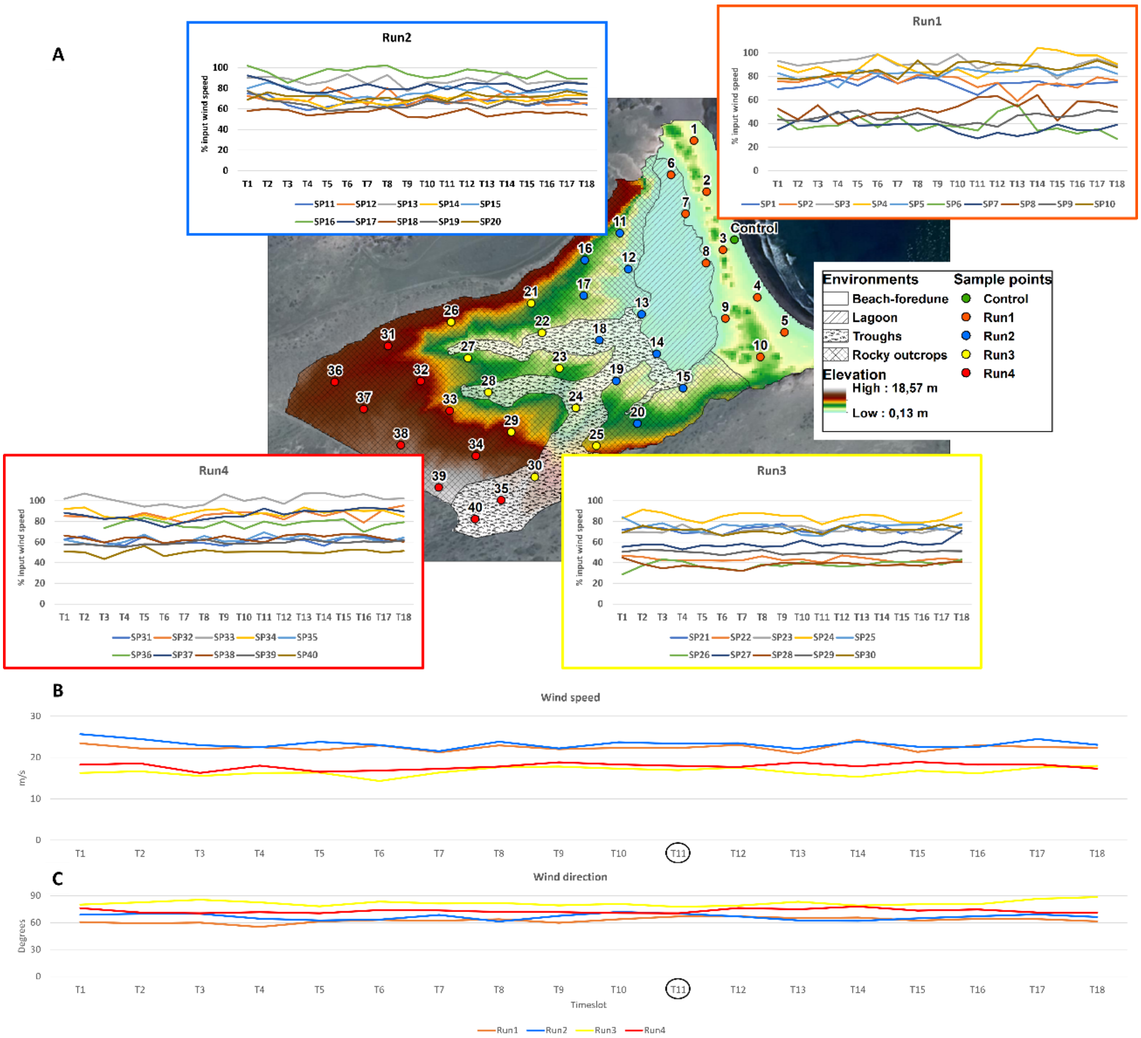

Figure 6. A) Location of sample points and temporal series of normalized wind speeds averaged every 30 seconds for each simultaneous run. B) Wind speeds averaged every 30 seconds at the control tower. C) Wind directions averaged every 30 seconds at the control tower. Timeslot T11 is highlighted because it is the input wind flow in Fig. 7.

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

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

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

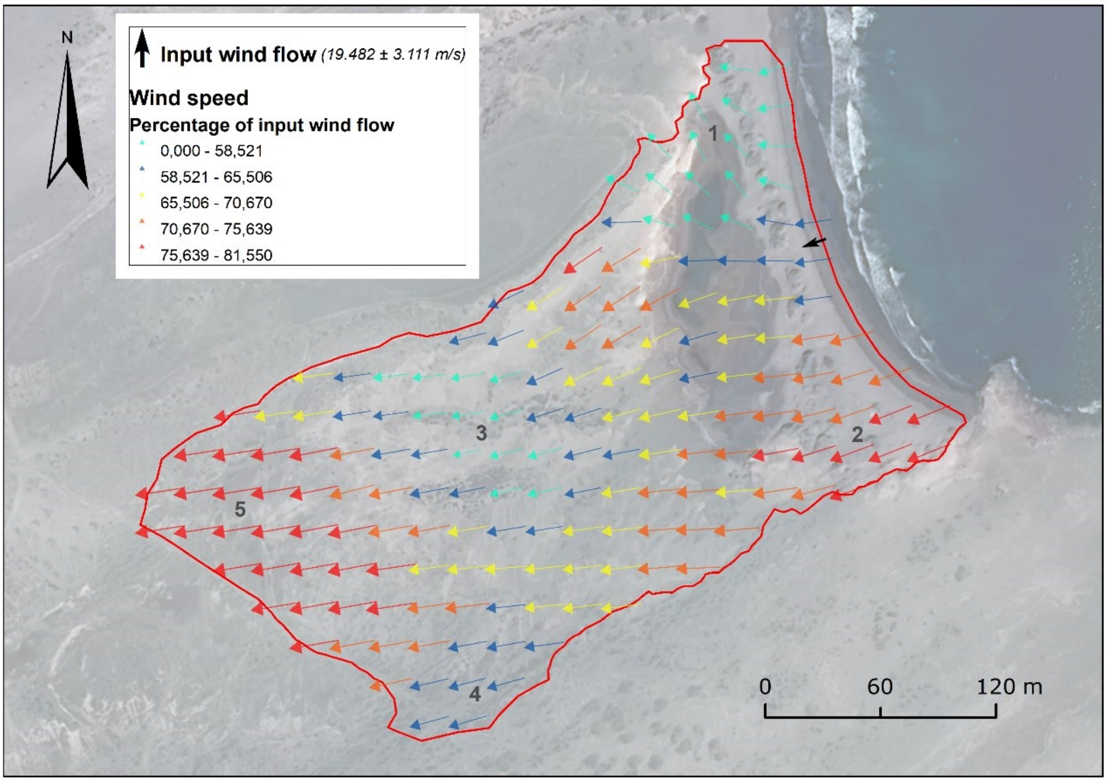

Figure 7. Airflow pattern at timeslot T11 (input wind speed = 19.482±3.111 m/s; input wind direction = 71.369 ± 3.918º).

4.3. Aeolian sedimentary transport patterns

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

In the first block (Figure 8, top), the results show two different patterns between wind and sorting/mean grain size. In the first case, the beach–foredune and troughs are environments where, according to the results, aeolian sedimentary transport is related to wind speed, as established by Bagnold (1941) and Fryberger et al. (1992). It was found that grain size tended to increase with the normalized wind speed at the sample points (positive trend), and that sediment selection improved as wind speed decreased (negative trend) or hardly varied, as the case of the beach-foredune environment. This could be attributable to the greater transport effect of stronger winds at the sample points, resulting in fine sediments having a saltation trajectory regardless of their vertical distribution (Farrell et al., 2012), while leaving larger grains at the sample points (Namikas, 2003). This could also explain why sediment with better sorting is found in areas with lower wind speed (opposite case) (Jerolmack et al., 2011). In this regard, in these two environments the results are related to sediment transport patterns described under natural conditions (Lancaster et al., 2002). In the second case, involving environments which are a direct consequence of anthropization as the result of aggregate extraction, namely the lagoon and the rocky outcrops, the patterns are totally changed, showing inverted trends in both sorting and mean grain size. It is thus understood that in these environments the aeolian sedimentary dynamics have been altered. Aeolian transport into the extraction area, as it moves away from the coastline, encounters two obstacles produced by aggregate extraction (i.e. the lagoon and the rocky outcrops) which do not allow natural aeolian sedimentary dynamics, even when the winds blow at an angle or oblique to the coastline, as Nordstrom et al. (2007) detected in a nourished fine sand beach without obstacles at Ocean City (New Jersey).

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

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

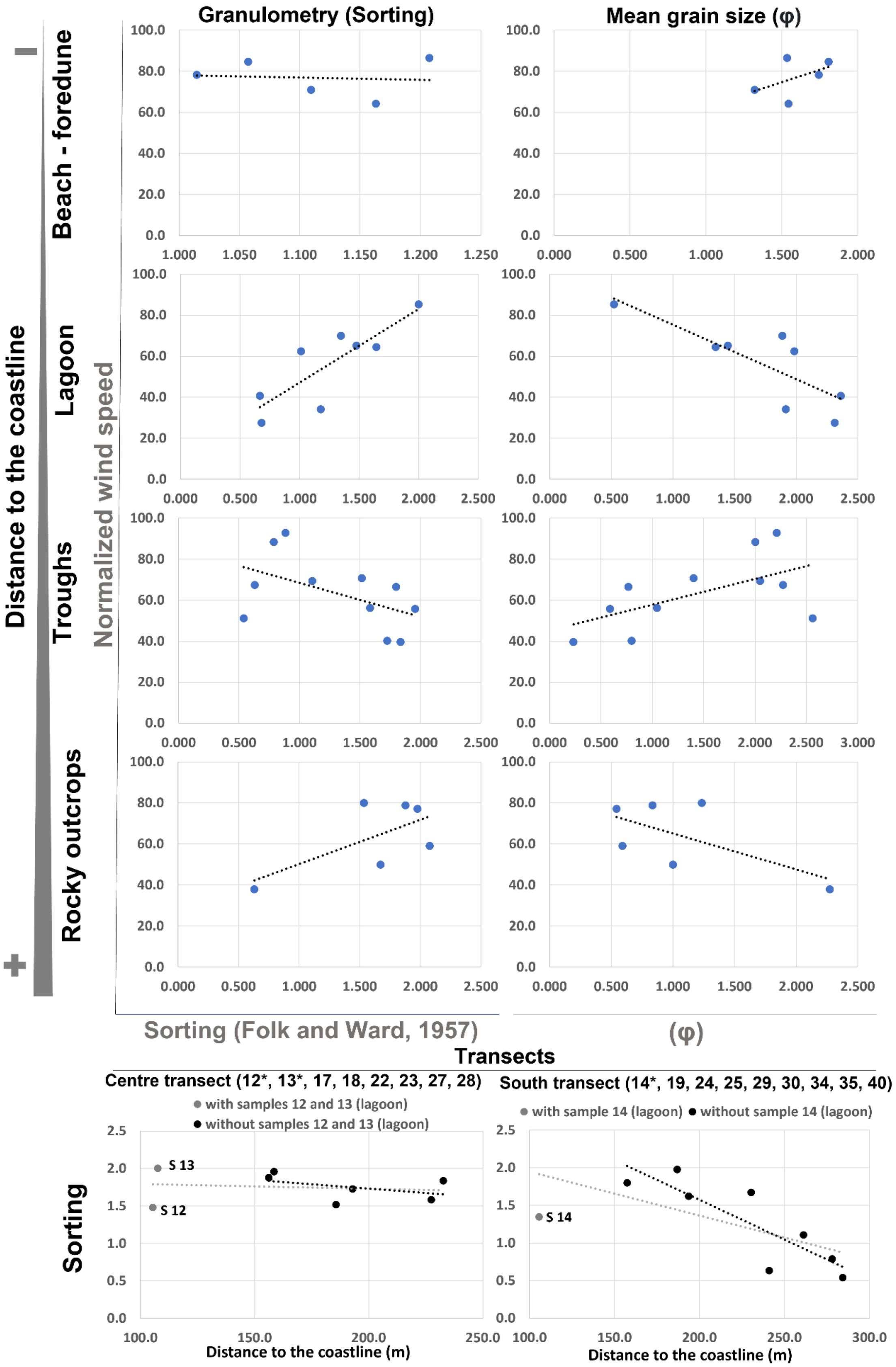

Figure 8. Trend patterns between normalized wind speed, distance to the coastline and sedimentary variables. Top: Trend patterns between normalized wind speed and sorting (left), and mean grain size (right) in different environments within the aggregate extraction zone with respect to the coastline. Bottom: Trend patterns between sorting and distance to the coastline in the centre (left) and in the

south (right) of the study area. Two situations are shown: i) with sample points around or within the lagoon (grey points); ii) without sample points around or within the lagoon (black points).

4.4. General discussion

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

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

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

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

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

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

5. CONCLUSIONS

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

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

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

The results can be used to enable the relevant authorities to make better-informed management decisions and help avoid impacts in these areas.

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Coastal dune restoration in El Inglés beach (Gran Canaria, Spain): a trial study

Abel Sanromualdo-Collado, Antonio I. Hernández-Cordero, Manuel Viera-Pérez, Juan Bautista Gallego-Fernández, Luis Hernández-Calvento

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Abstract

A trial study of foredune restoration on *El Inglés* beach (Gran Canaria, Spain) was carried out between July 2018 and December 2019 as part of the MASDUNAS program of the Gran Canaria Island Council. Among the objectives of that project was the sand relocation from the tip of *La Bajeta* to the *El Inglés* beach, the installation of sand collectors and the reintroduction of specimens of *Traganum moquinii* that act as generators of new mound dunes in the foredune. This study presents results, extracted from the scientific monitoring of the project, on the efficiency of the sand collectors and the evolution of the planted specimens of *T. moquinii*. The knowledge gained from this trial study is key to improve and adapt the coastal dune restoration procedure in arid systems.

Keywords: Maspalomas, sand collector, arid beach-dune system, nebkha.

1. INTRODUCTION

The restoration of degraded coastal dune systems has been carried out in many parts of the world, mostly in temperate areas such as Europe, the United States and South Africa (Lithgow et al., 2013). As a result, extensive knowledge has been gathered in these areas and different methodologies developed to restore this type of coastal dune characterized by the presentation of a continuous ridge morphology parallel to the coast and mainly vegetated by perennial herbaceous species (Ley et al., 2007; Nordstrom, 2008). However, considerably fewer studies have been carried out on arid dune systems (Burke et al., 2011; Lubke, 2013), and no specific methodology has been developed to date for the purposes of restoration. On arid coasts, the foredune is usually made up of mound dunes, commonly known as nebkhas, in which the vegetation tends to be shrub species. This is the case in the Canary Islands (Hernández-Cordero et al., 2019), northwest Africa (Hesp et al., *in press*) and Chile (Castro Avaria, 1987; Castro, 1988), among other places.

The restorations carried out in different dune environments have been, in descending frequency, in stabilized dunes, semi-mobile dunes, mobile dunes and dune slacks (Lithgow et al., 2013). In mobile dunes, one of the landforms most degraded by human activities is the foredune.

Regardless of the dune region, two main types of coastal dune restoration techniques can be distinguished (Ley et al., 2007): engineering techniques and ecological techniques. While the former simply contemplate the use of machinery for the reconstruction of the dune topography, ecological techniques are based on the recovery of geomorphological and ecological processes that allow the dune formation, restoring the morphology and characteristic vegetation according to the area where the intervention takes place (Ley et al., 2007). For this, native dune-building species that accumulate sand while consolidating the dune that is being formed can be planted, or sand can first be accumulated with passive collectors with revegetation taking place later (Gómez-Pina et al., 2002; Ley et al., 2007; Nordstrom, 2008).

The objectives of foredune restoration include the supply of sediments to the corresponding beaches, the recovery of morpho-ecological states and sedimentary dynamics, the restoration of natural vegetation and endemic species, the creation of refuge habitats, the protection of human infrastructures, the creation of leisure areas and the recovery of landscape values (Martínez et al., 2013). The restoration of coastal dunes in arid regions has been based fundamentally on facilitating the colonization of key plant species for the formation of this landform, as is the case of *Salsola nollothensis* in Namibia (Burke et al., 2011).

A few dune restoration projects have been carried out in the Maspalomas dunefield, located in the south of the island of Gran Canaria (Canary Islands, Spain). Between 2005 and 2007, the "2006-2007 *T. moquinii* repopulation project" (original title in Spanish - "*Proyecto piloto de refuerzo de las poblaciones de balancones 2006-2007*") was undertaken, promoted by the Gran Canaria Island Council, the governmental body in charge of managing the *Dunas de Maspalomas* Special Nature Reserve, and executed by the public company Gesplan. This project involved collecting *Traganum moquinii* (known locally as *balancón*) cuttings and seeds, transplantation and germination tests, the installation of fences, transportation and *in situ* planting and, finally, the monitoring of the evolution of plant growth (Gesplan, 2007). Unfortunately, most of these plants were planted too close to free dunes and were buried by them.

Another intervention was undertaken by the Gran Canaria Island Council in 2008 in the foredune area, consisting of the installation of sand collectors and the planting of associated *T. moquinii* specimens. At first, the type of collector used, a 2 m long double semicircular row of wicker rods to generate nebkhas, was effective and generated dunes. However, this action was ultimately unsuccessful as none of the plants survived (Fernández-Cabrera et al., 2011), most probably due to poor control by the administrative authorities of foredune use by public as well as a lack monitoring and maintenance of the actions that had been carried out.

The environmental changes that Maspalomas dunefield has experienced as a result of tourism development include: i) changes in geomorphological processes and types of landform due to modification of the aeolian sedimentary dynamics as the result of the construction of buildings and other infrastructure (Hernández-Calvento et al., 2014; Smith et al., 2017; García-Romero et al., 2019); ii) changes in vegetation, especially the decrease in the number of *T. moquinii* specimens, a plant species that generates the foredune and regulates the transport of sand into the system (Hernández-Cordero et al., 2017, 2018; García-Romero et al., *2021*); and iii) alteration of the landscape as a consequence of massive and disorderly public use (Cabrera-Vega et al., 2013a; García-Romero et al., 2016). To deal with this problem, a pilot study to relocate sand from the tip of *La Bajeta* to *El Inglés* beach (called in Spanish: "*Experiencia piloto de reposición de arena de la punta de La Bajeta a Playa del Inglés*") was initiated in July 2018 as part of the MASDUNAS program run by the Gran Canaria Island Council, with a budget of 1,155,018.33€ and a duration of 18 months. The objectives of this project included, as well as the sand relocation, the installation of sand collectors and the reintroduction of *T. moquinii* specimens, which act as builders of new dunes in the foredune. To evaluate these objectives, the project included the development of a scientific monitoring program.

This study presents a first exploration of the results of the scientific monitoring that was carried out on the efficiency of the sand collectors and the evolution of the specimens of *T. moquinii* that were planted as part of the project. The objective was to evaluate the extent to which the sand collectors and *T. moquinii* specimens contributed to the formation of mound dunes and to expand knowledge of the geo-ecological processes of the foredune of *El Inglés* beach. The results of the scientific monitoring of this experimental study will help to improve and adapt methodologies for the ecological restoration of foredunes in arid dune systems.

2. STUDY AREA

The Maspalomas dunefield (27°45′38″ N, 15°35′09″ W) is located in the southern vertex of the island of Gran Canaria on a deltaic platform at the mouth of the Maspalomas-Fataga ravine (Figure 1). At the south of the dunefield, the Maspalomas beach extends eastwards from the mouth of the Fataga ravine to the *La Bajeta* tip. The eastern boundary of the dunefield corresponds to *El Inglés* beach, aligned in a north-south direction, and is the main sediment supply to the dunefield. The beach stretches for 2,500 meters from the cliff of the *El Inglés* upper terrace (about 25 m above sea level), in the north, to *La Bajeta* tip, in the south. From the foreshore and up to 200 m into the dunefield there are specimens of the *T. moquinii* shrub. These plants, aligned from north to south, act as a dune-buider species and are responsible for the first natural retention of the sediments that advance inland. Their growth is stimulated by sand burial, which favors the formation of mound dunes (nebkhas). This first line of vegetated dunes forms the foredune of *El Inglés* beach. Its functions include the regulation of aeolian sedimentary transport into the dune system, the reduction of erosive processes and the promotion of the formation of barchan dunes and barchanoid ridges (Hernández-Cordero et al., 2012; Viera-Pérez, 2015). The height of the nebkhas that form the foredune of El Inglés beach ranges from 1 to 5 meters, associated to *T. moquinii* individuals that may reach 5 m in some cases (Hernández-Cordero et al., 2012; García-Romero et al., 2021).

The climatic characteristics of this environment are arid: the average temperature of 21 °C varies only slightly over the year, and mean annual precipitation is around 81 mm. The winds have two main directions: those from the W, which represent 19% of the annual frequency, and those from the E-ENE, which account for 15% (Hernández-Cordero et al., 2019). However, as the latter are the most intense (effective winds), the wind and marine sedimentary dynamics occur in the NE-SW direction (Máyer Suárez et al., 2012). The winds from the W, normally caused by the drift of the trade winds to the northern component and conditioned by the orography of the island, are usually mild (Viera-Pérez, 2015; Smith et al., 2021).

Several studies have confirmed a relative stability of El Inglés beach at different time scales (Alonso et al, 2001; Fontán-Bouzas et al., 2019; Di Paola et al., 2020). However, seasonally strong winds and energetic waves from the WSW-SW, associated with autumn-winter Atlantic storms, reverse the marine dynamics, and erode the Maspalomas beach. These storms are responsible for a significant sediment loss in the system (Fontán-Bouzas et al., 2019; Di Paola et al., 2020). In this context, sediments are transported eastwards to the the tip of *La Bajeta,* which grows until reaching a maximum limit marked by a drop-off. Consequently, part of the sand falls to deeper areas (below 20 m) where the waves are unable to recover the sediment and transport it back to the beach. In recent decades, the system has lost an average of 45,000 m^3 of sediment per year (Ministerio de Medio Ambiente, 2007), resulting in the identification of a sedimentary deficit (Hernández-Calvento, 2006). The consequences have been smaller dunes and a decrease in the area occupied by mobile dunes (Hernández-Calvento, 2006; Hernández-Cordero et al., 2017, 2018).

El Inglés beach is an area of considerable recreational activity, as it is one of the main areas of tourist development on Gran Canaria island. This intensive human activity has consequently had certain impacts on the foredune (Hernández-Cordero et al., 2017; Peña-Alonso et al., 2018b; Viera-Pérez et al., 2019) that have led to its deterioration and fragmentation (Sanromualdo-Collado et al., 2021). The presence of discontinuities in the foredune of *El Inglés* beach due to the decrease in the number of *T. moquinii* specimens and the disappearance of the associated dunes has resulted, in turn, in an acceleration of the aeolian sedimentary transport and the formation of deflation surfaces (Pérez-Chacón et al., 2007; Hernández-Cordero et al., 2012).

For this work, the study area extends longitudinally from north to south from *El Inglés* beach to the tip of *La Bajeta*, forming a polygon of about 1,200 x 400 m which includes the sand extraction area, the storage area, the sand collector zones and the sand relocation areas specified in the aforementioned "*Experiencia piloto de reposición de arena de la punta de La Bajeta a Playa del Inglés*" project (Figure 1).

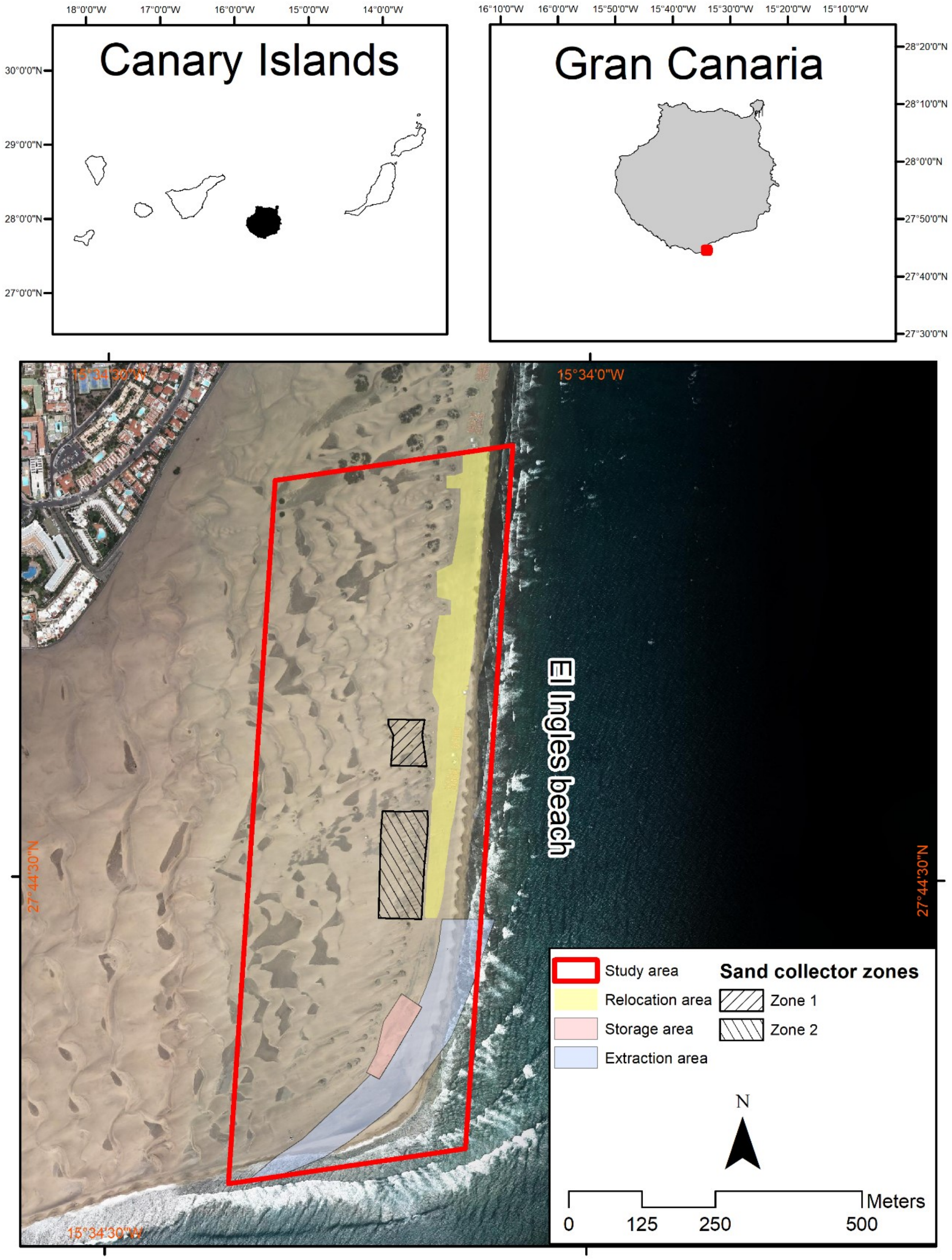

Figure 1: Study area and locations of sand mobilization and sand collector zones. Source of orthophotos: IDECanarias, GRAFCAN, S.A.-Canary Islands Government (2019). Coordinates UTM. Zone 28 N. Ellipsoid WGS 84. Datum REGCAN95.

3. METHODS

3.1. Project description

The experiments carried out in the framework of the project included the reintroduction into the dune system of 60,000 m^3 of sand from *La Bajeta* tip, as a source of sediments for dune formation. This was carried out before the SW storms occurred, in order to ensure their permanence in the system. For this, sand was dredged in the emerged area of this tip, setting it back up to a maximum defined by the inland beach profile registered in the last 40 years and relocating it in the *El Inglés* beach area. This sand relocation was carried out in three phases (*Table 1*). The relocated sand was exposed to the action of the wind, which would transport it to the foredune, where the planted *T. moquinii* specimens would intercept sediments, forming nebkhas and, subsequently, parabolic dunes and barchan dunes (Hernández-Cordero et al., 2012; Viera-Pérez, 2015). To favor the formation in the foredune of these first nebkhas associated with vegetation, a series of sand collectors were installed in various plots, and 21.04 ± 8.63 cm tall *T. moquinii* specimens with roots around 23 cm long were planted, some of them associated with sand collectors (plant-collector units) and others not.

Table 1: Schedule of the actions carried out in the project.

ACTION	DATES
Installation of sand collectors	23/10/2018 – 9/11/2018
Planting of *T. moquinii* specimens	25/10/2018 – 13/11/2018
Sand relocation	1. 22/10/2018 – 28/11/2018 (18,930 m^3) 2. 06/05/2019 – 07/06/2019 (24,705 m^3) 3. 14/10/2019 – 08/11/2019 (16,365 m^3)

The sand collectors and associated *T. moquinii* specimens were placed in two zones adjacent to the sand deposit area (Fig. 1). Zone 1 has a surface area of 4,599 m^2 and Zone 2 14,085.09 m^2. To determine the beneficial use or otherwise of sand collectors in each of these areas, two combinations were tested: i) the installation of sand collectors and the planting of associated *T. moquinii* specimens; and ii) only the planting of *T. moquinii* specimens.

In this way, Zone 1 (Figure 2, A) was subdivided into Zone 1 north (sand collectors with plants) and Zone 1 south (only plants). Zone 2 (Figure 2, B) was subdivided into Zone 2 north (sand collectors with plants), and Zone 2 south (including one area only with plants and another with both sand collectors and plants).

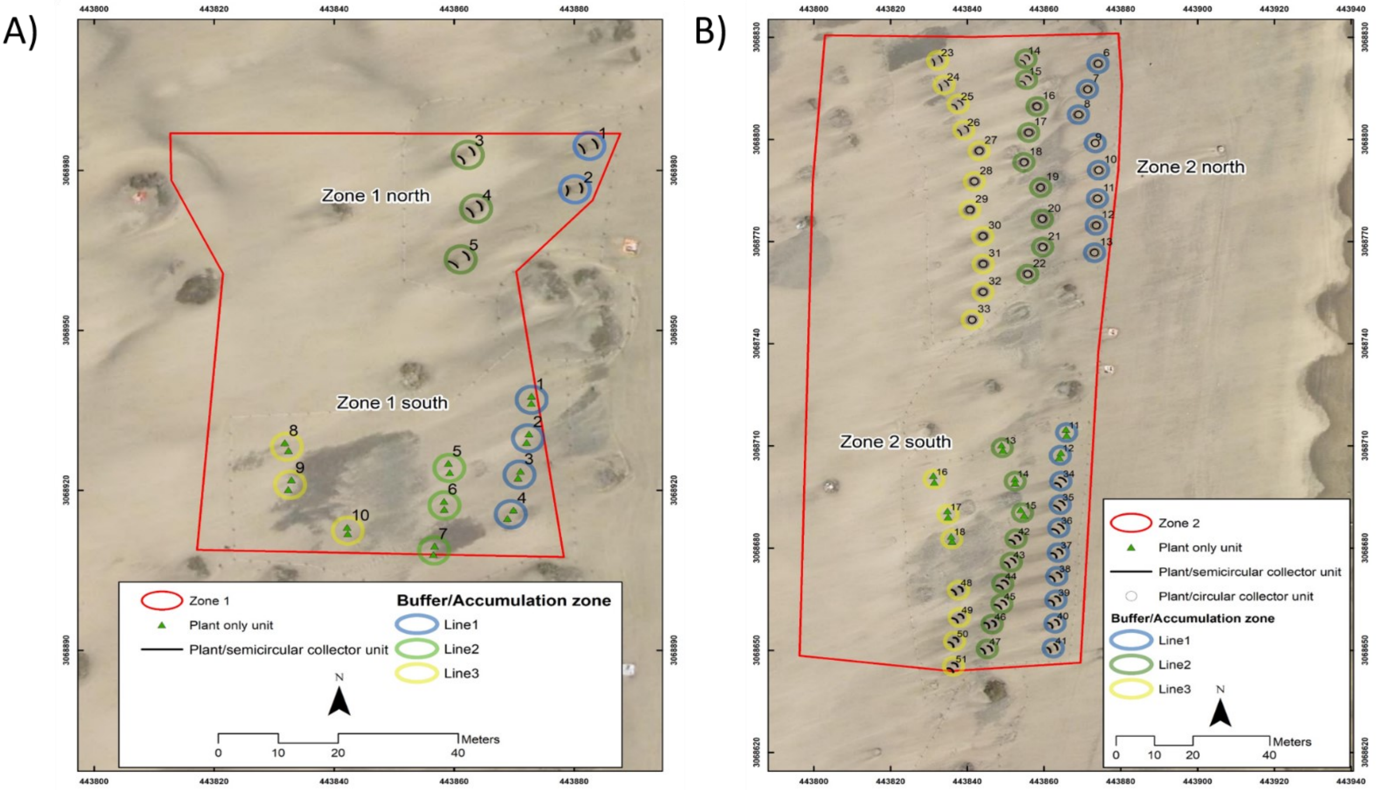

Figure 2: Layout of sand collectors and T. moquinii zones. A: Zone 1. B: Zone 2. Source of orthophotos: IDECanarias, GRAFCAN, S.A.-Canary Islands Government (2019). Coordinates UTM. Zone 28 N. Ellipsoid WGS 84. Datum REGCAN95.

The spatial arrangement of the sand collectors and plants consisted of two or three lines parallel to the coast, depending on the characteristics of each area. The location of the collectors on each line was designed following a N-S arrangement. The location of the sand collectors of the different lines was designed following a NE-SW arrangement between them (Table 2).

The sand collectors installed in the plots had two typologies:

- Double semicircular collectors (according to the tested design, see Fernández-Cabrera et al., 2011), comprising two semicircles of wicker rods 2 m apart and placed transversely to the effective winds (NE-SW). Each semicircle is 2 m long (Figure 3, A).

- Circular sand collectors (experimental model), comprising a closed circle of wicker rods with a diameter of 2 m. This model has an opening of about 50 cm on its south side to facilitate data collection (Figure 3, B).

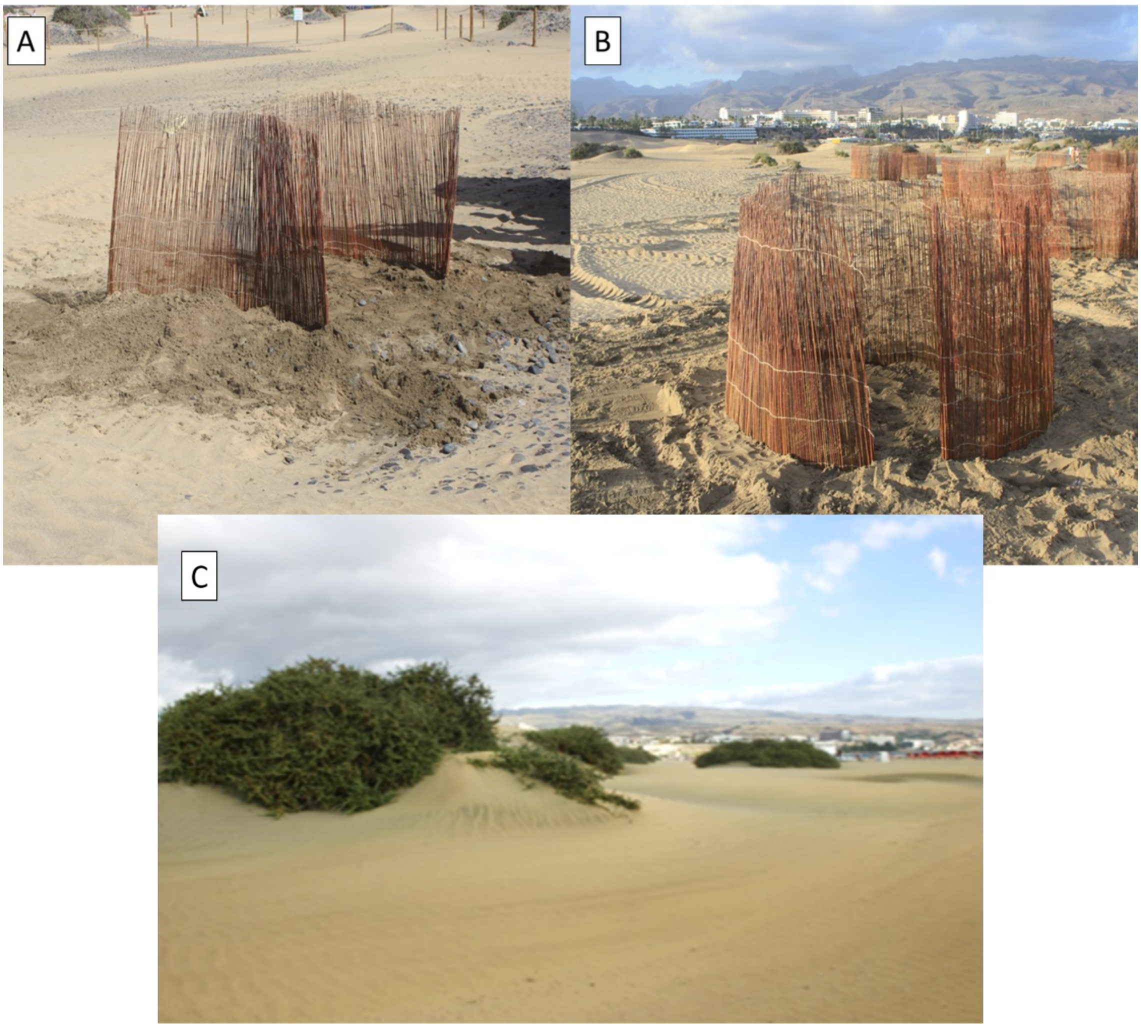

Figure 3: Typologies of sand collectors and natural T.moquinii specimens located in El Inglés beach foredune. A) Double semicircular sand collector. B) Circular sand collector. C) Natural T. moquinii specimens.

The wicker rods of each collector are 1.8 m tall and were buried to a depth of about 70 cm (40% of their length) to ensure good resistance to the wind. Associated with each sand collector, two specimens (left and right facing seawards) of *T. moquinii* were planted to increase the chance of successful repopulation. In the case of the semi-circular collectors, the specimens were planted about 2 m from the second row. In the case of the circular collectors, they were planted inside. In the cases of plants with no sand collector, these were planted in pairs approximately 1.5 m apart and aligned from north (left) to south (right).

Table 2: Count and distribution of sand collectors and T. moquinii specimens.

		Semicircular sand collector	Circular sand collector	*T. moquiini* without sand collector	Total sand collectors	Total *T. moquinii* specimens	Distance between plants or between sand collectors/*T. moquinii* units	Distance beetwen lines
Zone 1 north	Line 1	2	-	-	2	4	7.6 m	22 m
	Line 2	3	-	-	3	6	10–11 m	
Zone 1 south	Line 1	-	-	4	-	8	5–8 m	14–21 m
	Line 2	-	-	3	-	6	6–13 m	25 m
	Line 3	-	-	3	-	6	5–13 m	
Total		5	-	10	5	30		
Zone 2 north	Line 1	-	8	-	8	16	6–11 m	17–22 m
	Line 2	2	7	-	9	18	5–14 m	13–22 m
	Line 3	4	7	-	11	22	5–11 m	
Zone 2 south	Line 1	8	-	2	8	20	4–11 m	14–22 m
	Line 2	6	-	3	6	18	6–11 m	7–20 m
	Line 3	4	-	3	4	14	7–12 m	
Total		24	22	8	46	108		

3.2. Monitoring methodology

Monitoring the capacity of the sand collector installation and the planting of *T. moquinii* specimens for the formation of dunes was carried out by taking relative and absolute measurements in the field of the landforms and sand volumes around the plants and sand collectors. Similarly, measurements and observations were carried out with respect to the survival and morphological development of the plants. The sampling campaigns were carried out for 13 months, from November 2018 to December 2019, with a fortnightly frequency (25 campaigns). The wind speed and directions in this period were recorded every 10 minutes by a meteorological station located in *El Inglés* beach within the sand relocation area and less than 300 m from the sand collectors' installation and *T. moquinii* planting areas.

Monitoring of the planted *T. moquinii* specimens: the height and the largest and smallest diameters of each specimen were measured. With these data, its biovolume could be calculated by applying the following formula (Blanco Oyonarte and Navarro Cerrillo, 2003):

$$B_v = \pi * \left[\frac{Dm}{2}\right]^2 * h$$

where B_v is the biovolume, Dm is the mean diameter and h corresponds to the height of the plant.

This monitoring also enabled determination of the survival rate of the *T. moquinii* specimens, calculated as the percentage of the total number of specimens that remained alive. Likewise, information was collected on the state of vitality of each plant. The state of vitality was calculated according to a percentage scale. Each specimen was imaginarily divided into four equal parts. According to the number of parts that were green, the state of vitality was estimated as follows: excellent (> 75%; dark blue columns in the fig. 4), good (50-75%; orange columns in the fig. 4), regular (25-50% and/or partially withered or dehydrated leaves; grey columns in the fig. 4), bad (5-25% and/or withered or dehydrated leaves in a generalized way; yellow columns in the fig. 4), or dry (totally dry; light blue in the fig. 4).

Geomorphological monitoring: topographical measurements of the volumes of sand accumulated by the sand collectors and the associated *T. moquinii* specimens were taken (16 campaigns). This work was carried out with geomorphological control using a Leica TS06 Total Station with a laser device, which allowed detailed determination of morphological and volumetric changes. The topographical method was an inverse intersection from distances, from a series of fixed bases of known coordinates obtained using GPS (UTM-28N - Datum WGS84). To ensure complete data collection, the measurements were carried out in an area 5 m in diameter surrounding each collector-plant unit. With the collected data, digital elevation models (DEM) were elaborated by generating triangulated irregular networks (TIN), projected in UTM coordinates (WGS84). Subsequently, the TINs were converted to raster format with a pixel size of 0.10 m. The last step in the data treatment consisted of crossing the raster models on different dates to evaluate the evolution of the volumetric variations associated with each collector-plant unit and determine the type of sand collector that, together with the associated *T. moquinii* specimens, was more effective in generating mounds. The sediment retention and nebkha dune formation capacity of the sand collectors and the associated *T. moquinii* specimens was evaluated by means of the difference between the maximum height reached within the influence zone between the last and the first monitoring campaign.

4. RESULTS

4.1. Monitoring of planted *T. Moquinii* specimens

A progressive decrease in the survival rate of the plants was observed. The reduction was progressive and more pronounced in the specimens associated with sand collectors, with a survival rate at the end of the study period of 30%, although in certain periods survival was 20% (Fig. 4). However, the survival rate of *T. moquinii* specimens without sand collector was more stable, remaining between 70% and 80% for a significant portion of the study period. Two periods were identified in which there was a more pronounced decrease in the survival rate, both in plants associated and not associated with sand collectors, January-March 2019 and November-December 2019. For specimens without sand collector, periods of slight recovery were observed in June and October 2019. Plants associated with sand collectors seemed to begin to recover or unearth from the end of November 2019 (Figure 4).

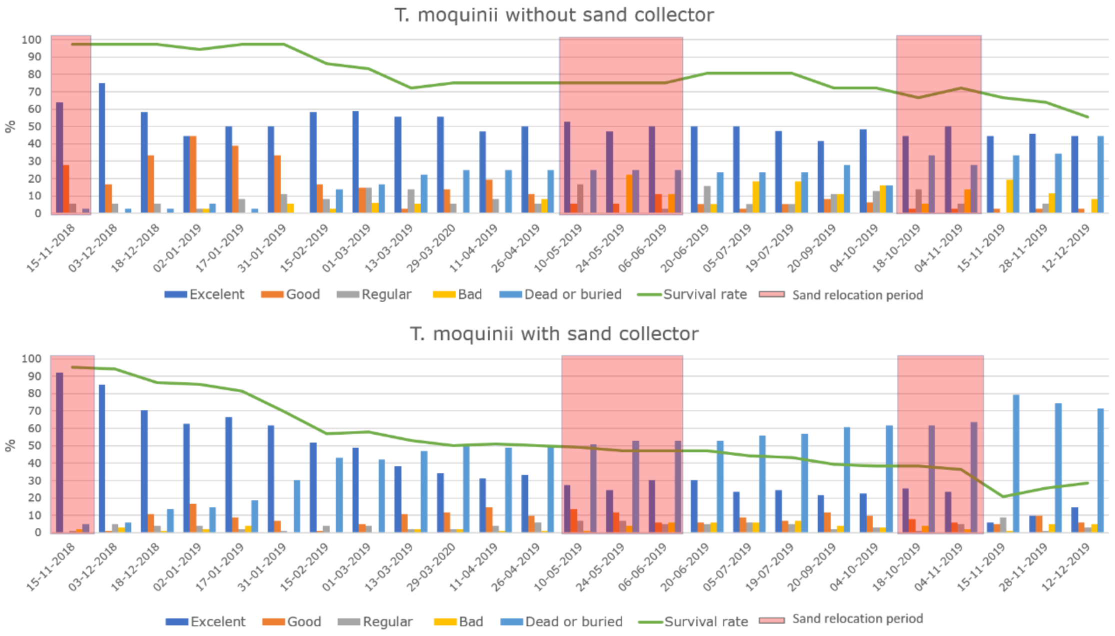

Figure 4: State of vitality and survival rate evolution of T. moquinii specimens. The top graph shows the evolution of specimens planted without sand collector (36), and the bottom graph shows the evolution of specimens planted with semicircular (58) and circular (44) sand collectors.

The biovolume of *T. moquinii* specimens, both those associated and not associated with sand collectors, increased exponentially after their planting (Figs. 5, A and 5, B). In both cases, the increase in biovolume was gradual during the first 10 months before a considerable increase began to take place in September 2019. This upward trend was interrupted in November 2019 when the *T. moquinii* specimens began to decrease in biovolume.

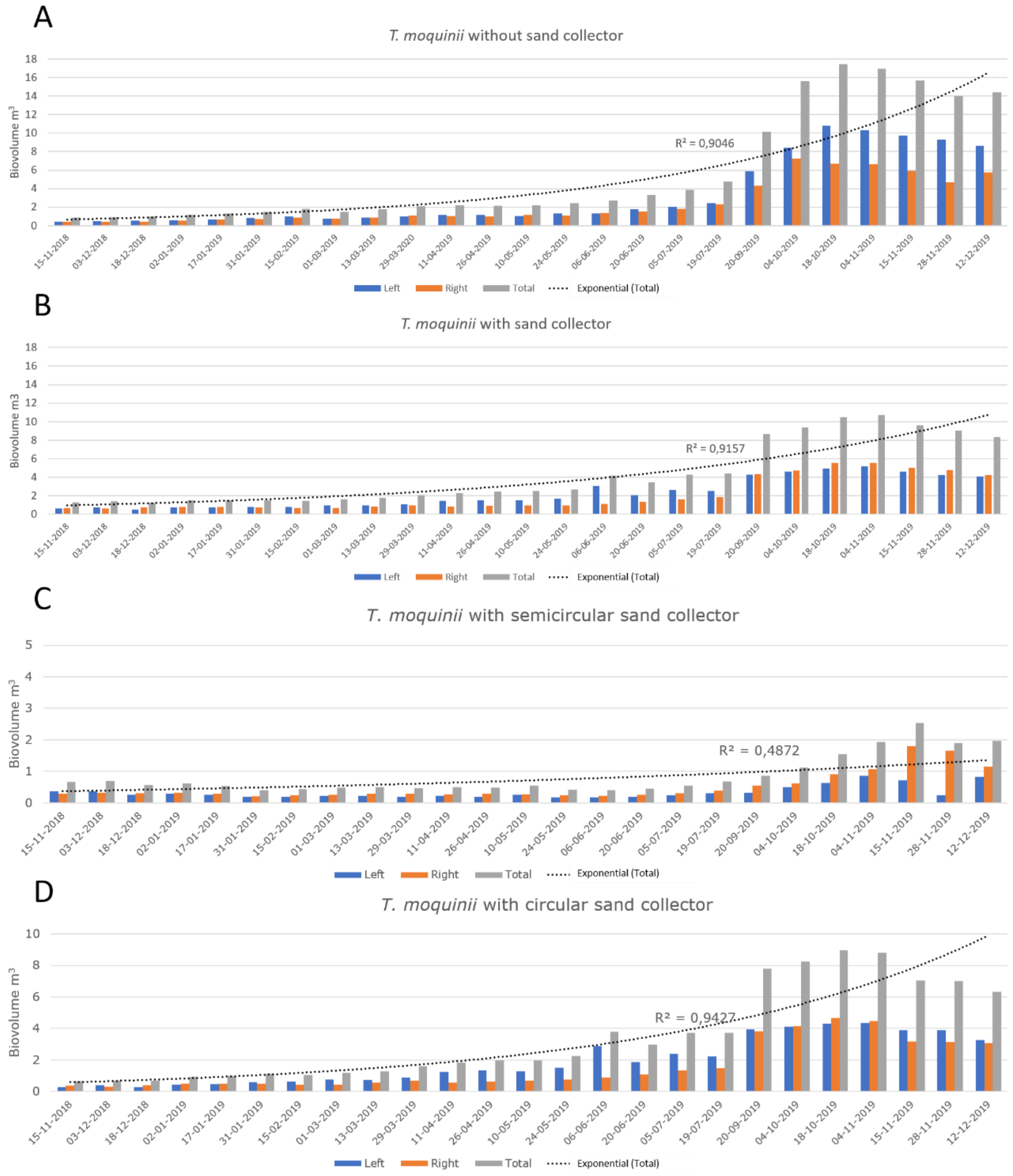

Figure 5: T. moquinii biovolume evolution. A) T. moquinii specimens without sand collector (36) ; B) T. moquinii specimens with sand collector (102) ; C) T. moquinii specimens associated with semicircular sand collector (58) ; and D) T. moquinii specimens associated with circular sand collector (44). Note diferences in vertical axis.

Focusing only on the biovolume of the plants associated with sand collectors, differences according to the type of collector were observed. The seedlings associated with circular sand collectors (Fig. 5, D) showed a higher growth rate than those associated with double semicircular sand collectors (Fig. 5, C). The latter plants accumulated a biovolume of less than 2 m^3 during the first year, only exceeding this volume in November 2019. During the last months of the study there was a decrease in the biovolume of these plants. In this case, it is worth noting that the seedlings planted to the right (orange columns) of the double semicircular collectors generally presented a greater biovolume than that of the specimens planted to the left (blue columns). For their part, the *T. moquinii* specimens associated with circular sand collectors grew more than those associated with double semicircular collectors, and experienced progressive growth that conforms to an exponential model. At the end of October 2019, these specimens attained their maximum biovolume, exceeding 8 m^3. As with the plants without sand collector and those associated with semicircular sand collectors, there was a decrease in biovolume in the last months of 2019 that broke the exponential growth trend of the series.

4.2. Geomorphological monitoring

Most of the collector-plant units accumulated sediment, increasing the height of the mound associated with its accumulation zone. However, in the case of *T. moquinii* specimens planted without a sand collector, the trend was not so clear and there were differences in behavior depending on the planting zone.

In Zone 1 north, all the elements accumulated sand in their area of influence, with the greatest height recorded for the collector-plant units located along Line 1 where values close to 1 m were reached. However, none of the specimens planted in this area remained alive at the end of the monitoring period. In Zone 1 south, where seedlings without a sand collector were planted, the difference in height in the volumes associated with these elements was lower than those of Zone 1 north, with heights ranging between 0.2 m and 0.8 m. However, the final survival rate of *T. moquinii* specimens in this area was 90%. In this area, there were some units around which accumulation was practically non-existent (Nos. 9 and 10) or which were eroded (No. 1) (Fig. 6, A).

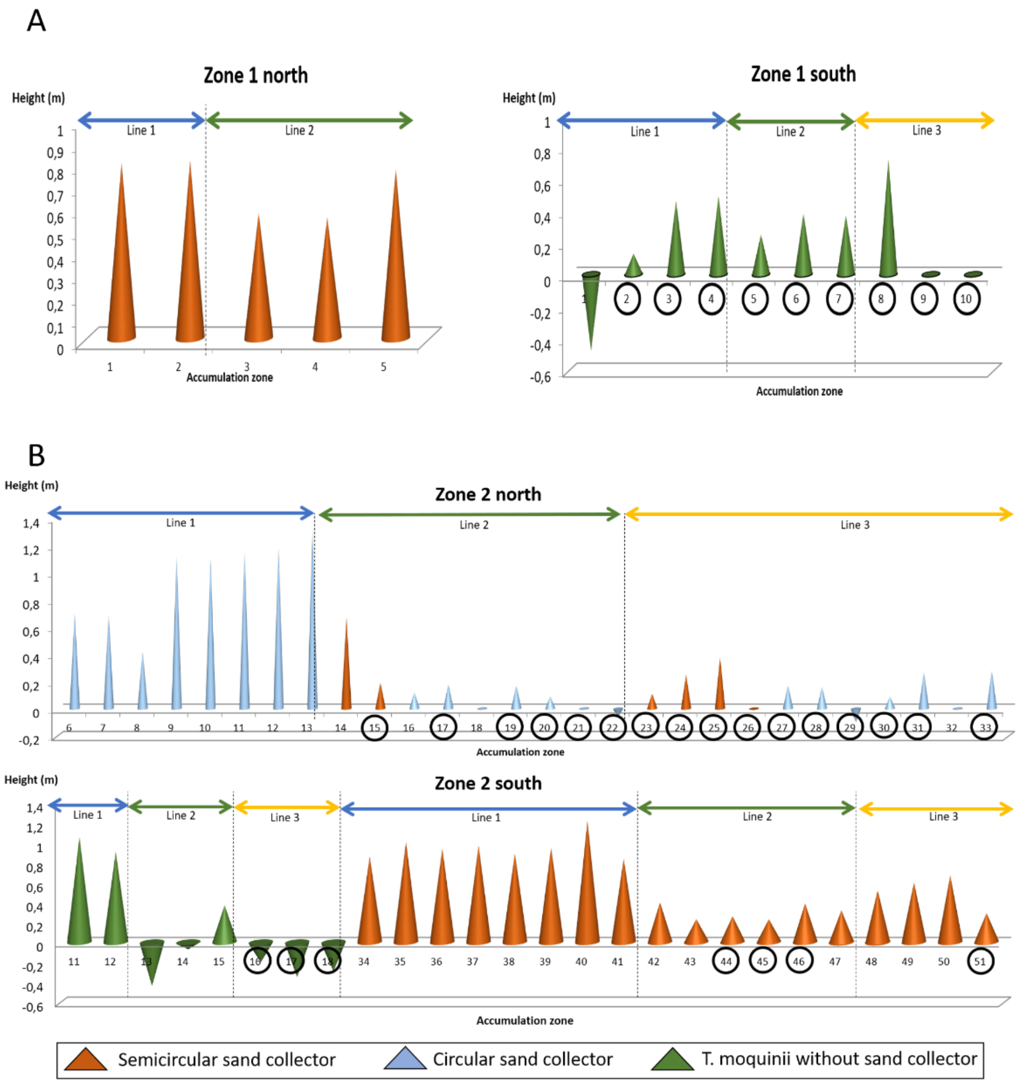

Figure 6: Maximum height difference in accumulation zones associated to sand collectors and T. moquinii specimens located in Zone 1 (A) and Zone 2 (B). Circled numbers correspond to T. moquinii specimens that were still alive at the end of the monitoring period.

In Zone 2 north, where different types of sand collector were combined, the highest volumes of sediment occurred in the accumulation areas associated with the circular typology, reaching heights of around 1.4 m in the first line. In the interior lines, the height differences were smaller, producing erosion in some cases. In this case, the *T. moquinii* specimens planted in the first line had a zero survival rate. In Zone 2 south, there were differences between sediment accumulation generated by *T. moquinii* specimens with and without a sand collector. The plants without sand collector located in Line 1 accumulated volumes of sand with a height of around 1 m, while those of the interior lines eroded, except for No. 15, which increased the height of its associated mound by 0.4 m. On the other hand, the specimens associated with double semicircular collectors showed a positive increase in their sand mounds. In this case, the collector-plant units located on Line 1 generated sand mounds with heights greater than 1 m, whereas the heights in the accumulation areas of Lines 2 and 3 ranged from 0.2 m to 0.8 m. Again, for this area, no *T. moquinii* were still alive in Line 1 at the end of the monitoring period. In the case of plants without sand collector, the mortality of all specimens extended to Line 2 (Figure 6, B).

The sediment capture in the elements located in Zone 2 was higher than in Zone 1. Again, the collector-plant units and the plants without an associated collector, located in Line 1, accumulated a greater amount of sand than those located in Lines 2 and 3.

5. DISCUSSION

The monitoring of the experimental actions of dune restoration carried out in *El Inglés* beach, has allowed reliable data that can help to improve the recovery protocols of the coastal dune of an arid dune system. This will be not only useful for the recovery of the foredune of *El Inglés* beach, but can also be applied to other arid dune systems in the Canary Islands, Cape Verde Islands and the African coast (from Agadir to Mauritania), where *T. moquinii* plays a structural role in foredune formation (Hesp et al., *in press*). In addition, this protocol could be adapted to other arid coastal dune systems in the world, although it must be adapted to their specific conditions.

In temperate climate zones, sand collectors have been widely used to facilitate the formation of dunes with morphologies appropriated to the characteristics of the intervened sites and the vegetation (Nordstrom, 2008; Grafals-Soto and Nordstrom, 2009; Grafals-Soto, 2012).

The inclusion of two experimental sand collector typologies has permitted the objective assessment of an efficient solution for the environmental restoration of foredunes in arid systems, a solution which is adapted to the particular geomorphological characteristics of the foredune in question by generating the mound morphology typical of this system (Hernández-Cordero et al., 2012). Thus, it has been found that the most efficient sand collector will be the type that gradually accumulates sediment, producing a balanced burial of the plants located in its area of influence and facilitating their progressive growth. This plant growth is in turn stimulated by its gradual burial in the sand, which enables a greater sand-holding capacity, allowing the development of mound dunes, a process described as a potential progressive growth system by Viera-Pérez (2015).

The use of sand collectors and *T. moquinii* specimens facilitated the generation of mound dunes at a greater speed and with a bigger height than the *T. moquinii* specimens planted without a collector. The mounds generated by the *T. moquinii* specimens without a sand collector were smaller than those associated with collectors and, in some cases mainly located in Zone 2 south, there was even a loss of height at the end of the study period (Figure 6, B). The difficulty, in this case, of the *T. moquinii* specimens to form and maintain mound dunes may be due, on the one hand, to having been planted in areas of wind flow acceleration caused by elements (beach equipment or other plants) situated in front of them that generate areas of high erosion. This seems to be the case of unit 1 (without sand collector) planted in Zone 1 south, located in an aeolian corridor generated by a pre-existing *T. moquinii* specimen (Figure 2, A). On the other hand, the wind flow acceleration that hinders sand accumulation around the specimens of *T. moquinii* without collector may also be due to the presence of stones or deflation surfaces in the planting area.

The efficiency in sand accumulation and the formed dune morphology depend on the characteristics of the sand collectors (Nordstrom, 2008). Although both sand collector types demonstrated their ability to retain sediment and generate associated mound dunes, the circular sand collectors achieved higher accumulation heights and greater stability of the generated mounds (Fig. 6). This is due to the fact that, unlike double semicircular sand collectors, this type of sand collector allows shelter of both the generated mound and the associated plants regardless of the direction of the effective winds. In contrast, in double semicircular collectors, the orientation of the installation is decisive, since they only induce dune formation downwind. This means that, in swirling wind conditions, the captured sediment moves, reducing the stability of the generated mound dune and varying its dimensions. Thus, effective SW, WSW and W winds (> 5.1 m/s) during the study period (Fig. 7) were responsible for remobilizing the sediment accumulated by the double semicircular collectors. Moreover, the plants associated with this type of sand collector would have been exposed to the direct action of the wind when not proceeding from the predominant direction, and thus would have been subjected to greater movement affecting their photosynthetic activity and growth (Smith and Ennos, 2003).

The participation of natural processes is essential to achieve a successful dune restoration (Gallego-Fernández et al., 2011; Ley, 2012). The wind transports the sand deposited in the back beach to the sand collector areas, where it sediments and favors the establishment of vegetation until it achieves a bearing that allows the balanced growth of both mound and plant. In this sense, the specimens planted next to the sand collectors must meet certain characteristics that allow plant survival after exposure to the natural conditions of the environment in which they are to be introduced. It is also important to consider how the collectors will affect the burial of the plant in the sand. The planted specimens need long roots to ensure rapid and effective rooting for plant stability and the acquirement of the water necessary for its survival which rises by capillarity from a water table that is usually, depending on the area, at depths of 20-40 cm (Viera-Pérez, 2015). Likewise, the aerial part of the plant must have sufficient length and size to cope with temporary burial (partial or absolute) and to ensure its progressive growth and development. When the necessary humidity is present, the vegetative growth of *T. moquinii* is greater during the hotter summer months (Viera-Pérez, 2015), and so its planting is recommended during the months of April-May.

The rapidly falling survival rate of the planted seedlings during the first 6 months (Figure 4) suggests that the characteristics of the specimens that were introduced did not correspond to those indicated above, and that the plants could have been too small to be introduced into the system. The high mortality rate during these months could be due to the inability of the plants to reach the water table and/or the absence of fresh water supplies, as well as to sudden and rapid burial due to their small size and the large volumes of transported sediment. When there is a lag between collector installation and *T. moquinii* planting, the mound generated by the sand collector will accelerate the capillarity increase of the water table to levels where it can be captured by the roots of the plant that will subsequently be planted. However, in this case, collector installation and *T. moquinii* planting was undertaken simultaneously, which meant that insufficient time was allowed for the rise of the water table and hindered the rooting and survival of the planted specimens. This absence of lag could partly be compensated by applying irrigation, but this must be underground (not less than 20 cm) in order to avoid the formation of saline crusts that can produce deflation zones around the plants. Nonetheless, the fact that survival was greater in plants not associated with sand collectors, added to the low or zero survival rate of specimens associated with sand collectors in the lines closest to the sand relocation area, reinforces the idea of sudden burial, suggesting the drowning of the plants located in the sand collectors, that were unable to cope with the sand accumulation. The high frequency of effective winds during the initial months after planting (Figure 7) led to the inland transport of a large part of the volume from the first sand relocation (Table 1), which could also have caused the sudden burial of the newly planted specimens.

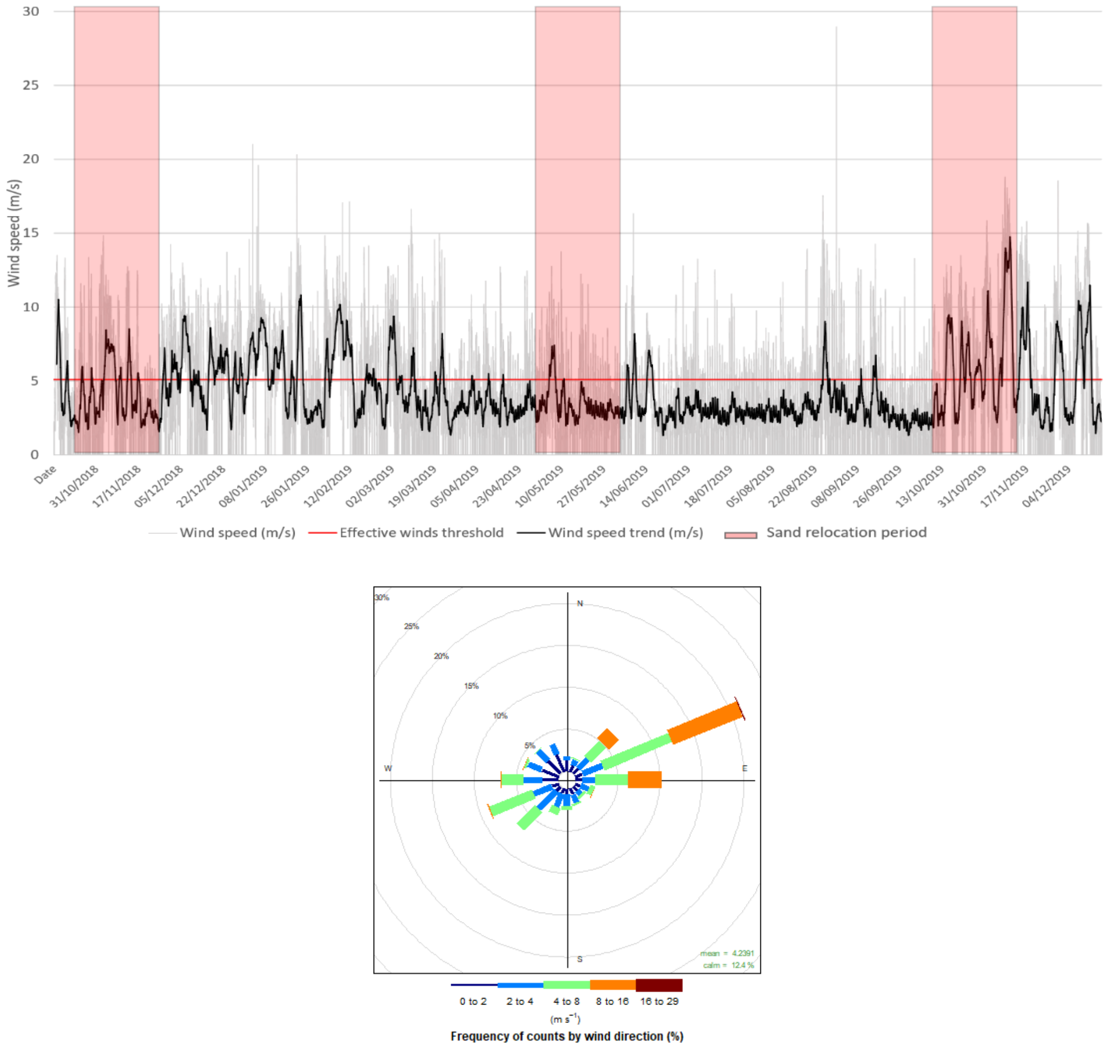

Figure 7: Wind speed and direction data series in El Inglés beach.

The practical absence of effective winds to transport sand into the system between the second and third sand relocations (Table 1) may be responsible for the second period of high mortality from October and November 2019, when the third sand relocation was performed and effective winds arose again (Fig. 7). The period between the second and third sand relocations coincided with the summer season when effective NE winds do not normally occur (Máyer Suárez et al., 2012). This lack of sediment mobility between sand relocations caused approximately 30,000 m^3 worth of sand accumulation in the relocation area, which began to be transported to the collector areas in a massive way from October 2019. This massive entry of sediment into the collector areas during the last months of 2019 caused a new sudden burial of collectors and *T. moquinii* specimens that collapsed the system. This is reflected in a further decrease in the survival rate in this period (Fig. 4) and in a decrease in plant biovolume (Fig. 5). Again, the mortality rate due to burial was higher in specimens associated with sand collectors than in specimens planted without a collector, which reinforces the hypothesis that mortality is associated with plant drowning by burial. In this sense, the massive entry of sediment into the system after the third relocation of sand may explain the fact that height increases occurred in areas of influence of *T. moquinii* specimens without a collector where the plant did not survive, as is the case of Line 1 in Zone 2 south (Figure 6, B). In these cases, the increase in height is not due to the formation of mound dunes, but rather to the advance of the sand front from the relocation.

It is important to highlight that the success of the management actions carried out depends to a large extent on the total elimination or reduction to compatible levels of the causes that have led to the alteration of the dune system (Ley et al., 2007). In this sense, the high occupancy and constant tourist activity in *El Inglés* beach represent a major impediment to the survival of *T. moquinii* specimens, to the generation of mound dunes and, even, to the maintenance of the natural dynamics that act as the engine of the system (Hernández-Cordero et al., 2017). Despite the use of protection systems (with enclosures and marking of the sand collector areas) and an information program for citizens (which included posters and informative days, among other strategies), user activities were observed that undoubtedly hindered the success of the restoration actions. On the one hand, invasion by users of the collector areas caused trampling of the planted seedlings, which would have been another important cause of plant mortality. On the other hand, the use of the collectors by users as windbreaks or even as clotheslines had a direct impact on the sand mounds generated, which were often flattened by the user to make them more comfortable to lie on. This would have reduced collector porosity, modifying its sediment retention capacity and similarly affecting the incipient dunes.

The construction or installation of windbreak structures (known locally as *goros*), as well as the presence of artificial elements installed by the beach management, such as trash cans or kiosks, interacted with the aeolian dynamics of the system and altered the natural transport of the sand. These obstacles led, in some cases, to the acceleration of transport in their area of influence, causing the loss of sedimentary accumulations in their surroundings (Sanromualdo-Collado et al., 2021). The loss of sediment resulting from wind acceleration due to the presence of obstacles would have led to the uprooting of the plants and another cause of their mortality.

Despite the possible impact of users activities in the restoration project, the results have proven to be invaluable with respect to improving the restauration protocols in arid dune systems. The results of the present study form the basis for a second project that will be executed within the framework of the MASDUNAS2 program over the course of 2021. In this second phase, around 100 new specimens of *T. moquinii* will be planted, including a group cultivated in long pots to prolong the roots. In addition, monthly irrigation of the planted seedlings for a year is proposed, following the recommendations of Viera-Pérez (2015). These specimens will be planted on the dunes generated by the collectors during the first restoration trial, replacing the lost specimens and giving a second chance to foredune restoration in a context without extraordinary sediment contributions and with mound dunes already formed.

Finally, the usefulness of the data obtained from scientific monitoring that took place has been shown. As an experimental project, the data offers the possibility of further analysis, with the results highlighting the need to disaggregate or aggregate certain data in order to perform a more exhaustive analysis of the scientific monitoring data in future research.

6. CONCLUSIONS

Valuable conclusions can be drawn from this experimental project to restore the coastal dune of *El Inglés* beach. The results showed that the installation of double semicircular collectors and circular collectors is effective for the generation of mound dunes, although the dunes generated by circular collectors are larger and have greater stability. Consequently, the *T. moquinii* specimens associated with sand collectors must be adapted to the conditions of the environment in which they are to be planted. They must be hardened plants with long roots and stems that allow their survival against burial and a lack of fresh water from the water table.

The results of this study suggest that the main cause of plant mortality was the sudden and massive burial of specimens. To avoid this, larger specimens should be planted, allowing burial to be more progressive. Moreover, the accumulation of sand from contributions in the relocation area should be avoided. It is essential not to make new contributions until the volume of sand introduced in the previous sand relocation has been completely incorporated inside the system by aeolian transport, in order to avoid the sudden burial of collectors and plants.

It is suggested that the planting of *T. moquinii* specimens in the foredune of *El Inglés* beach should be carried out from the months of April-May, so that a minimum of 5 months elapse to allow the plants to reach a size capable of supporting the burial that can be caused by the effective winds of autumn. There should be a lag between the installation of sand collectors and the planting of *T. moquinii* specimens in order to allow the ascent by capillarity of fresh water from the water table. In the absence of this lag, or if it is insufficient for the moisture to be made available to the plant, it is necessary to assist the planting of seedlings with underground irrigation. Nevertheless, the actions of certain users represent a handicap for the success of the restoration program, despite the efforts made in protection and information systems.

Finally, the results highlight the need to implement a scientific monitoring program that collects the results of any foredune restoration project. Monitoring allows early detection of problems that may occur and the establishment of rapid adaptive response measures. In addition, it allows determination of which measures are appropriate and which are not for future restoration projects.

The findings of this study make the "*Experiencia piloto de reposición de arena desde la punta de La Bajeta a la Playa del Inglés*" a valuable reference to help the development of a more effective coastal dune restoration protocol applicable in arid dune systems.

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DISCUSIÓN GENERAL

Los resultados presentados como fruto de esta investigación han permitido dar cumplimiento a los objetivos planteados y verificar su hipótesis de partida. En consecuencia, se concluye que el conocimiento detallado de las interacciones naturales entre las distintas unidades biogeoformológicas y los procesos sedimentarios eólicos que dan lugar al establecimiento y funcionamiento de la *foredune* en sistemas sedimentarios eólicos áridos, así como de las principales interferencias y efectos asociados que las actividades humanas pueden tener, a distintas escalas, sobre ellas, permiten desarrollar estrategias bien informadas para la gestión, la conservación y, de ser necesario, la restauración de estos espacios.

El interés científico a nivel general sobre los procesos que rigen la formación y el funcionamiento de las *foredunes*, así como sobre su naturaleza, los impactos ambientales a los que se pueden ver sometidas, o su gestión, se pone de manifiesto en la literatura científica que se ha publicado al respecto en las últimas décadas. Sin embargo, el grueso de esta literatura científica se ha centrado en los sistemas de dunas costeros localizados en áreas templadas del planeta, siendo escasa la investigación dirigida al estudio de las *foredunes* localizadas en regiones áridas. Así, el enfoque holístico de esta investigación, orientado específicamente hacía el conocimiento sobre la naturaleza, las amenazas y la gestión de las *foredunes* de sistemas sedimentarios eólicos áridos se puede considerar pionero. Por primera vez, se abordan cuestiones clave identificadas en la literatura y enteramente centradas en *foredunes* de costas áridas, como la interacción de los procesos biogeomorfológicos y las actividades socioeconómicas en la evolución de *nebkhas* y *foredunes* en climas con escasez de precipitaciones. Además, junto con trabajos recientes de miembros del Grupo *Geografía Física y Medio Ambiente* (IOCAG-ULPGC), los estudios presentados en los artículos suponen la consolidación de una línea de trabajo esencial para el conocimiento sobre la interacción playa-duna y el comportamiento de campos dunares en regiones áridas.

De este modo, el conocimiento detallado adquirido a través de este trabajo sobre la naturaleza de las *nebkhas* que conforman la *foredune* de los sistemas playa-duna áridos de las islas Canarias (Objetivos 1, 2), así como la identificación y caracterización de las actividades y usos humanos que las amenazan y sus efectos (Objetivos 2, 3, 4), ha servido para evaluar las medidas de gestión desarrolladas y analizar la respuesta ambiental de los sistemas (Objetivos 2, 3, 4, 5). Sobre esta base, se han propuesto algunas medidas de gestión y de restauración ambiental de estas *foredunes* que atienden a las especificidades climáticas, sociales y biogeomorfológicas de los sistemas playa-duna áridos (Objetivo 5).

La heterogeneidad en la selección de sistemas playa-duna localizados en sistemas sedimentarios eólicos de las islas Canarias, como área de estudio, en cuanto a su tipología, la vegetación presente, el aporte sedimentario, el nivel de protección y los usos humanos históricos y actuales desarrollados, convierten los resultados de este estudio en paradigma adaptable y aplicable en una amplia tipología de sistemas playa-duna localizados en distintas regiones áridas (BWh) del mundo.

Por otro lado, los resultados de esta investigación aportan conocimiento susceptible de contribuir al esfuerzo científico realizado en los últimos años en lo referente al desarrollo y aplicación de modelos conceptuales, físicos o numéricos, tanto para la evolución geomorfológica de sistemas playa-duna como para la dinámica eólica alrededor de determinadas geoformas eólicas u obstáculos. Así, se abre la posibilidad de adaptar, aplicar, calibrar y validar en sistemas playa-duna áridos: i) modelos de evolución morfodinámica costa-playa-duna (Bauer and Davidson-Arnott, 2002; Costas et al., 2020b; Delgado-Fernandez, 2011; Galiforni-Silva et al., 2020b, 2020a; Itzkin et al., 2021; Kombiadou et al., 2021; Moulton et al., 2021; Parteli et al., 2014; Pellón et al., 2020; Roelvink et al., 2009; Roelvink and Costas, 2019; Silva et al., 2019); y ii) de desarrollo de la *foredune* (Cohn et al., 2019; Davidson-Arnott et al., 2018; Delgado-Fernández, 2010; Goldstein and Moore, 2016; Keijsers et al., 2016; Zhang et al., 2015). Además, los resultados pueden contribuir al desarrollo de modelos que permitan: i) analizar la distribución de la vegetación (Badreldin et al., 2015; Charbonneau et al., 2022; Guisan et al., 2002; Kéfi et al., 2007; Quets et al., 2013); ii) analizar el flujo de viento y el transporte sedimentario eólico sobre superficies vegetadas (Cheng et al., 2018; Dupont et al., 2014; Gillies et al., 2014; Li et al., 2022; Liu et al., 2018; Mayaud et al., 2017b, 2016; Mayaud and Webb, 2017; Okin, 2008; Okin and Gillette, 2001; van Rijn, 2022; van Rijn and Strypsteen, 2020); y iii) analizar el flujo de viento y el transporte sedimentario sobre determinadas geoformas eólicas (Araújo et al., 2013; Hesp and Smyth, 2019b, 2017, 2016a; Jackson et al., 2013; Parsons et al., 2004a, 2004b; Piscioneri et al., 2019; Smith et al., 2017a; Smyth et al., 2019; Smyth, 2016; Smyth and Hesp, 2015; Wakes et al., 2010). Por último, se aporta información relevante para el desarrollo y aplicación de: i) modelos de distribución del flujo de viento y el transporte sedimentario eólico sobre elementos, naturales o antrópicos, que obstaculizan dicho flujo de viento (Eichmanns and Schüttrumpf, 2022; Lima et al., 2020; Poppema et al., 2021; Smith et al., 2017b; Wijnberg et al., 2021); y ii) modelos de evolución del paisaje (Baas, 2013; Baas and Nield, 2007; Keijsers et al., 2016; Kim and Yu, 2009; Marco et al., 2011; Mayaud et al., 2017a; Nield and Baas, 2008a).

Relación entre variables de control para la formación y evolución de* nebkhas *y* foredunes *áridas

Las particularidades naturales de los sistemas de dunas costeros de regiones áridas resultan en las *nebkhas* como unidades biogeomorfológicas fundamentales para estructurar la *foredune*. El artículo 1, "*Environmental variables affecting an arid coastal nebkha*", muestra que el surgimiento, crecimiento y desarrollo de estas *nebkhas* es resultado de la estrecha interdependencia entre variables de distinta tipología que, de manera ordenada, contribuyen a dicho fin. Este hecho provoca que estas unidades biogemorfológicas fundamentales de la *foredune* conformen, a su vez y por sí mismas, sistemas, que pueden ser más o menos complejos en función de la morfología, la configuración y la fisiología de la planta formadora. Las relaciones entre la morfología y configuración de la planta formadora de la *nebkha* y la altura de esta en relación con el sedimento atrapado han sido ampliamente estudiadas (Arens et al., 2001; Hesp, 1981; Hesp et al., 2019; Khalaf et al., 2014; Kidron and Zohar, 2016; Li et al., 2014, 2021; McGuirk et al., 2022; Pool et al., 2013), aunque no así las relaciones entre el enterramiento de las plantas formadoras de *nebkhas* y su crecimiento (Dech and Maun, 2006; Gilbert and Ripley, 2010, 2008; Luo and Zhao, 2019). Viera-Pérez (2015) documentó la activación del crecimiento que el enterramiento progresivo produce sobre ejemplares de *T. moquinii* y el efecto sinérgico que este crecimiento tiene sobre la retención de arena y el crecimiento simultáneo de la *nebkha* asociada, introduciendo la idea de considerar a las *nebkhas* como sistemas interdependientes en lo que denominó "sistema *Traganum*-montículo (STM)". Sin embargo, puesto que este proceso sinérgico no es exclusivo de *nebkhas* generadas por ejemplares de *T. moquinii* (Gilbert and Ripley, 2010; Maun, 1998; Maun and Lapierre, 1986), se podría definir como *sistema nebkha* aquellas dunas en montículo en las que se produce un crecimiento biogeomorfológico progresivo interdependiente por interferencia de la planta en la dinámica sedimentaria eólica. Así, los STM (Viera-Pérez, 2015) tratados en esta tesis serían un tipo concreto de *sistema nebkha* formado por ejemplares de *T. moquinii*.

Puesto que en condiciones naturales y bajo condiciones estables los *sistemas nebkha* dependen de un gran número de variables de distinta naturaleza, es lógico pensar que su surgimiento, crecimiento, desarrollo y mantenimiento estén condicionados por esta estabilidad y se puedan ver amenazados por cualquier cambio medioambiental significativo que interfiera en dichas variables o en los procesos que las interrelacionan.

Efectos de la actividad urbano-turística sobre la foredune y sus nebkhas

El uso intensivo que la actividad humana hace de los sistemas playa-duna resulta a menudo en la modificación y alteración (directa e indirecta) de los procesos y las dinámicas que rigen estos sistemas, lo que puede llevar a su pérdida y destrucción (Martínez et al., 2013). A través de los procesos y dinámicas, la actividad humana desarrollada en los sistemas playa-duna y sus alrededores es susceptible de alterar las características de la vegetación (Delgado-Fernández et al., 2019b; García-Romero et al., 2021; Hernández-Cordero et al., 2017; Kelly, 2016, 2014), la geomorfología (Ferrer-Valero et al., 2017; Hernández-Cordero et al., 2018; Marrero-Rodríguez et al., 2020a; Peña-Alonso et al., 2018b) y los patrones sedimentarios (García-Romero et al., 2019a; Jackson and Nordstrom, 2013, 2011; Marrero-Rodríguez et al., 2020b; Nordstrom et al., 2007; Poppema et al., 2022; Pourteimouri et al., 2021; Smith et al., 2017b). Puesto que la formación, el desarrollo y el mantenimiento de las *nebkhas* que conforman la *foredune* de sistemas áridos depende de la interrelación entre estas variables, las actividades, estructuras o usos que alteren las características de cualquiera de ellas pueden suponer una amenaza para la estabilidad y el funcionamiento de la *foredune*.

La actividad humana en el campo de dunas transgresivo de Maspalomas y sus alrededores, ligada al desarrollo urbano-turístico de las islas Canarias, como fuente de impactos ambientales ha sido anteriormente estudiada a distintas escalas (Cabrera-Vega et al., 2013a; García-Romero et al., 2021, 2019a, 2019b, 2016; Hernández-Calvento, 2006; Hernández-Calvento et al., 2014; Hernández-Cordero et al., 2018, 2012; Martínez, 1990; Ministerio de Medio Ambiente, 2007; Peña-Alonso et al., 2019; Pérez-Chacón et al., 2007; Smith et al., 2017b), pero pocos han puesto el foco concreto en las actividades humanas realizadas en la playa (Alonso, 1998; Díaz Guelmez and Hernández-Calvento, 2004; Hernández-Calvento, 2002; Instituto Tecnológico Geominero de España, 1990; Martínez, 1990; Ministerio de Medio Ambiente, 2007; Suárez Rodríguez and Hernández-Calvento, 1998). Hernández-Calvento et al. (2014) anticiparon que, si la presión derivada del turismo se mantenía, o incluso proliferaba, en áreas áridas y turísticas populares, aumentaría la evidencia de sistemas de dunas afectados por esta actividad, lo cual se confirma con la extensa investigación realizada en los sistemas de dunas de Canarias desde entonces, entre la que se incluyen los resultados publicados en el artículo 2, "*Spatiotemporal analysis of the impact of artificial beach strcutures on biogeomorphological processes in an arid beach-dune system*".

Debido a que se trata de sistemas activos en los que el transporte se inicia en la playa, los procesos naturales que se suceden hacia el interior de los sistemas están conectados, por lo que las interferencias que se produzcan en la playa repercutirán en todo el sistema. En tanto que la actividad humana autorizada en estos espacios está determinada por las decisiones de gestión llevadas a cabo por parte de las administraciones competentes, estas serán las responsables últimas de las consecuencias ambientales derivadas de dicha gestión. En el caso de la Playa del Inglés, como entrada al sistema de dunas transgresivo de Maspalomas, se ha detectado una incongruencia en tanto que la estabilidad relativa de la playa en el largo plazo (Alonso et al., 2001; Di Paola et al., 2020; Fontán-Bouzas et al., 2019) no es coherente con la pérdida documentada de superficie de la *foredune* (García-Romero et al., 2021; Hernández-Cordero et al., 2018), el déficit sedimentario en la *foredune* y en el conjunto del sistema de dunas (Ministerio de Medio Ambiente, 2007; Pérez-Chacón et al., 2007), y con el retroceso de la línea de costa en la playa de Maspalomas a la salida del sistema (García-Romero et al., 2019a, 2016; Hernández-Calvento, 2006; Hernández-Cordero et al., 2018). A la vista de estos datos, es lícito pensar que las actividades humanas desarrolladas en la playa estén relacionadas hasta cierto punto con esta circunstancia, promoviendo una estabilidad artificializada de la Playa del Inglés para su mejor aprovechamiento recreativo a costa de un déficit sedimentario en el interior y en la salida del sistema de dunas. La gestión de esta problemática se ve complicada por la distribución y reparto de las competencias por parte de las distintas administraciones responsables del espacio, lo que dificulta la unificación de los criterios de gestión. Así, en la actualidad, la gestión de los sistemas de dunas bajo figuras de protección ambiental están en manos de administraciones de carácter insular (en el caso concreto de Maspalomas, del Cabildo de Gran Canaria), mientras que la gestión de las playas es competencia de la Dirección General de la Costa y el Mar, del Ministerio para la Transición Ecológica y el Reto Demográfico, del Gobierno de España que, a niveles prácticos, tiene cedidas las competencias a las administraciones locales (en el caso concreto de Maspalomas, al Ayuntamiento de la Villa de San Bartolomé de Tirajana). La definición de una frontera administrativa entre la playa y las dunas es un hándicap para la gestión de los espacios, en tanto que estos son continuos y los impactos ocasionados por, o derivados de, la gestión de la playa se heredan en el interior de los sistemas de dunas, pudiendo permanecer y avanzar en el espacio y en el tiempo (Díaz Guelmez and Hernández-Calvento, 2004; Hernández-Calvento, 2006; Suárez Rodríguez and Hernández-Calvento, 1998). Otro factor importante a tener en cuenta en este sentido es la paradoja que genera el hecho de que la disponibilidad en la playa de algunos de estos servicios o actividades que pueden ser susceptibles de amenazar la geomorfología del espacio y, por tanto, su calidad ambiental, se valore positivamente para la obtención de determinadas certificaciones de calidad ambiental, como es el caso de la

Bandera Azul (Mir-Gual et al., 2015; Roig-Munar et al., 2018; Zielinski et al., 2019).

A la vista de esta problemática, es fundamental identificar y caracterizar de manera independiente y objetiva las fuentes de amenaza para los sistemas playa-duna áridos y sus efectos para poner de acuerdo a las administraciones implicadas en la gestión de estos espacios. Para ello, es imprescindible una estrecha colaboración y coordinación entre dichas administraciones y los organismos de investigación (binomio investigación-gestión) que garantice, por una parte, la aplicación de medidas de gestión basadas en el conocimiento científico y, por otra parte, que la investigación se nutra de las experiencias de gestión.

La identificación, caracterización y, en última estancia, gestión de las posibles amenazas para los sistemas playa-duna áridos procedentes de la actividad humana desarrollada en estos espacios, en general, y en su duna costera, en particular, requieren recurrir a su estudio en una escala de detalle. Del conjunto de actividades y usos humanos identificados como fuentes susceptibles de amenaza para las dunas costeras (Jackson and Nordstrom, 2011; Kutiel et al., 1999; Martínez et al., 2013; Zielinski et al., 2019) y, en particular, para los sistemas playa-duna áridos de Canarias (Cabrera-Vega et al., 2013a; García-Romero et al., 2016; Peña-Alonso et al., 2018b; Suárez Rodríguez and Hernández-Calvento, 1998) la construcción de cortavientos de piedra no había sido caracterizada y analizada en detalle con anterioridad.

La metodología empleada en el artículo 3, "*Effects of stone-made wind shelter structures over and arid nebkha foredune*", para caracterizar los efectos de la presencia de *goros* en la *foredune* de regiones áridas estructuradas por *nebkhas* es susceptible de ser reproducida en otros lugares donde aparecen estructuras similares, o adaptada en cierto modo para el estudio de los efectos de otras fuentes de amenaza similares, como quioscos o contenedores de basura. El análisis multiescalar realizado de los efectos que los cortavientos de piedra tienen sobre la *foredune* de sistemas playa-duna áridos es, además, paradigmático de cómo prácticas aparentemente inofensivas o con unos efectos puntuales localizados derivan en impactos a mayor escala cuando se acumulan debido al elevado número de personas realizando la misma actividad (Gross, 2018). La gestión de estas amenazas "invisibles" supone un reto para la gestión de los espacios, puesto que la falta de conocimiento sobre los efectos perjudiciales de la actividad lleva asociada, generalmente, una falta de regulación específica. Por ello, es necesaria la investigación que identifique estas amenazas y caracterice sus efectos sobre los procesos biogeomorfológicos a distinta escala, partiendo de las interferencias puntuales a nivel de detalle y llegando a una escala que permita interpretar las consecuencias sobre el conjunto del sistema playa-duna.

Potencial de recuperación pasiva y respuesta post-impacto en foredunes áridas

La gestión de las actividades y usos humanos que amenazan la formación y el mantenimiento de la *foredune* en sistemas playa-duna áridos no solo debe contemplar la regulación de dichas actividades, sino también facilitar la respuesta hacia la recuperación de las condiciones naturales de los sistemas una vez concluida la actividad. En este sentido, nuevamente, el conocimiento exhaustivo y detallado de las variables y los procesos biogeomorfológicos que rigen estos sistemas playa-duna áridos en condiciones naturales se hace imprescindible para poder evaluar la respuesta de estos espacios tras el cese de las actividades que generan algún tipo de impacto (Marrero-Rodríguez et al., 2020a). También, únicamente de este modo, tal y como se muestra en el artículo 3, se pueden obtener protocolos de actuación y restauración (si fuera necesario) lo suficientemente robustos para eliminar (en el caso de los *goros*), restaurar las geoformas eólicas y conservar los individuos vegetales asociados (*T. moquinii*) que han sido afectados.

El estudio de la respuesta de la *foredune* del sistema sedimentario eólico de El Médano cuatro décadas después del cese de una actividad humana que ha afectado al sistema playa-duna a nivel global puede servir como ejemplo de respuesta y adaptabilidad en el largo plazo de los sistemas playa-duna áridos a los efectos de las actividades que los amenazan. El uso desarrollado en el espacio, concretamente la extracción de áridos, provocó impactos en las características de las *nebkhas*, en la distribución de especies vegetales y en la topografía y disposición de sedimento (Marrero-Rodríguez et al., 2020a). La actividad humana ha interferido en la interrelación entre variables sedimentarias, de vegetación y de relieve que rigen el mantenimiento de las *nebkhas*, y los efectos se traducen en impactos que afectan al sistema playa-duna en general, y a su *foredune* en particular.

Los resultados del artículo 4, "*Foredune responses to the impact of aggregate extraction in an arid aeolian sedimentary system*" ponen de manifiesto como las amenazas susceptibles de interferir en los procesos biogeomorfológicos de los sistemas playa-duna áridos pueden dar lugar a cambios en el entorno que condicionen irreversiblemente la respuesta del sistema, especialmente en el caso de acciones que resulten en la modificación artificial de la topografía. El enfoque multiescalar en el análisis de la respuesta medioambiental del sistema ha mostrado que la distribución actual de las especies vegetales y del sedimento, así como los patrones de transporte sedimentario eólico actuales están condicionados por el uso histórico desarrollado. En el largo plazo, la situación actual, tras 40 años desde el cese de la principal actividad impactante, pone de manifiesto que las ya mencionadas especificidades climáticas y sociales de los sistemas áridos dificultan la recuperación espontánea de la vegetación y de los procesos biogeomorfológicos (Baasch et al., 2012; Duan et al., 2008; Fernández Montoni et al., 2014).

La respuesta adaptativa de los sistemas tras el cese de la actividad a las nuevas condiciones ambientales está ligada a su resiliencia geomorfológica (Kombiadou et al., 2019) que, a su vez, está influenciada por las medidas de gestión llevadas a cabo en los sistemas playa-duna (Peña-Alonso et al., 2018b). Así, la gestión no es sólo relevante a la hora de autorizar y desarrollar usos y actividades, sino también una vez finalizados estos. Es el caso de las medidas de gestión enfocadas hacia la recuperación natural o hacia la restauración de los sistemas. En cualquier caso, la primera medida de gestión imprescindible para la recuperación o restauración de un sistema playa-duna amenazado por una o varias actividades o usos debería ser el cese de dichas actividades impactantes. Tras ello, se requieren medidas de gestión específicas (e. g. vallado, restricciones de paso, etc.) incluso cuando se prevea promover la respuesta natural del sistema, para evitar la interferencia de la actividad humana.

¿Es posible restaurar la foredune y sus nebkhas tras estos impactos?

Las particularidades de los sistemas playa-duna de regiones áridas también son determinantes a la hora de implementar medidas para su restauración (Peña-Alonso et al., 2018b). Sin embargo, en España, estas particularidades no han sido consideradas en las herramientas de gestión desarrolladas para la restauración de dunas costeras (Ley et al., 2007), aplicándose generalmente medidas basadas en indicadores diseñados para regiones templadas (García-Mora et al., 2001, 2000). Este déficit de medidas se ha traducido en una falta de actuaciones específicas durante las últimas décadas para la protección y recuperación de la duna costera en los sistemas playa-duna áridos (García-Romero et al., 2021; Hernández-Calvento, 2006; Hernández-Cordero et al., 2012; Viera-Pérez, 2015).

La experiencia de restauración de la *foredune* de la Playa del Inglés realizada en el año 2018 y los resultados extraídos de su seguimiento científico, publicados en el artículo "*Coastal dune restoration in El Inglés beach (Gran Canaria, Spain): a trial study*", recogieron parte del conocimiento desarrollado hasta el momento sobre las particularidades de las *foredunes* de sistemas áridos y aplicaron de manera pionera medidas de restauración adaptadas a las especificidades ambientales y sociales de los sistemas playa-duna áridos. Los resultados mostraron la viabilidad de restaurar las *nebkhas* de la foredune sobre la base del conocimiento científico de la ecología de la vegetación (en este caso, *T. moquinii*) y de los procesos biogeomorfológicos que rigen la dinámica sedimentaria eólica que resulta en la formación y mantenimiento de la *foredune* (Viera-Pérez, 2015).

A su vez, el conocimiento adquirido durante el seguimiento de la ejecución de las medidas de restauración permitió validar y evaluar su eficacia, contribuyendo a la mejora del protocolo de restauración aplicado y poniendo de nuevo de manifiesto la eficacia del binomio investigación-gestión para la gestión efectiva enfocada a la conservación del espacio.

El seguimiento de las medidas de restauración de la *foredune* de la Playa del Inglés no sólo ha permitido ampliar el conocimiento en lo relativo a la recuperación ambiental de los sistemas playa-duna áridos, sino que ha contribuido, a su vez, a identificar y caracterizar nuevas amenazas (e. g. enterramiento súbito por reposición de arena) y a expandir la frontera del conocimiento referente a la naturaleza de las *nebkhas* que estructuran la *foredune* de estos sistemas.

El reto de la gestión de nuevas amenazas

El grueso de esta investigación en lo referente a la gestión y las amenazas de las *foredunes* de sistemas playa-duna localizados en regiones áridas se ha centrado en impactos procedentes o relacionados con la actividad humana. Sin embargo, existen otras amenazas para estos sistemas que suponen un reto para la gestión de estos espacios y que deben, cuando menos, ser aquí mencionadas para su posterior caracterización y análisis.

Efectos que amenazan la estabilidad de los ecosistemas costeros como la inundación por agua de mar, los daños e inundaciones por tormentas, la erosión costera o la intrusión salina, entre otros, pueden verse incrementados en un escenario de cambio climático que contemple aumento del nivel del mar, aumento de la intensidad y frecuencia de las tormentas o variaciones en el clima marítimo (Nicholls et al., 2007; Ranasinghe, 2016). La aceleración del aumento del nivel del mar y su continuidad en las próximas décadas (IPCC, 2021) repercute no solo en la erosión directa de las costas arenosas expuestas, sus playas y sus sistemas de dunas asociados (Amoura and Dahmani, 2022; Luijendijk et al., 2018), sino que puede inducir otros cambios ambientales que amenacen a la vegetación dunar. Entre estas amenazas se pueden incluir variaciones en el enterramiento de las plantas y en el ciclo global de algunos nutrientes debidas a cambios en la circulación atmosférica (Frosini et al., 2012), o alteraciones en la sucesión de especies (Feagin et al., 2005). Otras variables íntimamente relacionadas con el desarrollo y crecimiento de la foredune en sistemas playa-duna áridos, como la salinidad del suelo, el spray salino marino, el tamaño de grano que el oleaje pone a disposición de la dinámica eólica o la temperatura del sustrato también son susceptibles de verse afectadas por cambios medioambientales tanto a escala global como a escala local, por lo que se debe profundizar en el conocimiento que estos cambios pueden tener a medio y largo plazo sobre los sistemas. En este sentido, los sistemas playa-duna objeto de esta investigación son susceptibles de albergar estudios sobre los efectos potenciales del cambio climático en sistemas playa-duna de regiones áridas, puesto que se encuentran catalogados como zonas costeras de alto riesgo acumulado por cambio climático en Canarias (Gobierno de Canarias, 2022).

CONCLUSIONES

El establecimiento, mantenimiento y funcionamiento de la duna costera en ambientes áridos surge como resultado de un sistema complejo de interacciones entre controles que operan a una variedad de escalas (e. g. el transporte de sedimentos o el crecimiento de vegetación especializada) y cuya combinación da lugar a unidades biogeomorfológicas (nebkhas) singulares. La formación de nebkhas en ambientes costeros áridos depende, a escala de parcela o de geoforma, de las características de la planta formadora de la nebkha, de las propiedades del sedimento puesto a disposición de la dinámica eólica y de los atributos y características morfológicas que la propia nebkha va desarrollando a medida que se genera.

Interferencias humanas a distinta escala sobre las variables o procesos implicados en la formación de la foredune en ambientes áridos producen impactos sobre esta. Las playas suponen la principal fuente de aporte de sedimento a la foredune, a la vez que son zonas de gran ocupación y actividad humana. Esta investigación muestra cómo los usos humanos de la playa pueden afectar a la formación, el mantenimiento y el funcionamiento de las foredunes en estos ambientes.

La presencia de determinados servicios y equipamientos de playa puede transformar la morfología y la estructura de la *foredune* de sistemas sedimentarios eólicos áridos. Instalaciones en las playas como quioscos o conjuntos de hamacas y sombrillas, asociadas a decisiones de gestión de estos espacios, influyen en el estado de conservación o degradación de los sistemas de dunas asociados. Los efectos perjudiciales desencadenados por la presencia de estas estructuras, como es el caso de las superficies de deflación asociadas a los primeros quiscos instalados en Playa del Inglés en la década de 1970, pueden no solo mantenerse a lo largo del tiempo sino incluso incrementarse.

La relevancia de la gestión y el manejo de sistemas de dunas costeros áridos en general, y de sus playas en particular, no es solo fundamental en lo referente a infraestructuras y servicios, sino también en lo que corresponde a los usos permitidos en estos espacios. El trabajo presentado resalta algunos usos humanos percibidos como “inofensivos” pero que también pueden afectar a los sistemas a distinta escala espaciotemporal.

Una de estas actividades es la construcción y el mantenimiento de estructuras cortavientos (*goros*) realizadas con piedras sobre la playa y la *foredune*. A pesar de estar expresamente prohibidos en algunos lugares, es común encontrarlos en sistemas sedimentarios eólicos. La presencia de *goros* sobre las *nebkhas* interfiere en su funcionamiento natural, manteniendo artificialmente pendientes empinadas en los flancos de la *nebkha* y confinando volúmenes de arena que limitan la formación de dunas de sombra. Estas estructuras también reducen el crecimiento de la planta y modifican la porosidad de la *nebkha* frente al viento, limitando la capacidad de retención de sedimento en la *foredune* e, incluso, generando áreas de erosión. Los efectos ambientales de la presencia de *goros* se ven amplificados cuando hay un número elevado de usuarios que realiza una misma acción en un mismo lugar durante un largo periodo de tiempo. En este sentido, la alteración sobre los procesos biogeomorfológicos no es puntual sino acumulativa.

Los usos y actividades desarrollados, y su nivel de impacto, en las *foredunes* de sistemas playa-duna áridos condicionan la respuesta ambiental del sistema una vez cesa la actividad. En este trabajo se muestra la evolución de sistemas sometidos a actividades humanas que superan la capacidad de resiliencia del sistema, como el caso de la extracción de áridos en el sistema sedimentario de El Médano (Tenerife). En casos como este, puede que no ocurra la recuperación del sistema hacia los patrones naturales identificados antes del impacto. En su lugar, las dunas costeras fuertemente impactadas pueden evolucionar hacia una respuesta adaptada a las nuevas condiciones ambientales impuestas.

En determinados casos, el impacto humano es tal que la respuesta natural (respuesta pasiva) de los sistemas es insuficiente para paliar las consecuencias ambientales de la actividad humana sobre la *foredune* de sistemas sedimentarios eólicos áridos. En estos casos, se hacen necesarias estrategias de restauración activa enfocadas a la recuperación de la estructura y el funcionamiento de la duna costera. Para la implementación de dichas medidas de restauración se deberán tener en cuenta las especificidades climáticas, ambientales y sociales de los sistemas playa-duna en regiones áridas para adaptar los procedimientos a seguir.

Debido a la importancia ambiental, social y económica de los sistemas playa-duna en regiones áridas, y de las amenazas a las que se encuentran expuestos, es fundamental entender su funcionamiento natural y las interferencias producidas por las actividades humanas. Medidas basadas en el conocimiento científico, que incluyan información sobre la dinámica de las *nebkhas* en costas áridas, permitirán mejorar las acciones de gestión y, en su caso, de restauración, así como facilitar el uso sostenible de estos espacios y la conservación de sus funciones ambientales.

CONCLUSIONS

The formation, maintenance and functioning of foredunes in arid environments results from a complex system of interactions in which landforms and multi-scale processes combine to generate biogeomorphological units (*nebkhas*). The formation of *nebkhas* in arid coastal environments depends, at the plot or landform scale, on the characteristics of the *nebkha*-forming plant, the properties of the sediment available for aeolian processes and the morphology and morphodynamics generated by the evolving *nebkha*.

Human impacts at different scales interfere with the processes involved in foredune formation in arid environments. Beaches are the main source of sediment input to the foredune, as well as areas heavily occupied by human activities. This research illustrates how human uses of the beach can affect the formation, maintenance and functioning of foredunes of beach-dune systems of arid coastlines.

The presence of beach services and equipment can affect the morphology and structure of the foredune of arid aeolian sedimentary systems. These include kiosks, sunbeds and umbrellas, which are often a direct result of beach management decisions, and which affect the state of conservation or degradation of dune systems. The negative effects due to the presence of these structures has not only been maintained but also increased in some locations, as in the case of the deflation surfaces associated with the first kiosks installed in Playa del Inglés in the 1970s.

The management of human activities on arid coastal dune systems should therefore include the beaches in front, and it is not only fundamental to regulate facilities and services, but also a variety of uses. The work presented here highlights those certain human activities commonly perceived as ‘harmless’ that can affect arid coastal dune systems at different spatiotemporal scales.

One of such activities is the construction and maintenance of stone-made wind shelter structures (*goros*) on the beach and on the foredune. This is expressly prohibited in some places, yet common along many coastlines. The presence of *goros* over nebkhas interferes with their natural functioning, artificially maintaining steep slopes on the *nebkha* flanks and trapping large volumes of sand that limit the formation of lee-side shadow-dunes. These structures also reduce plant growth and modify the porosity and roughness of the *nebkha*, limiting sediment retention capacity of the foredune and even creating erosion zones. The environmental effects of *goros* increase with their number, and when many users build them at the same location over a long period, this affects the biogeomorphology of the entire foredune and dune field landwards.

The type of uses, and their level of impact on foredunes of arid beach-dune systems condition the environmental response of the system once the activity ceases. This work investigated the evolution of coastal dunes subject to human impacts that exceed the resilience of the system, as in the case of aggregate extraction in El Médano (Tenerife). In cases such as this, full recovery of natural patterns identified before the impacts may not happen. Instead, heavily impacted coastal dunes can evolve towards adaptation to the new imposed conditions.

In cases where the passive response of the system is insufficient to mitigate the impacts on the environment, active restoration strategies can aid in the recovery of the structure and functioning of the foredune and dune field. For a successful implementation of effective and sustainable restoration procedures, the climatic, environmental, and social characteristics of beach-dune systems in arid regions must be considered.

Due to the environmental, social, and economic importance of beach-dune systems in arid regions, as well as the threats identified, it is imperative to understand their natural functioning and the interferences produced by human activities. Science-based policies that include information on nebkha dynamics in arid coastlines will lead to improved management and, where appropriate, restoration actions, as well as facilitate the sustainable use of these spaces and the conservation of their environmental functions.

PERSPECTIVAS

Los resultados obtenidos en esta tesis doctoral permiten ampliar la línea de investigación en la que se insertan, acogiendo nuevas perspectivas de investigación que posibilitarán ampliar la frontera del conocimiento en lo relativo a las especificidades de las *foredunes* formadas por *nebkhas* en sistemas sedimentarios eólicos áridos en varias direcciones.

En lo relativo a su naturaleza:

- A escala de detalle y mediante la captación de datos en el campo por métodos experimentales, el estudio de los procesos sedimentarios eólicos (dinámica eólica y transporte sedimentario) que tienen lugar en distintas zonas de los sistemas *nebkha* y las *shadow dunes,* y sus posibles relaciones con variables del relieve, la vegetación y el sedimento podrán contribuir a la validación y mejora del modelo conceptual propuesto. La combinación de dicho modelo conceptual con futuros modelos numéricos abre la puerta a nuevos estudios cuyo objetivo sea cuantificar y predecir la dinámica de *nebkhas*.
- Con el objetivo de valorar si la heterogeneidad en la distribución espacial de las variables presente en las *nebkhas* repercute, a su vez, en el desarrollo de la planta, se propone profundizar en el conocimiento sobre la ecología de *T. moquinii*. Para ello, sobre la base de las investigaciones realizadas por Viera-Pérez (2015), se propone el diseño de ensayos de laboratorio sobre la germinación y el crecimiento de esta especie en distintas condiciones de salinidad, tamaño y naturaleza de grano, enterramiento o riego. Estos estudios también pueden constituir un avance que permita inferir sobre el comportamiento de las poblaciones de *T. moquinii*. Dado que el *T. moquinii* es la principal planta involucrada en la formación de *nebkhas* en Canarias, el estudio de sus cambios con variables como la temperatura o el aporte sedimentario contribuiría también al análisis de la evolución de las formas dunares asociadas bajo diferentes escenarios medioambientales.
- Es evidente el interés en estudiar en detalle el funcionamiento de los sistemas *nebkha* como elementos principales de las *foredunes* en

ambientes áridos. Sin embargo, además de las *nebkhas*, existen otras unidades comprendidas en las *foredunes* (*shadow dunes, tongue dunes*, espacios *inter-nebkha*…), por lo que es fundamental conocer el funcionamiento detallado de estas estructuras dentro de la *foredune* utilizando metodologías similares a las desarrolladas en esta investigación. Esto contribuiría a una mejor delimitación de las *foredunes* en ambientes áridos, identificando con mayor exactitud sus límites, así como a la caracterización de zonas de distinta vulnerabilidad dentro del espacio. Del mismo modo, es necesario extender los estudios realizados sobre *nebkhas* con *T. moquinii* a otras *nebkhas* localizadas en la *foredune* formadas por otras especies y comparar resultados.

- Se ha apuntado la necesidad de caracterizar la amenaza provocada por la erosión costera, para lo cual es necesario hacer un esfuerzo en la valoración de la aplicación de los modelos actuales de evolución del perfil playa-duna (generalmente 2D) a la tridimensionalidad intrínseca de una *foredune* formada por *nebkhas* y, en caso necesario, proponer y desarrollar modelos de acreción-erosión del perfil playa-duna (playa-*foredune* árida) adaptados a estos ambientes. Esta perspectiva toma especial relevancia en el contexto de un posible aumento de la erosión costera como consecuencia del incremento del nivel del mar y de tormentas, asociados al cambio climático.
- La evolución de sistemas playa-duna con el aumento del nivel del mar en zonas áridas está por estudiar. Los últimos años han visto el desarrollo de varios modelos conceptuales y numéricos que indican que las costas arenosas no tienen por qué erosionarse con el ascenso del nivel del mar si hay espacio para que el sistema sedimentario migre tierra adentro (e.g. Davidson-Arnott and Bauer, 2021). Esta migración también será en la vertical, permitiendo el mantenimiento de los volúmenes de arena guardados en cada zona del perfil costero (*nearshore, beach, dunes*). Dichos modelos están adaptados, sin embargo, a zonas costeras en latitudes templadas, caracterizadas por *foredunes* continuas y campos dunares con vegetación. Hasta el momento no hay estudios sobre los mecanismos involucrados en la evolución de *nebkhas* y campos dunares áridos como respuesta al ascenso del nivel del mar.

- Tal y como se ha puesto de manifiesto, el conocimiento derivado de esta investigación es susceptible de ser aplicado de manera general en sistemas playa-duna localizados en otras zonas del planeta con características climáticas similares (Sahara Occidental, Mauritania, Australia…). Sin embargo, cada una de estas zonas podrá estar sujeta a sus propias especificidades en lo referente a la vegetación. Por ello, se propone ampliar el muestreo a otras zonas de estudio localizadas en sistemas playa-duna áridos con el objetivo de validar allí la aplicabilidad de los resultados obtenidos para los sistemas playa-duna áridos de Canarias.

En lo referente a los distintos efectos que la actividad humana tiene sobre ellas:

- Sobre la base de las amenazas analizadas, se hace necesario seguir identificando, caracterizando y analizando actividades, usos y estructuras artificiales desarrolladas en el interior y los alrededores de los sistemas playa-duna áridos susceptibles de amenazar la formación, desarrollo y mantenimiento de las funciones naturales de la *foredune* en estos sistemas. La identificación de estas actividades, usos y estructuras artificiales, así como la caracterización de la amenaza que suponen, es fundamental para desarrollar medidas de gestión que minimicen el posible impacto sobre los sistemas playa-duna de regiones áridas.
- Se ha puesto de manifiesto la importancia de los efectos que las actividades realizadas en las playas que funcionan como áreas de entrada de sedimentos tienen sobre los patrones sedimentarios de los sistemas playa-duna. Sin embargo, no solo las actividades, servicios e infraestructuras localizadas en las playas son susceptibles de ocasionar impactos sobre estos sistemas. Se propone identificar y, en su caso, caracterizar las posibles amenazas antrópicas para los sistemas playa-duna áridos localizadas tanto en el interior de la *foredune* como a sotavento de estas (e.g. carreteras que atraviesan longitudinalmente la *foredune* como es el caso de Caleta de Famara, en Lanzarote).
- Valorar, a distinta escala, la amenaza de nuevas fuentes de impacto humano sobre estos sistemas que no han sido contempladas hasta el momento (e.g. posibles efectos de plásticos y microplásticos).

- Se propone implementar técnicas de modelado físico (túnel de viento) y numérico (dinámica de fluidos computacional) para estudiar en detalle las interferencias que los obstáculos localizados en la playa y la *foredune* provocan sobre la dinámica eólica y el transporte sedimentario, así como sobre la vegetación presente a sotavento de estos obstáculos. También se plantea el uso de estos modelos para proponer y valorar alternativas de diseño de instalaciones, infraestructuras y equipamientos con formas aerodinámicas que minimicen el efecto adverso sobre la dinámica sedimentaria eólica.
- La perspectiva propuesta del estudio de la amenaza debido a la erosión costera deberá contemplar necesariamente escenarios de cambio climático. La amenaza a las *foredunes* de regiones áridas, derivadas del cambio climático, se deberán contemplar desde la perspectiva natural, pero también desde el plano socioeconómico, en tanto que este afectará a la actividad humana desarrollada en torno a los sistemas playa-duna áridos.
- De forma similar a lo anteriormente propuesto con respecto a ampliar la zona de estudio a otros sistemas playa-duna áridos en el mundo y con distintas condiciones de vegetación, se propone contemplar la ampliación del área de estudio a otras *foredunes* áridas sometidas a distintos niveles de presión antrópica, en las que se realicen o se hayan realizado actividades y usos del espacio, distintos de los aquí estudiados, que puedan amenazar el correcto desarrollo y mantenimiento de los sistemas playa-duna áridos.

En cuanto a la restauración y recuperación de estos sistemas:

- Dentro del proceso de revisión, evaluación y mejora que debe acompañar a las acciones de restauración, se propone la experimentación, el seguimiento y la evaluación de distintas estrategias de restauración adaptadas a las especificidades de las *foredunes* áridas que contribuyan a mejorar los protocolos de restauración ambiental en estos ambientes, atendiendo, ente otros factores, al diseño y disposición de captadores, a las características y cuidados de la vegetación trasplantada, o a los métodos de seguimiento de las acciones llevadas a cabo.
- Los resultados obtenidos del experimento de desmantelamiento de estructuras de piedra cortavientos a escala de *nebkha* evidencian una respuesta positiva de la unidad biogeomorfológica hacia la recuperación de

sus condiciones naturales. Es necesario, pues, valorar en una escala espaciotemporal superior la respuesta de la *foredune* a la retirada progresiva de todas las estructuras cortavientos construidas sobre ella.

- Se propone evaluar la respuesta y, en su caso, la recuperación de sistemas playa-duna localizados en regiones áridas alrededor del mundo donde se hayan aplicado distintas estrategias de gestión y restauración, con el objetivo de comparar los resultados con aquellos derivados de la presente investigación y desarrollar protocolos universales para la restauración de sistemas playa-duna áridos.

FORMACIÓN, INTERNACIONALIZACIÓN, PRODUCCIÓN CIENTÍFICA, DIVULGACIÓN, DOCENCIA, PARTICIPACIÓN EN PROYECTOS Y TRANSFERENCIA

El desempeño de la actividad investigadora durante el periodo del doctorado que ha dado lugar a la presente tesis doctoral se ha complementado con otras actividades de distinto tipo que han contribuido a la formación y a la consecución de los objetivos transversales planteados. Entre estas actividades podemos destacar las siguientes:

ACTIVIDADES FORMATIVAS

a) Programa de Doctorado

- Introducción a Matlab y R. 60 horas. Sobresaliente.
- Ocean Data View. 60 horas. Sobresaliente.
- Búsqueda de referencias bibliográficas sobre resultados de investigación. 10 horas. Sobresaliente.
- Presentación pública de trabajo de investigación desarrollado. 10 horas. Sobresaliente.

b) Actividades formativas complementarias

- Competencias digitales en la gestión de la información. ULPGC. 25 horas.
- Recursos e índices para la valoración de publicaciones periódicas para la acreditación y reconocimiento de tramos de investigación. ULPGC. 30 horas.
- Gestión de referencias bibliográficas con Mendeley. ULPGC. 25 horas.
- Redacción de artículos científicos en ciencias. ULPGC. 6 horas.
- Herramientas Office 365 para el docente. ULPGC. 15 horas.
- Uso eficaz de las tecnologías de la información y las comunicaciones para la realización de la tesis doctoral. ULPGC. 8 horas.
- Cómo evitar el plagio. ULPGC. 25 horas.

- MATLAB Tools for teaching and learning. ULPGC. 4 horas.
- Inglés para la comunicación científica: características y herramientas. ULPGC. 15 horas.

MOVILIDAD A OTROS CENTROS DE INVESTIGACIÓN O UNIVERSIDADES

- Edge Hill University (Reino Unido). Del 15/12/2020 al 15/03/2021. Estancia en el Departamento de Geografía y Geología bajo la supervisión de la Dra. Irene Delgado Fernández para la adquisición de competencias en la obtención, procesado y análisis de datos de viento y transporte de sedimento.
- Universidad do Algarve (Portugal). Del 26/09/2022 al 06/11/2022. Estancia en el Centre of Marine and Environmental Research (CIMA) bajo la supervisión de la Dra. Susana Costas para profundizar en el conocimiento sobre modelado morfodinámico de dunas costeras.

COAUTORÍA DE ARTÍCULOS CIENTÍFICOS

- Pinardo-Barco, S., Sanromualdo-Collado, A. and García-Romero, L. Environmental effects of intensive beach cleaning using heavy-duty machinery on an arid beach-dune system. (*with editor after peer review in Journal of Environmental Management).*
- Marrero-Rodríguez, N., García-Romero, L., Sanromualdo-Collado, A., Peña-Alonso, C. (*in press*). Las campañas de voluntariado como herramienta didáctica en Geografía. *Didáctica geográfica.*

DIVULGACIÓN CIENTÍFICA

a) Participación en congresos internacionales

- *VII International Symposium on Marine Sciences*. Barcelona, julio de 2020. Presentación del poster "Interaction between different nature variables affecting arid nebkha foredunes".
- *Oxford Geoheritage Virtual Conference*, junio de 2022. Participación en la ponencia "Urban-touristic impacts on the natural geoheritage of the aeolian sedimentary systems from Canary Islands (Spain).

- *VIII International Symposium on Marine Sciences*. Las Palmas de Gran Canaria, julio de 2022. Presentación del poster "The impacts of beach kiosks on arid foredunes".
- *VIII International Symposium on Marine Sciences*. Las Palmas de Gran Canaria, julio de 2022. Participación en el poster "A preliminary study about changes on aeolian sedimentary dynamics in beach-dune systems through long-term monitoring of vehicle tracks and heavy-duty machinery in El Inglés beach (Gran Canaria, Spain)".
- *VIII International Symposium on Marine Sciences*. Las Palmas de Gran Canaria, julio de 2022. Participación en el poster "A sudden beaches formation on the coastal lava-deltas of the 2021 volcanic eruption on La Palma".
- *9th Biennial International Tourism Studies Association*. Gran Canaria, julio de 2022. Participación en el poster "Monitoring the socio-economic impact of COVID-19 in the Maspalomas touristic area".

b) Participación en congresos nacionales

- Miembro del Comité Organizador de las *Jornadas Técnicas "La capacidad de carga a debate"*. Las Palmas de Gran Canaria, noviembre de 2019.
- *X Jornadas de Geomorfología Litoral*. Castelldefels, septiembre de 2019. Presentación de la ponencia "Resultados preliminares del análisis de relaciones entre variables ecológicas y sedimentológicas en la foredune de un sistema de dunas árido".
- *XI Jornadas de Geomorfología Litoral*. Santiago de Compostela, julio de 2022. Presentación de la ponencia "Cortavientos de piedra sobre nebkhas áridas: anatomía e impactos".

c) Otras actividades de divulgación científica

- Participación en la sección "*Preséntame tu tesis*" del programa *El Laboratorio* de RTVC.
- Participación en *Macaronight – La noche de los investigadores*. Septiembre 2021. Presentación de la ponencia "Impactos humanos sobre la Reserva Natural Especial (RNE) de las Dunas de Maspalomas".
- Participación en *XVIII Feria de la Ciencia de La Orotava*. Noviembre de 2021.

- Coautoría del artículo "COVID-19: ¿Se han recuperado las dunas de Maspalomas durante el confinamiento?", publicado en *The Conversation* (España) en julio de 2020.
- Participación en las *I Jornadas sobre la Cultura de la Sostenibilidad "Las Ciencias Aplicadas al Servicio de los ODS en Nuestra Sociedad"*, organizadas por el Ayuntamiento de la Villa de San Bartolomé de Tirajana en marzo de 2022.

PARTICIPACIÓN EN ACTIVIDADES DOCENTES

- Desempeño de un total de 28 horas de actividad docente en la asignatura "Análisis y modelización territorial en Geografía" del Grado de Geografía y Ordenación del Territorio de la Universidad de Las Palmas de Gran Canaria durante los cursos 2019/2020 y 2020/2021.
- Desempeño de un total de 23 horas de actividad docente en la asignatura "Tecnologías de la Información Geográfica" del Grado de Geografía y Ordenación del Territorio de la Universidad de Las Palmas de Gran Canaria durante los cursos 2020/2021 y 2021/2022.
- Desempeño de un total de 3 horas de actividad docente en la asignatura "Cartografía básica en Geografía" del Grado de Geografía y Ordenación del Territorio de la Universidad de Las Palmas de Gran Canaria durante el curso 2020/2021.
- Impartición del taller "Modelización territorial mediante Sistemas de Información Geográfica" de 3 horas de duración en el marco de la asignatura "Análisis y modelización territorial en Geografía" del Grado de Geografía y Ordenación del Territorio de la Universidad de Las Palmas de Gran Canaria. Octubre 2021.
- Impartición del taller "Análisis local mediante Sistemas de Información Geográfica" de 3 horas de duración en el marco de la asignatura "Tecnologías de la Información Geográfica" del Grado de Geografía y Ordenación del Territorio de la Universidad de Las Palmas de Gran Canaria. Octubre 2021.
- Participación como docente invitado con la conferencia "Impactos humanos sobre la RNE de las Dunas de Maspalomas (Gran Canaria)" de 2 horas de duración en el marco de la asignatura "Cultura, Medio

Ambiente y Sociedad" del Grado de Ingeniería Ambiental de la Universidad Rey Juan Carlos. Diciembre 2020.

- Codirección del Trabajo de Fin de Grado en Geografía y Ordenación del Territorio "Riesgo asociado al incremento del nivel del mar en la costa de los municipios de Arucas y Moya en el contexto del cambio climático global", realizado por Carlos Avigdor Suárez Pérez para la Universidad de Las Palmas de Gran Canaria.
- Supervisión del Trabajo de Fin de Grado en Ciencias del Mar "Afecciones de vehículos y maquinaria pesada de limpieza debido al crecimiento turístico y residencial en el sistema playa-duna de Maspalomas (Sur de Gran Canaria, España)", realizado por Silvia Pinardo Barco para la Universidad de Alicante.

PROYECTOS DE INVESTIGACIÓN

- Miembro del equipo de trabajo en el proyecto "Los sistemas playa-duna áridos ante el Cambio Climático" (CEI2020-10), financiado por la Agencia Canaria de Investigación, Innovación y Sociedad de la Información.
- Miembro del equipo de trabajo en el proyecto "Análisis de procesos naturales y humanos asociados a los sistemas playa-duna de Canarias" (CSO2016-79673-R), financiado por el Ministerio de Economía y Competitividad.
- Miembro del equipo de trabajo en el proyecto "Creación de herramientas para el monitoreo del impacto socioeconómico de la COVID-19 en el entorno turístico de Maspalomas" (COVID-19-12), financiado por la Universidad de Las Palmas de Gran Canaria.
- Miembro del equipo docente en el proyecto "Georrutas, usando el entorno como recurso educativo". Curso 2021 – 2022. Financiado por la Consejería de Educación, Universidades, Cultura y Deportes del Gobierno de Canarias.

TRANSFERENCIA DE CONOCIMIENTO

- Monitor en la actividad "Salida interpretativa al entorno cercano del espacio natural protegido: las Dunas de Maspalomas (Gran Canaria)", organizada para los alumnos de 4º de E.S.O. del I.E.S. Carrizal el 13 de junio de 2022.

- Participación en las Jornadas Masdunas III organizadas por el Cabildo de Gran Canaria, con la ponencia "Efectos de uso público en la playa del Inglés sobre la duna costera".
- Presentación de resultados de investigación y puesta en común en reuniones con agentes responsables de la gestión de la Reserva Natural Especial de las Dunas de Maspalomas y su entorno (Dirección General de Costas, Cabildo de Gran Canaria, Ayuntamiento de la Villa de San Bartolomé de Tirajana, asociaciones de hosteleros…).
- Miembro del grupo de trabajo encargado de la adaptación al castellano del proyecto "Coasts for Kids".

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